RMIT UNIVERSITY

Wind analysis in the early design stage:
An empirical study of wind visualisation techniques for architects

A thesis submitted in fulfilment of the requirements for the degree of Doctor of Philosophy

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Declaration

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March 2015

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Abstract

This research develops a study about wind analysis techniques for rapid wind visualisation in the early design stage. It develops protocols for rapid visualisation and evaluation of wind phenomena around groups of buildings and complex architectural and urban windbreak screen morphologies for feedback into design.

Interaction between wind and buildings produces aerodynamic phenomena, affecting the comfort level of pedestrian areas in urban environments. For this reason, architects have incorporated, in the design process, wind analysis technologies and expert consulting, to anticipate the possible wind effects that could require mitigation measures and even modifications in the final form of a project. In this sense, wind analysis in the earlier stage of the design process is a strategy that allows architects to consider wind in the conceptual designs of a project and to develop more sophisticated strategies to interact with and mitigate wind phenomena.

Examples of the integration of wind visualisation in the early design stage are the CFD-PST (computational fluid dynamics - performance sketch tools), which have been developed to facilitate basic and preliminary wind analyses, conducted by architects, in the first stage of the conceptual design process. Previous research has addressed their impact in the design process and architects' practice (including other analysis and simulation programs) with comparisons between programs and interviews with architects. However, the performance of CFD-PST in resolving the problem of rapid wind visualisation for architects has not been well evaluated in more complex scenarios than those originally proposed, for instance, with multiple buildings or with wind porous architectural screens or in comparison with other techniques such as physical visualisation methods.

The aim of this research is to investigate, through empirical wind visualisation studies

and architectural explorations of windbreaks, the CFD-PST and other techniques for rapid wind visualisation, in order to evaluate their efficacy for architects' practice in the early design stage. The results of this research present an evaluation of these wind visualisation technologies as a clear hierarchy of efficacy for rapid feedback, regarding requirements of visualisation complexity and extension of generation process. In addition, the study suggests architectural protocols for rapid visualisation and feedback in design process workflows. Finally, this research examines design rules of aerodynamic features, through rapid wind visualisation, to improve architectural exploration of windbreak design, for outdoor microclimatic control.

The topics explored in these investigations have been presented in the conferences eCAADe[1] 2012, 2013, 2014, CAADRIA[2] 2014 and SimAUD[3] 2015 (see appendix).

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[1]Education and research in computer aided architectural design in Europe conference
[2]Computer-aided architectural design research in Asia conference
[3]Symposium on Simulation for Architecture and Urban Design

Glossary

Glossary of terms

(Mini) airflow tunnel: for this research a mini airflow tunnel is a small scale and low-tech wind tunnel used to visualise the air moving past solid objects. It is called a low-tech mini airflow tunnel because it is a low cost, hand-made tool for small experiments of airflow visualisation, but without an accurate wind flow simulation.

Beaufort scale: empirical measure that relates wind speed to observed conditions at sea or on land. It is used as wind comfort criterion.

Building performance simulation: programs to simulate and predict the performance of a building design (energy consumption, performance of ventilation systems and other design strategies).

Boundary layer: the layer of fluid in the immediate vicinity of a bounding surface where the effects of viscosity are significant. The atmospheric boundary layer (ABL) is the lowest part of the atmosphere and its behaviour is directly influenced by its contact with the land, decreasing the velocity near the ground.

Bubble test: is a visualisation technique for physical experiments that use a flow of gas bubbles transported by wind.

Canyon effect: vortex of airflow in a street that is flanked by buildings on both sides creating a canyon-like environment. This configuration modifies both the speed and the direction of winds, when the wind flows perpendicular to the canyon.

Channel effect: airflow that runs parallel to a street flanked by buildings on both sides, increasing the airflow velocity.

CFD: computational fluid dynamics. It is the term given to a variety of numerical mathematical techniques applied to solving the equations that govern fluid flows and aerodynamics.

CFD-PST: computational fluid dynamics - performance sketch tool. It is a definition for CFD simulation and analysis programs that are targeted at the early design stage. They are more simplified tools than traditional CFD software, developed for users without a theoretical background in aerodynamics, such as architects, and they provide more simple visualisations and less accurate outcomes for rapid feedback.

Contour plots: a graphic representation for 2D visualisation of CFD results. It is a map of lines indicative of some property that is constant in the space (also called isoline or isocurve).

Corner effect: is when the wind flow changes the direction and accelerates around the edges of a building face.

Digital mesh: the computational domain is split up into a number of elements or cells defining the discrete points at which the numerical solution is computed. The points are normally the cell centres or cell vertices. Another name used for the digital mesh is grid (Vasari).

Domain: the geometrical region over which a simulation is performed. Sometimes referred to as the analytical domain or computational domain.

Downwash effect: is the change in direction of air vertically deflected by the façade to the bottom of a building.

Eddy: is the swirling of a fluid and the reverse current created when the fluid flows past an obstacle.

Elevated vortex pair: two upward airflows with a spiral movement behind a solid object in the wake region.

Erosion test: is a visualisation technique for physical experiments that use particles transported by wind to print movement patterns on the ground.

Freestream flow: is the flow ahead of and outside of the immediate influence of the body.

Horseshoe vortex: is a vortex of strong winds that form around the base of a tall building.

Isosurface: is an equivalent graphical representation in three dimensions of contour plots or isolines.

Leeward-side reattachment line: boundary of the cavity zone, behind a building, at ground level, where there is a divergence of airflow directions.

Numerical simulation: is the simulation based on computer models where equations are numerically solved.

PIV: particle image velocimetry. It is an optical method of flow visualisation and measurement of velocities in fluid, tracking particles in the flow.

Separation zone: area where a wind boundary layer separates from a surface or at an edge.

Shear layer: is a flow region that separates freestream flow on one side from the wake region.

Stagnation point: point on the windward face of a taller building where wind is deflected in several directions and the local velocity of the airflow is zero.

Streamlines: graphical representation of curves that are instantaneously tangential to the velocity vector of the flow. In a visualisation, these show the direction a massless fluid element will travel in at any point in time.

Vector field: graphical representation of a flow in a region by the assignment of a vector (arrow) to each point in the space. It is used for wind visualisation and it can represent wind direction and speed (by the size of the arrow).

Venturi effect: is the reduction in fluid pressure that results when a fluid flows through a constricted section of pipe. As a result the velocity of the flow increases in the constricted section. In an urban environment this effect can be observed on gaps in façades or indoor passages.

Vortex: spiral movement of air that increases the wind speed.

Wake region: is the region of recirculating airflow immediately behind a building.

Wind tunnel: tool used to study the effects of air moving past solid objects. It consists of a tubular passage with the object under test mounted in the middle, and the air flowing on the object via a powerful fan system. For architecture analysis it is used the atmospheric boundary layer wind tunnel, which produces an effect of decrease in the airflow velocity near ground.

Wind velocity profile: is a graphical representation of vertical gradient of the mean wind speed, which can be flat at the high level or parabolic near the ground.

Wind visualisation technique: method to graphically visualise the wind movement around a solid object or display information of wind properties. These techniques can be numerical CFD programs, programs of PIV or wind tunnels.

2D and 3D wind flow simulation: numerical simulation of a fluid moving in a 2D or 3D domain. In the case of a 2D domain, the fluid can only move vertically or horizontally.

Acronyms

ABLWT: atmospheric boundary layer wind tunnel.

BPS: building performance simulation.

EDS: early design stage.

CFD: computational fluid dynamics.

CFD-PST: computational fluid dynamics - performance sketch tool.

CAADRIA: computer-aided architectural design research in Asia conference.

DNS: direct numerical simulation.

eCAADe: education and research in computer aided architectural design in Europe conference.

JPIV: Java based Particle Image Velocimetry.

LES: large eddy simulation.

MAT: mini airflow tunnel.

PIV: Particle Image Velocimetry.

RANS: Reynolds Averaged Navier-Stokes.

RMIT: Royal Melbourne Institute of Technology.

SIAL: Spatial Information Architecture Laboratory.

SimUAD: symposium on simulation for architecture and urban design.

CHAPTER 1

Introduction

1.1 General statement

Research aim

The aim of my research is to critically assess techniques of wind visualisation and analysis, called computational fluid dynamics - performance sketch tools (CFD-PST), used for the early design stage of designing structures and building groupings, in order to evaluate the performance of these techniques for more complex scenarios than buildings with a closed form. This can contribute to establishing protocols for rapid wind analysis in early design stage and elements for a basic criterion of improvement for these rapid wind visualisations tools.

These CFD-PST (named by Emanuele Naboni) are aimed at architects and designers for wind analysis of building design concepts in scenarios where the main geometric configurations are regular prisms or an urban configuration with canyon and channel geometries. However, it is not clear to what extent these tools fulfil the design process of more sophisticated strategies to interact with wind phenomena in outdoor environments, such as controlling the gradual boundaries of wind protection and comfort regions in pedestrian areas, using artificial screens with aerodynamic features (Figure 1.1).
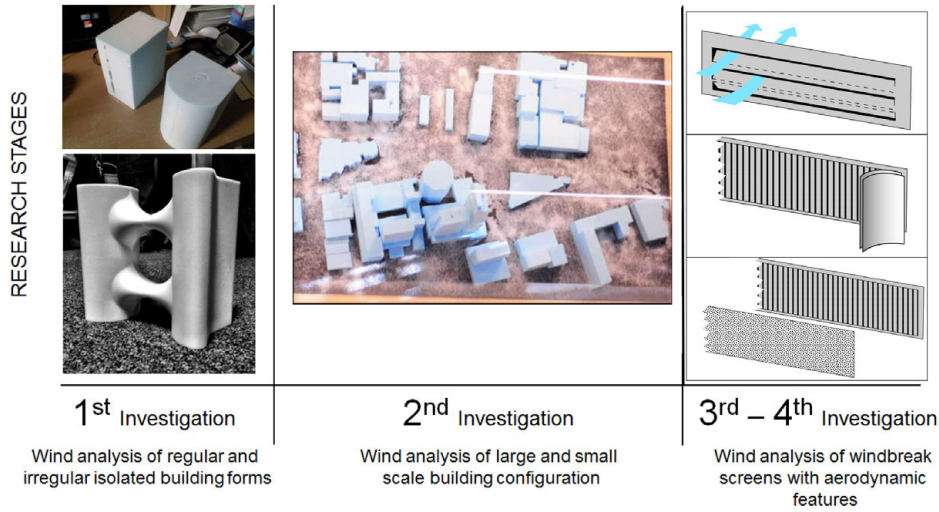
Figure 1.1: Spatial contexts of wind analysis in the early design stage. Left: wind flow around an isolated building. Middle: wind analysis through a built environment. Right: wind analysis around permeable structures with aerodynamic features to produce wind mitigation and protection regions in the outdoor environment. (Source: left and middle: author. Right: Author's sketch based on (Gandemer et al. 1978).)

I define this aim for my research because I consider the wind visualisation in the new CFD-PST programs as crucial in the further development of these tools that allow architects to use the wind as a creative strategy from the early design stage. More than numerical simulation methods, this research emphasises the visualisation method to observe the dynamics of wind, an aspect that I think is more relevant at the beginning of the design process. Moreover, previous research has not given enough relevance to this area in the analysis of a new generation of CFD-PST tools, because they have not critically evaluated these visualisation techniques in more complex scenarios of application or with more sophisticated designs. This level of evaluation could lead to new ways for improvements in the development of wind analysis tools for architects.

My research does not try to develop new technologies, and it is not a technical analysis about the accuracy levels of this simulation tools. The aim of this research is to identify the current scope and boundaries where wind visualisation with CFD-PST is dealing with the current requirements of architects for wind analysis in the early design stage. This work will allow designers to know what they can expect from this new generation of CFD-PST programs, and will provide some suggestions for methodological use of wind analysis

tools to facilitate rapid feedback at the beginning of the design process.

Research question

Previous research that has studied the use of building performance simulation tools (BPS) in the design process, has not given enough critical attention to techniques of digital wind visualisation and analysis, developed to be used by architects (CFD-PST), for preliminary wind analysis of concept designs (see literature review section). In general, they have been focused on general aspects of these tools and their impact in the architect's work, without analysing the limitations of the visualisation experience provided by these techniques that are different from traditional and more sophisticated CFD software used by external consulting and wind engineering.

According to the previous arguments developed here, a main question of this research is:

To what extent has CFD-PST technology contributed solutions to the problem of wind visualisation and analysis for architects in the early design stage?

I consider this question as the best way to start an exploration about the current status of architects' wind visualisation, during concept design. Through this question my research analyses the limits of some representative CFD-PST programs that allow architects to explore concept design with wind analysis as part of the form-making process.

Method and secondary objectives

My research is defined as a PhD by project. Therefore, to investigate the research question I worked with several techniques of wind analysis, conducting empirical experiments of rapid wind visualisation, through four investigation projects. These projects involved visualisation, observation and design exploration, following the experiences and methods of workshops developed by professors Manuel Casanueva, Michael Hensel and Achim Menges. This method is the most convenient strategy for a qualitative approach based on direct observations of a subject under practice (wind visualisation feature). This is something relatively unusual considering the current works developed by previous researchers such

as E. Naboni (2013) and F. Farias (2013) who have conducted studies with surveys and interviews of architects. As a final definition, for the purpose of this research, I define a rapid wind visualisation process as a method of visualisation of wind phenomena, with a short and simplified set up step of wind parameters, a graphical visualisation of results for a rapid feedback and a qualitative level of analysis.

The research stages have four secondary objectives developed through four investigation projects. These objectives are to evaluate:

- CFD-PST and other techniques for rapid visualisation of main wind movement patterns around an isolated closed building form

- CFD-PST for rapid visualisation of the main wind movement patterns through a large built environment and around an artificial windbreak in a local context

- CFD-PST and CFD for rapid visualisation of wind flow through isolated windbreak screens with aerodynamic features

- CFD-PST and other techniques for rapid visualisation of wind flow through a configuration of parallel windbreak screens with aerodynamic features (for an urban shelter)

This group of secondary objectives provide the observations and outcomes to expose the high and low performance of these tools for early design stage requirements and to define the key elements for a better rapid feedback process for wind analysis in the early design stage. Besides, the intention is to propose some protocols for rapid wind visualisation in complex workflows, for rapid design evaluation based on wind analysis of windbreak features and for a better wind visualisation experience in the early design stage.

The criterion of evaluation changes from one investigation to another, trying to go through each objective with an approach related to the experiment aims in each stage. Even though the criteria are explained in detail at the beginning of each chapter, in general, they are a qualitative assessment that considers the performance of the technique to resolve several tasks during the experiments, being categorised as "yes", "no", "yes/difficult",

"yes/easy" or "yes/complex" to the tool and its rapid visualisation process. In addition, observations about potential incidences in the early design stage are registered during each task. For the first investigation these tasks are the visualisation of certain wind phenomena around isolated buildings already classified by the literature. In the second investigation, the task is the identification of several urban wind phenomena from different visualisation methods (horizontal or vertical wind visualisation). For the third investigation the task is the visualisation of wind phenomena associated with a windbreak barrier (vertical wind deflection, wake region). Finally, in the last investigation, the requirements consider some functionality of the tools for wind analysis and a focused visualisation of specific wind phenomena associated with the aerodynamic features of a windbreak.

My approach is an exploratory work with a qualitative analysis where I have observed the work developed by other users using these wind visualisation techniques, but also conducted experiments where I actively manipulated conditions to analyse the relationship between the digital technique of wind visualisation and the analysis of preliminary design concepts. I think that a qualitative approach in the observation of experiments is the best way to evaluate these programs under rapid wind visualisation tests because, in that way, the exploration of their possible limitations and performance can consider contextual conditions.

The investigative projects have two parts: the first part was the selection of wind visualisation techniques to be tested. This area included a group of wind analysis software programs, the elaboration of two hand-made mini airflow tunnels and the development of experiments in an atmospheric boundary layer wind tunnel (ABL). The second part of the projects was to design a group of aerodynamic experiments to address three analysis contexts with a progressive geometrical complexity:

- aerodynamic phenomena around closed building forms, such as boxes or more irregular façades

- wind phenomena through built environments with spacial configuration of canyons and channels

- thin and porous screens with aerodynamic features (Figure 1.2).
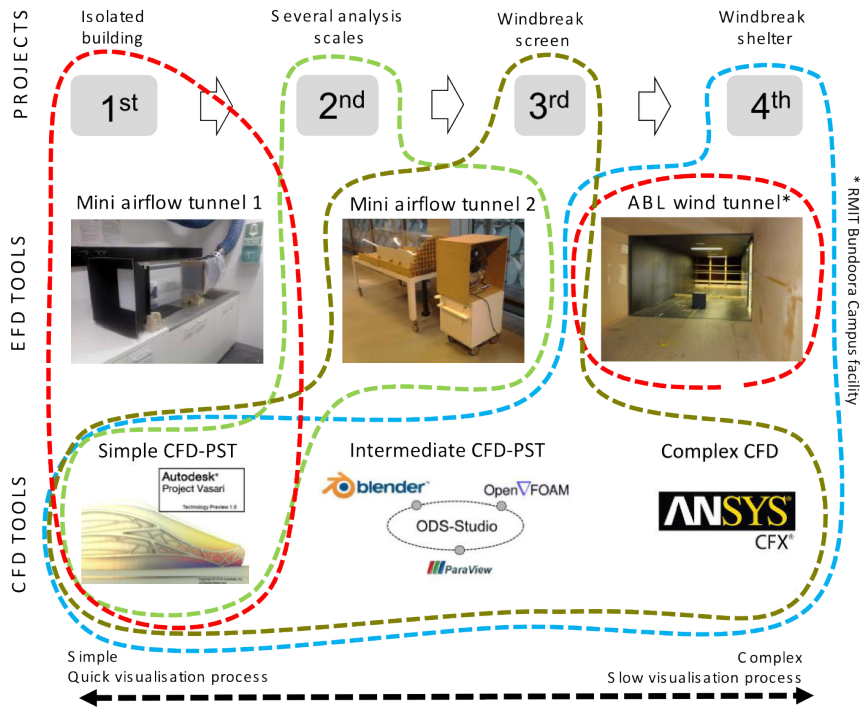
Figure 1.2: Structure of research method with four investigation projects. It shows the aim of each investigation and the tools used in the experiments. (Source: author)

After each investigative project, specific lines of action were derived for analysis in the next project. I defined this strategy considering that these projects involved tests, but at the same time, a grade of experimentation with designs interacting with wind. In this sense, the SIAL at RMIT University provided the necessary technical and theoretical environment to engage my studies in workshops that allowed me to get valuable feedback.

During the whole process of each investigation, the experiments and aims were supported with a selected literature, which I progressively classified in four areas: general aerodynamics (introduction to aerodynamics concepts); simulation and analysis tools in the design process; urban aerodynamics; and windbreak aerodynamics (mitigation strategies based on artificial windbreaks).

Scope of thesis

The scope of this research involves qualitative evaluation of the techniques of wind visualisation in CFD-PST programs for wind analysis, used on identification of outdoor wind phenomena around buildings, with an approach in the early design stage.

This research tests a group of tools including programs recently developed to create visualisations of wind flow with much flexibility, simplicity and few parameters, for rapid feedback with architects. Even though the tools tested in this study consider sophisticated programs and technologies, traditionally used in the engineering field, the analysis and evaluation is focused on programs for wind analysis around structures in the early design stage (outdoor airflow), such as CFD Autodesk Vasari and ODS-Studio. Other more sophisticated programs were used for comparison purposes such as ANSYS CFX and an industrial wind tunnel. In addition, wind visualisation experiments were conducted with two hand-made mini airflow tunnels (Figure 1.3). For the use of these tools, each experiment was designed with simple and standard parameters: constant wind velocity and simulation of an ABL for the last group of experiments. The rest of the wind conditions (normally found in urban context) were omitted or simplified.
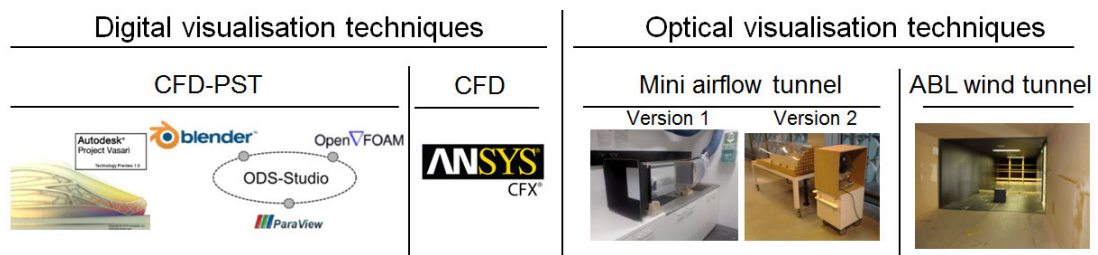
Figure 1.3: Visualisation techniques used in this research. CFD-PST: Vasari, ODS-Studio. CFD: ANSYS CFX. Mini airflow tunnel: V1 and V2. ABL wind tunnel: RMIT Bundoora Campus. (Source: author)

Even though the functions of simulation and visualisation are both integrated in these tools, my research has mainly focused on wind visualisation features. The simulation conditions of these programs are not considered, to facilitate the comparison and evaluation as visualisation tools. Technical aspects and comparisons of levels of accuracy between different numerical simulation methods were not analysed. The accuracy of a numerical

simulation of a real wind flow, generated by these CFD-PST programs, is not a matter for this research, regarding the differences between CFD-PST and traditional CFD programs and their methods of modelling, parameters of wind, strategies of validation and turbulence models (Table 1.1). For instance, the CFD models are generally classified as direct numerical simulation (DNS), Reynolds Averaged Navier-Stokes (RANS) equation modelling and large eddy simulation (LES) (Chen and Jelena. 2000). There is little literature about Project Falcon, which is the simulator of Vasari, but basically Falcon is a simplified version of CFD software using LES as the method of simulation (Autodesk 2013a). On the other hand, OpenFOAM in ODS-Studio and ANSYS CFX used RANS (k-epsilon model) for the experiments of outdoor airflow in this investigation, which would be acceptable under the approach of early design stage (Lau and Tsou 2009). The evaluation developed in my research is not based on these kind of differences. In fact, this research considers wind visualisation from a qualitative approach focused on the problem of comprehension about pedestrian comfort issues in areas near buildings. In this sense, the accuracy of a preliminary wind analysis is not so relevant compared with other wind effects, such as structural wind load (Lau and Tsou 2009).

	Domain		Wind parameters				Simulation parameters		Validation method	
	3D Model	Digital mesh	Speed	Direction	ABL profile	Turb %	Turb Model	Other	Convergency	Grid ind. results
Vasari	Modelling and import	Basic Grid	Yes	Horizontal	No	No	LES	2D/3D wind flow	No	No
ODS-Studio	Modelling and import	PolyMesh	Yes	Yes	Yes	No	RANS	3D wind flow	No	No
ANSYS CFX	Modelling and import	HybridMesh	Yes	Yes	Yes	Yes	RANS	3D wind flow	Yes	Yes

It does not consider

It considers but with simple parameters

I considers with complex parameters

Table 1.1: Table of parameters that determine the level of accuracy for each wind analysis program. This table shows the differences between each program. Some of them only work with simplified parameters, others do not consider validation methods. There is a difference in the turbulence model used. This makes it very difficult to compare programs; for this reason, this approach is not considered in this research. (Source: author)

Moreover, the intention is not to evaluate the CFD-PST programs through quantitative data. It is a qualitative analysis based on an architectural exploration with a limited group of tests, focused on the direct observation of the performance of these techniques under different requirements for an architectural exploration, rather than conducting surveys and interviews of users.

Background

Architecture and urban design are influenced by the wind in many ways, including structural loading considerations, building natural ventilation and minimisation of ground level winds with design of pedestrian shelters. At the same time, in the building's outdoor environment, the wind movement is affected by building geometries and configurations generating aerodynamic phenomena in the space between them (Stathopoulos et al. 1992, Ricciardelli and Polimeno 2006). For this reason, the study of the interaction between aerodynamic phenomena and architecture has become very important in many fields such as sustainability, environmental design or human comfort (Hutchinson 1978, Boris 2007). For instance, the growing number of high-rise and high-density buildings, due to drastic urbanisation, is causing a number of problems with respect to wind environment (Lee and Song 2010). In fact, the attention to micro-climatic conditions in built environments has increased among researchers in the last decades, as they try to understand the wind effects over the boundaries of architecture and public space, especially when it causes discomfort in pedestrian areas (Stathopoulos 2009).

To address the effects of interaction between wind dynamics and architecture, architects have started to incorporate wind analysis as a part of the design process, through technologies of simulation and wind expert consulting. However, when the wind analysis suggests radical modifications in the final form of a project (aesthetics) at the end of the design process, the question that arises is how to anticipate those changes. In other words: how to design with the wind.

Exploring the relationship between wind, aesthetics and architecture, the Chilean researcher Professor Manuel Casanueva asked himself the same question (Casanueva 2009). In 1995 he designed and built an experimental house in a coastline location in Chile, developing an architectural design for a sophisticated interaction with the coastal wind (Casanueva 1996). As a response to the question about designing with the wind, he used as strategy, techniques of wind visualisation in a mini wind tunnel, to analyse the interaction between wind and the conceptual form of the project. This means, he integrated techniques of wind visualisation from the early stage of the design process (Figure 1.4).

(March 2015)
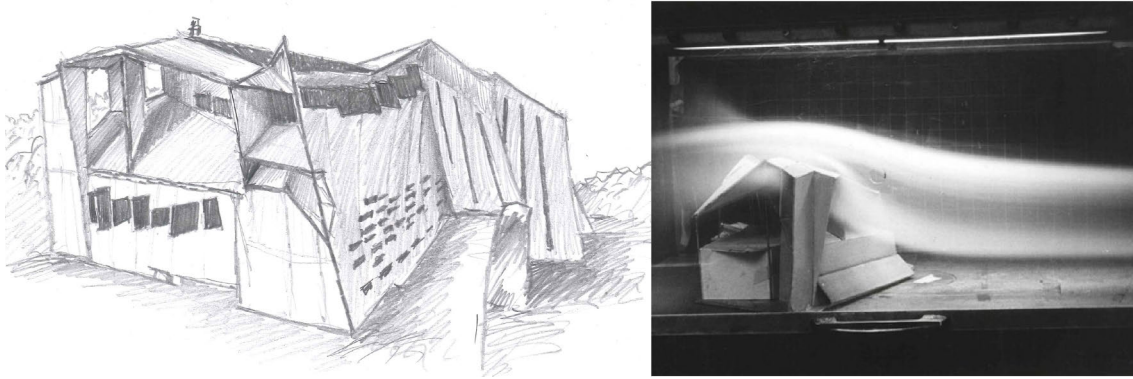
Figure 1.4: Left: Hospederia del Errante, Ritoque, Chile (1995) with wind accelerator slots in the south façade as aerodynamic feature for wind deflection and increase of protection zones (Source: author's sketch based on (Casanueva 2003)). Right: Wind visualisation in a mini wind tunnel of preliminary Hospederia del Errante façade model. Experiments conducted during the first stage of the design process. (Source: author)

Currently, wind analysis and visualisation has been incorporated in the early stage of the design process through the gradual introduction of software for building performance simulation (BPS) by architects (Naboni 2013, Ianni and Sanchez de Leon 2013). Software from the computational fluid dynamics field (CFD), such as Design BuilderCFD and Autodesk Vasari, presents a new approach for designers, facilitating the graphical visualisation of wind and the analysis of aerodynamic phenomena, with a focus on the early design stage, and being called CFD-PST (computational fluid dynamics - performance sketch tool) for this reason (Naboni 2013). However, these technologies, that are mainly used for preliminary analysis of the wind around isolated building masses and through environments of building configurations, have not been evaluated in other scenarios to test their performance as wind visualisation tools specifically developed for architects. Recent studies have analysed the performance of these BPS tools in the design process, but with a global approach on energy simulation functions, without specific attention to the performance of digital wind visualisation and analysis techniques that have been incorporated, and without testing these tools with different requirements than the visualisation of wind flow around closed building forms. For instance, testing these CFD-PST for analysis in workflows, with different urban context scales, different complex structures such as porous screens or comparing them with other techniques of graphical wind visualisation.

(March 2015)

My research presents an empirical study of digital and mixed reality visualisation techniques for wind analysis, developed for assistance to architects in the early design stage (CFD-PST). I compare them with other techniques and test them with more complex designs, which represent a different analysis context from isolated buildings or building groups. To achieve this aim I chose to research this topic by project as the strategy of study, analysing different wind visualisation techniques through a group of four investigative projects. These investigations have an exploratory approach to the relationship between the digital techniques for wind visualisation, the analysis of wind dynamics and its interaction with solid and regular structures or thin and permeable surfaces. This study evaluates the performance of these tools to assist architects in the identification of aerodynamic phenomena during the development of design concepts in the early design stage, where architects can explore more creative and sophisticated strategies of micro-climatic control for wind comfort levels in pedestrian environments.

The next section presents a literature review about some of the topics involved in this study of wind visualisation techniques and aerodynamic phenomena around buildings.

1.2 Literature review

Through this literature review the scope of my research is presented in three main parts. The first part refers to the relevance of wind visualisation and analysis for architects, to improve comprehension about wind dynamics around buildings.

The second part presents the field of wind visualisation in the architects' work and how it has been integrated into the design process. It presents the gap in the literature about how new CFD-PST are being studied by researchers (in architectural design).

Finally, the last part describes the progressive levels of complexity in the architects' design that wind visualisation techniques should address to resolve the design of windbreak structures for mitigation for wind discomfort issues. This part refers to more complex requirements of analysis for this new generation of wind analysis tools.

Visualisation of wind dynamics

Visualisation is an important tool in experimental fluid dynamics, which can provide the overall picture of the flow field. Methods of wind visualisation are generally applied to elucidate the interaction between fluid dynamics and geometries, and provide quantitative data (Ristic 2007).

For architects, the visualisation of wind flow is crucial to fill the gap between knowledge of wind dynamics (as part of general climatic knowledge), and the design. The theoretical knowledge of wind dynamics is usually not incorporated into the background of architects. Due to this, the ideas that architects have about wind dynamics can be different from the concepts used by wind engineers. This difference has already been noticed from the engineering discipline. For instance, it is mentioned in the paper "Shape and flow" (Aynsley 1999), where R. M. Aynsley uses these terms to refer to representation of aerodynamic shapes that architects had during the Modernism period: a wind flow representation associated with "clean smooth curved streamlined shapes" (Aynsley 1999; p. 69). This aesthetic representation was mainly inspired by the idea of objects moving through the air, rather than the movement of the atmosphere. To illustrate, the sculptures *Winged Victory of Samothrace* (190 BC) with its dress folds printed for the wind,

or Umberto Boccioni's work *Unique Forms of Continuity in Space* (1913), were considered aesthetic representations of wind, where the body takes this form by its movement through the air (Figure 1.5).

Figure 1.5: Artistic representations of a body moving through the space; from a representation of a fabric printed with folds to an armour of geometrical surfaces. In both sculptures we visualise the dynamics of the space around (air). Left: *Winged Victory of Samothrace* (190 BC). Right: *Unique Forms of Continuity in Space* (1913).(Source: left image: Marie-Lan Nguyen. Right image: Wmpearl. Wikimedia Commons, public domain.)

Moreover, Jacob Wisse stated in his paper "A philosophy for teaching wind in the built environment": "this knowledge is not integrated into the design of urban environments by the urban designer and by the architect" (Wisse 1988; p. 157). Also, he considered this different interpretation as a difficulty in the communication of wind knowledge to professionals of architecture. However, the visualisation of wind dynamics can change the architect's mental representation of wind from a dynamic body to a dynamic airflow, improving their comprehension.

The techniques of wind visualisation contribute to sharing a field of knowledge between wind engineering, architecture and urbanism. Wisse postulated to institute a "shared image" of the wind outdoor environment, and a "shared knowledge" of aerodynamic concepts to facilitate the communication and interaction between wind engineers, architects and urban planning designers (Wisse 1988). This "shared image" is the wind represented as a map of areas or regions around a building with different wind speed ra-

tios; a representation of the shelter parameter around a building, which means the ratio of the wind condition from comfort to discomfort (Figure 1.6).
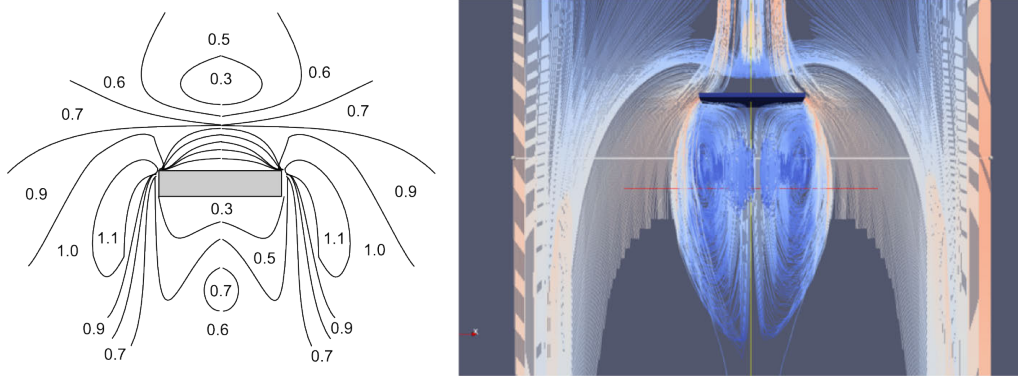
Figure 1.6: Modern visualisations to understand the wind movement around a building as intensity regions and turbulence regions. Left: Image of wind velocity ratio regions around a building (diagram elaborated by the author, based on (Wisse 1988)). Right: Computational fluid dynamics (CFD) streamline visualisation of wind flow around a wall of $2\,m \times 2\,m$. (Source: author).

In the same way, architects recognise that techniques of wind visualisation facilitate the incorporation of wind dynamics knowledge in the work of designers. This is an approach to the discussion about the differences between design methodology and science (Cross 1993). Evans and De Schiller identify the relevance of visualisation in conflict between knowledge that is coming from a scientific field and a learning method, whereas "architects' training has a strong visual and graphic emphasis required to solve the complex problems of developing 3D solutions for buildings, urban designs, and town and regional plans" (de Schiller and Evans 1990; p. 51). Thus, with this approach of incorporating knowledge through visual methods, Evans and Schiller consider a wind tunnel, used for architectural studies in their university, as a valuable tool of visualisation, that was "designed to allow students to test models of projects and visualise air flows in outdoor spaces and in cross-ventilated buildings" (de Schiller and Evans 1990; p. 51).

In professional practice, the use of wind tunnels for wind visualisation and analysis, especially those that can simulate the atmospheric boundary layer (ABL), are suggested as wind analysis tools for architects to study the performance of a project, in the design process (Aynsley 1999). However, setting up experiments and simulations of aerodynamic

phenomena with this technology would be a complex task for designers alone, and its incorporation in the design process, from the early stage, could present difficulties.

Wind visualisation and analysis tools in the early design stage.

Wind analysis with wind tunnels. Wind visualisation, as part of physical techniques of wind simulation for architecture, is performed with low speed ABL wind tunnels. This is due to the fact that buildings are placed on the ground and are relatively low height, with respect to the height of the ABL (Ricciardelli and Polimeno 2006). Therefore, the wind simulation with equivalent boundary layer, in terms of average speed and turbulence level, becomes a challenging problem (Gonzalez Hernandez et al. 2013). Early studies with wind tunnels focused on the reproduction of a real wind flow which were performed in wind tunnels of 12 m length. The first wind tunnel designed to reproduce the real wind boundary layer was built in 1965, with a section of 2.4 m width, 2.15 m height and 33 m length (Diana et al. 2013). In other words, the conditions to reproduce ABL require large and expensive facilities, including advanced data acquisition systems (sensors) and processing systems to measure quantitative data in modern wind tunnels (Cermak 2003). As such, this technology is not fully integrated into the design process workflow of architects. In general, these tools are operated by experts, who assist architects as consultants with simulations and recommendations. As a consequence, the visualisation techniques used with this technology are not a common method of analysis for architects, only being reserved for large projects and major professional offices.

However, some experiences of qualitative wind visualisation using mini wind tunnels have been used by architects in the design process. The case of the *Escuela Naval* project (1956) in Valparaiso, Chile, with studies of visualisations of vertical wind deflections at the top of buildings (Ureta Morande 2007) and the *Hospederia del Herrante* project (1995) developed in Ritoque, Chile (Casanueva 2003) are examples of design process workflow integrating techniques of qualitative wind visualisation (Figure 1.7). In both cases, small hand-made wind tunnels were built to perform wind analysis and exploration of design alternatives using technologies called low-tech tools, in an early design stage (Salim and

Moya 2012). In these examples, the architects' interest was the comprehension of the main wind movement through the visualisation rather than high precision measurements.
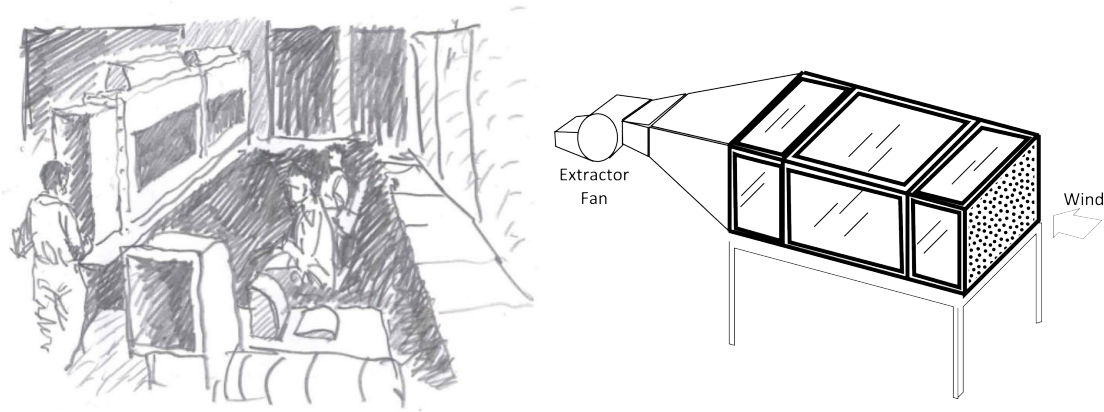
Figure 1.7: Techniques of wind visualisation and analysis in the early design stage. Left: mini wind tunnel built and used by architects for preliminary wind visualisation, during the design process of *Escuela Naval* project in 1953 (Author's sketch based on (Ureta Morande 2007)). Right: mini wind tunnel (black box under letter B) used for the *Hospederia del Errante* project in 1995, to test preliminary designs of the project (Author's sketch based on (Casanueva 2003)).

Non-optical techniques of visualisation used in wind tunnels are tracer methods of the flow such as fog/smoke emission, the use of particles or gas bubbles. Other methods applied to trace air movement patterns on model surfaces use dye or oils (Ristic 2007). In general they provide a qualitative approach of the pattern of wind vortexes, separation flows, turbulences and changes of wind direction. The visualisation of these wind movement patterns provides a comprehension about aerodynamic phenomena, associated with effects such as the comfort levels in pedestrian areas near the buildings. Thus, it is possible to identify areas that need wind mitigation measures: areas affected for a vortex of wind (spiral movement of the air that increases the wind speed), parts of a building that produces separation flows (with a high speed air stream), and so on. Besides, other techniques can be used for wind environmental analysis, in a post-process to gather quantitative data, such as the erosion technique (Eaddy and Flay 1998, Dezso 2006) and the use of PIV technique (particle image velocimetry) (Kellnerova et al. 2012).

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Wind analysis with CFD technology.   On the other hand, wind analysis using digital technologies is part of the field of numerical simulations technologies. "The CFD (computational fluid dynamics) technique numerically solves a set of partial differential equations for the conservation of mass, momentum (Navier-Stokes equations), energy, species concentrations, and turbulence quantities" (Chen 2004; p. 4). The CFD technology for the wind analysis of complex wind patterns around buildings, in the lower part of the ABL, started around 15 to 20 years later and its development has continued until the present day. B. Blocken (2013) presents a global picture of this technique in his paper "50 years of computational wind engineering: past, present and future", prepared for the Sixth European and African Conference on Wind Engineering (Baker et al. 2013). Based on Blocken's study it is possible to say that the main studies are focused on methods to ensure the reliability of this technology that highly depends on good control of several factors by the user: this one requires manually setting up a wide group of parameters (target variables, turbulence model, computational domain, digital mesh, etc.), which need a knowledge about theoretical concepts and practice guidelines (the elaboration of these guidelines is a recurrent topic in the papers about CFD) (Blocken et al. 2009). In addition, it is suggested that a workflow that involves CFD wind analysis should consider validation methods of the results, such as repetition of simulations with different digital mesh density for a grid independent solution or comparison with physical measurements in a wind tunnel and on-site studies (Blocken 2013).

From the point of view of the architects' work, these requirements for wind analysis with CFD tools, once they are incorporated in the architecture design practice, have had an impact in the methodology, times and qualifications of the people required along the design process. For instance, the time consumed during the design process, by validation methods of the wind analysis, makes the feedback for the making-form course of a project much slower. This is especially problematic at the beginning of a design. However, these difficulties or other issues associated with wind visualisation are not mentioned in the text or literature analysed by Blocken.

CFD has been progressively incorporated into the architectural design process as part of the building performance simulation tools (BPS) (Naboni 2013) (Table 1.2). These tools

simulate hypothetical environmental scenarios for building design and allow architects to visualise the outcomes. In the case of wind analysis with CFD technique, this was initially used to analyse ventilation and internal airflow and later outdoor wind environment and conditions of pedestrian wind comfort (Jones et al. 2004). The last one is an important issue that has become relevant for designers and has been considered in the design process of high buildings.

	Geometry and Data Modeling	Energy and thermal simulation, climate analysis	Daylighting simulation	Computational fluid dynamic simulation
Main scope	Create geometrical and data models that support simulations	Predict the impact of architectural design on energy consumption and emissions	Anticipate natural light quality and visual comfort as a function of a space's geometry and material surfaces	Model airflows inside and outside the,buildings, predict comfort
Concept design	Rhino, Sketchup, Vasari	Ecotect Sun Tool, Ecotect, Vasari (Beta), Climate Consultant, EcoDesigner, ComFen	Ecotect, VeluxDaylighting Visualiser, Radiance, DIVA	Vasari Wind Tunnel (Beta), Design BuilderCFD
Design development	Revit, Archicad	OpenStudio, EnergyPlus, DesignBuilder, IES-VE, eQuest,	3DS Max, Radiance, Daysim, DIVA	Fluent, Virtual Wind
Parametric design	Grasshopper, Dynamo	JePlus, JePlus AE	Grasshopper and various plug-ins	

Table 1.2: Table of main building performance simulation tools (BPS) used today in the analysed architectural practices. These are some of the more popular programs identified by researchers recently. Different programs of wind visualisation and analysis are being developed for each stage of the design process. (Taken from (Naboni 2013))

The incorporation of these simulation technologies and the performance analysis for architectural projects moved architects to include specialised teams of experts in simulation and new work methods, including wind analysis, in the staff organisation of their offices and design workflow (Naboni 2013, Ianni and Sanchez de Leon 2013). However, this is more feasible for major professional offices than small designer teams and the costs can be justified mainly with large, complex and expensive projects (Farias 2013). However, researchers of the design process with BPS tools mention that the incorporation of CFD wind analysis into the architects' design process has presented difficulties, because CFD tools require specialist knowledge for modelling as well as for the interpretation of results (Kirkegaard et al. 2008). However, these difficulties are not a problem related only to CFD software. This is a common issue in the field of BPS tools, since many architects and designers are still finding it difficult to use even basic tools, because they are not compatible with architects' work methods (Attia et al. 2009).

Moreover, BPS tools have been mostly used at the final stages of the design process to evaluate the building, when most of the design decisions have already been made (Reichard and Papamichael 2005). In fact, wind analysis with sophisticated tools such as wind tunnels and CFD software has been mainly used as a validation tool of forms rather than a tool in the early design stage (Kirkegaard et al. 2008). But a change of paradigm aims at the idea that simulation must be used from the beginning of the design process to improve communication between professionals of different disciplines and to provide information to support the whole decision making process (Weinstock and Stathopoulos 2006, Reichard and Papamichael 2005). It means that simulation is moving from just analysis to analysis and design aid (Lima et al. 2012). In the same way, this paradigm applies to wind analysis based on CFD tools.

Wind analysis and the early design stage. It seems that stages of the design process have been redefined by the new methodologies and analysis tools used. For instance, in the literature the wind analysis in the early design stage, for outdoor environments near buildings, is mainly presented as preliminary wind studies of abstract masses or simplified configuration of buildings, analysing several design alternatives in a comparative process, rather than to produce realistic simulations or generate accurate data (Roset Calzada and Vidmar 2013, Naboni 2013). It is mentioned that the early stage is characterised by design work based on a rapid feedback and qualitative level of analysis, generally being an activity of a visual nature (Roberts and Marsh 2001). Moreover, the early design stage is a moment of communication of general concepts to sell ideas to the client, prior to developing more technical discussions with experts in advanced design stages (Farias 2013). However, from a practical point of view, the importance of wind analysis in the early design stage is to make possible the prediction of potential wind comfort issues and possible damage produced by strong wind gusts in the surrounding space of a building (Lee and Song 2010). This allows the design of more efficient strategies of wind mitigation at a stage of the planning process, when it is possible to institute radical changes in the design, rather than later, when only small modifications are feasible (Attia et al. 2009, Frazer 2013). An ideal situation is what Lau and Tsou states in their paper "Building innovations from

computational fluid dynamics": "The aim of the CFD simulations in the early planning and design stage is to generate visualized flow phenomenon of a particular flow problem; and through which to understand the wind environment and create innovative solutions to the particular problems" (Lau and Tsou 2009; p. 4). This objective is achieved through a CFD workflow of several steps for exploring and comparison of concept and design strategies (Figure 1.8).
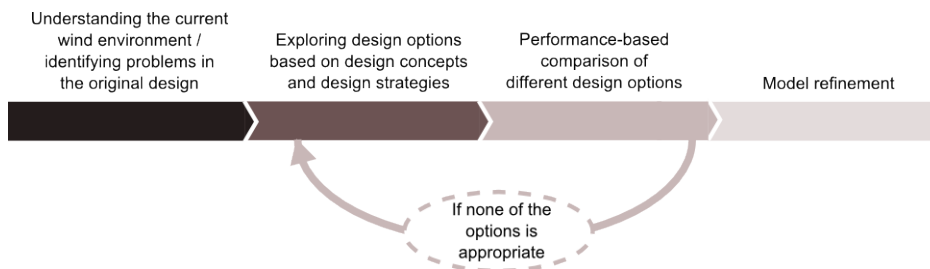
Figure 1.8: Structure of work developed by Lau and Tsou (2009) for the use of CFD for urban wind environment and natural ventilation simulation in the early planning and design stage. (Source: author).

On the other hand, the conditions of wind analysis in the early design stage seem quite far from the strict standards of the good practices guidelines promoted by wind engineers. early design stage usually involves design alternatives with low levels of detail and requires rapid feedback of analysis, which is independent of later wind analysis in further stages. Working with similar analysis standards for both stages could increase the time and costs of the design process. Therefore, there is a gap between the statements of wind engineering practice and architects requirements in the early design stage, about wind analysis based on CFD tools. In fact, until recently there was not a clear methodology of analysis for outdoor environment wind comfort during the early design stage (Lee and Song 2010). On account of this difference of practices between wind analysis and early design stage, new wind analysis tools were developed to assist architects with preliminary visualisation and analysis for early studies of concept designs (Lima et al. 2012). Software developers are aware of the difficulties typically experienced by designers when they use energy simulation tools. Therefore, wishing to tap into a potentially large market created by the neearly design stage of architects, software houses are developing very simple tools that are targeted at the early design stage, called performance sketch tools, to make the

distinction from those simulation tools for a more accurate analysis, used in further stages of the design process (Naboni 2013).

Computational Fluid Dynamics - Performance Sketch Tool (CFD-PST). Due to the evolution and change of paradigms of BPS tools, a new generation of software for numerical simulation has been developed to bring wind visualisation and analysis to architects in the early design stage. Autodesk Vasari[1], DesignBuilder CFD[2] and ODS-Studio[3] are examples of user friendly software for wind visualisation and analysis for concept design (CFD-PST). They have been recently developed and have differences from more sophisticated CFD technologies traditionally used by engineers (Sheppard 2012). Their technical features are focused on those required by users: that tools must be highly visual and interactive, and provide feedback on different levels of details (Lima et al. 2012). Moreover, researchers have conducted interviews with architects to learn their opinion about the use of some of these tools in their professional practice. For this topic, it is worth seeing the studies of Emanuele Naboni (2013) and Fernando Farias (2013). In the last one, it is mentioned that Autodesk Vasari is used because it integrates several simulation features plus CFD wind analysis, and facilitates the interoperability with other programs already used by designers such as Revit. One of its roles is to provide preliminary performance building analysis in stages of pre-design or concept design to show and sell ideas to a client (Farias 2013) (Figure 1.9).

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[1]autodeskvasari.com
[2]www.designbuilder.co.uk
[3]www.ods-engineering.com

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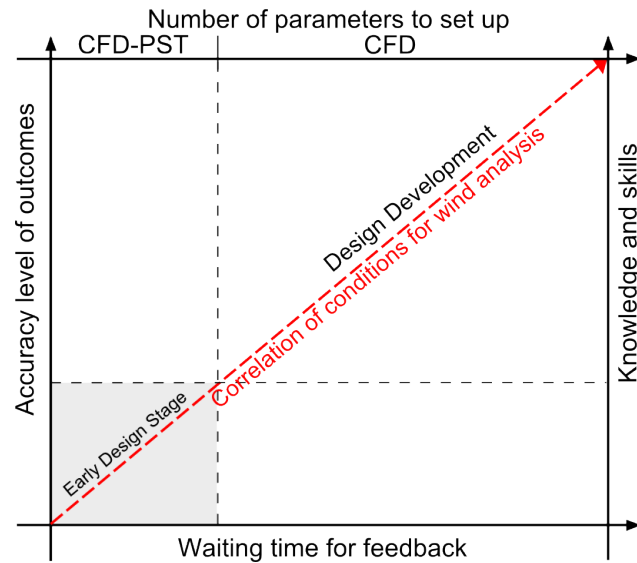
Figure 1.9: Wind analysis involved in the design process. The red line is the correlation between different conditions for a wind analysis. A wind analysis with high level of accuracy neearly design stage more time and parameters to set up. On the other hand, in the early design stage the level of accuracy in the analysis is low, but with rapid feedback. (Source: author).

These CFD-PST programs for digital wind visualisation and analysis, developed for the early design stage, are relatively new. The studies about BPS tools already conducted by Naboni (2013), Farias (2013), Vidmar (2013), Attia (2009), Lima (2012) and Koss (2014) have analysed some of them, evaluating the technical aspects and their general impact on architects' work. However, in the literature, the performance of the wind visualisation techniques used by architects during the early design stage is not deeply explored.

In general, the study of technical features of wind visualisation techniques has been missing in the literature about BPS tools developed for the early design stage. The normal approaches have been to compare technical features between programs to establish a ranking and to analyse their performance as general tools for simulation of phenomena (Roset Calzada and Vidmar 2013, Attia et al. 2009, Attia and LEEDAP 2011). Only a few researchers, such as Naboni (2013), have analysed the incorporation of CFD technology, for each stage in the design process, making a difference between sophisticated programs (ANSYS CFX) and simplified software (CFD-PST). In this sense, it is suggested that

in this stage of the design process, the visualisation technique is more relevant than the technique of simulation of wind. In fact, Kirkegaard (2008) has already defined the differences between flow simulation and representation tools (ANSYS CFX versus RealFlow), considering that tools for representation of flow are more suitable for wind analysis at the beginning of the design.

What limitations do these programs present for wind visualisation and analysis? In fact, some of these tools are focused on simulating and visualising outdoor wind flow around closed form buildings profiles (Autodesk 2013a, Sheppard 2012). And, the limits of these techniques to visualise wind phenomena with more complex analysis contexts are not identified. Thus, I develop a study on new tools for wind visualisation and representation to support the early conceptual phases of the design process.

Low-accuracy wind visualisation for rapid feedback. As a final observation about techniques of wind visualisation, another alternative has been studied: the visualisation of scientific data and wind flow patterns superimposed on the real world, with the goal of communication and comprehension, even with qualitative representations. In the case of scientific data, the development of a platform for human-building interaction, integrating CFD analysis and augmented reality is an example of providing information in a comprehensive way using as platform a new digital interface (Schubert et al. 2003, Malkawi and Srinivasan 2005). On the other hand, digital visualisation of wind movement in physical models, without the intention of measuring or replicating wind conditions accurately, is a method to facilitate the communication of complex phenomena between people with different backgrounds. With this intention a representation does not need to be accurate. For instance, the project Tangible Teamwork Table by Flora Salim (TTTHub) (Figure 1.10) or the prototype of a "tangible user interface" are cases of a digital and physical representation overlapped to communicate the complexity of wind dynamic flow in a built environment, in a more understandable way (Kieferle et al. 2006, Salim 2013; 2014).

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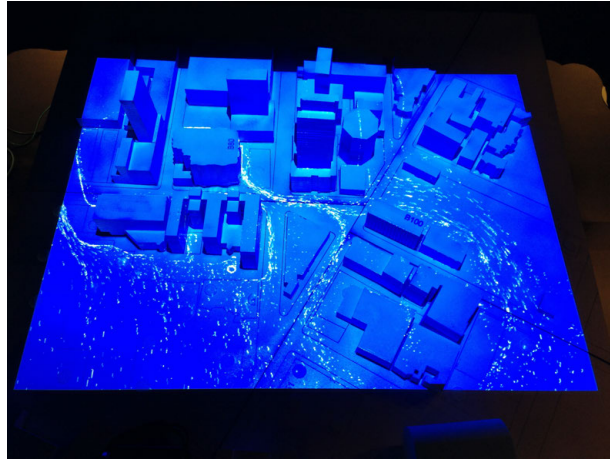
Figure 1.10: The TTTHub project is a platform of urban aerodynamic representation only for interactive visualisation. The platform does not pretend to simulate real flow conditions. Thus, this shows that simulation and visualisation of wind flow are concept not necessarily attached. (Taken from (Salim 2014)

Visualisation of wind around buildings and through pedestrian areas

Wind visualisation techniques not only allow the theoretical comprehension of wind dynamics or the design of an individual building. The digital wind visualisation platform developed by the TTTHub by Flora Salim (2014) project shows the wind movement patterns through a built environment that is useful to analyse wind phenomena associated to urban configurations, such as dispersion of gaseous pollutants in the streets, accumulation of dirt, accumulation of snow or aggravation of rainfall effects. These effects can lead to poor pedestrian comfort in some public areas (Stathopoulos 2011).

The wind visualisation allows an understanding of the relationship between building geometries and wind patterns. In some cases, the scope of analysis refers to spaces of a built environment with canyons and channels. In other instances, the scope is the space near the building form. That is the case of the phenomena associated to the height of a building, such as the downwash effect on the building's façade, which depends of the local gradient of pressure (Stathopoulos 2011), and the shielding effect, which is the shadow area at the leeward side of the building where the wind speed is reduced and eddies are formed (Figure 1.11). These phenomena have a significant effect on comfort levels in outdoor environments near the buildings. For example, the downwash effect is a downward

deflection of an airstream that flows to the ground level affecting the pedestrian areas at the bottom of the windward façade, where is the main entrance of the building. In some cases, this effect produces a spiral movement of wind (vortex) in the space of the street, next to the building, increasing the velocity of the airflow in the footpaths (Penwarden et al. 1975). On the other hand, the shielding effect of a building may produce a region of protection, at the ground level, in an environment with strong wind.
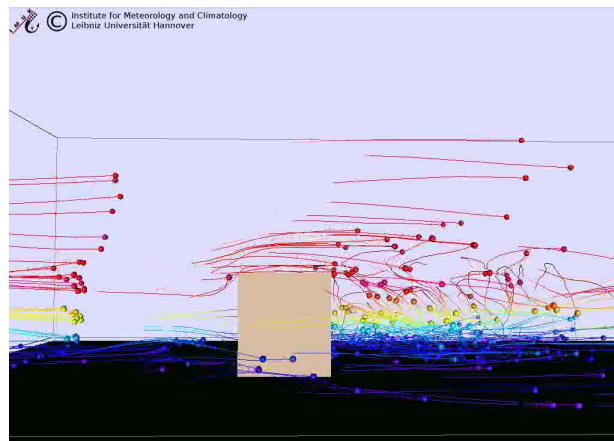
Figure 1.11: For an accurate or extremely large CFD simulation, to produce a 3D visualisation of realistic wind deflection patterns and turbulences, it is necessary to set up many parameters and lot of time for calculation process conditions that are not possible at the beginning of the design process. The image shows a visualisation of wind flow around a single building, produced by PALM, a large eddy simulation (LES) model for atmospheric and oceanic flow simulations, that works on massively parallel computers. (Taken from http://palm.muk.uni-hannover.de)

Similarly, wind visualisation allows architects to understand how a building orientation changes the shape pattern of this wind area around the building (Beranek 1984b), especially when wind flows through a group of buildings. For example, experiments of visualisation in a wind tunnel, with different building group configurations, showed that patterns of wind flow can be repetitive in regular configurations of buildings. If these patterns are associated to grades of discomfort, the repetition means continuous corridors of discomfort regions along the urban grid (Figure 1.12).

Figure 1.12: Visualisation of wind pattern through a built environment with three different building configurations. Position of buildings can prevent continuous regions of high wind speed flow. These experiments of wind visualisation were conducted in an ABL wind tunnel, using erosion technique. (Sketch elaborated by the author, based on (Beranek 1984a))

Thus, despite the random nature of wind, information provided for visualisation techniques allows the association of these wind patterns with the urban configuration. Classifications of wind phenomena affected by the built environment are the channel effect, canyon effect and row effect (Gandemer et al. 1978).

Another role for wind visualisation tools is for aspects such as information display, that facilitate the analysis of wind environmental conditions. For instance, wind discomfort in pedestrian areas has received much attention during the last decade (Stathopoulos 2009). However, the task to establish a comfort criterion is quite complex, because the comfort conditions are affected by several climatic variables (Stathopoulos 2011). With wind visualisation tools this kind of analysis can be done through more direct methods, adapting parameters that are considered as valid, such as wind velocity and its mechanical and thermal effects, for levels of wind comfort (thermal or discomfort) or wind danger (physical risk of stability) (Blocken and Carmeliet 2004). However, wind visualisation tools that are integrated in the BPS do not display the information using evaluation criteria such as the Beaufort wind force scale, with the Penwarden's modification to reflect the relation between a person and wind speed (Penwarden 1973). That could be a useful metric for a quick analysis.

From the perspective of wind comfort, the challenge for architects is using techniques of wind visualisation, from the early stage of the design process, to analyse design strategies for wind mitigation, developing forms that progressively become more complex. In general,

the strategies or methods to ameliorate pedestrian wind conditions basically are: building massing and orientation; influence of terrain configuration; use of landscaping foliage to avoid horizontal wind acceleration (ASCE 2004); and use of auxiliary elements such as canopies, artificial windbreaks, building height, shape geometry and structures of podiums (Cochran 2004, Penwarden et al. 1975).

One case where the wind analysis determined the general geometry of the project was the 30 St Mary Axe building (2004) by Foster+Partners. During the early design stage, after defining several alternatives of massing for the project already permitted by authorities, the general geometry of the building was delineated by wind analyses using numerical simulations. Because of the size of the tower, the air currents sweeping around produce whirlwinds at the ground level, with negative effects on the comfort of pedestrians. Conducting preliminary wind visualisations, it was possible to determine that a cylindrical shape and a vertical curvature of the tower façade, with a maximal diameter at the sixteenth floor, would help to minimise winds at its slimmer base (Massey 2013). This case is an example how the wind analysis in the early design stage was used to define a shape of the building, among several alternatives, and developing a refined aesthetic in terms of the wind conditions of comfort in the surrounding space (Figure 1.13).
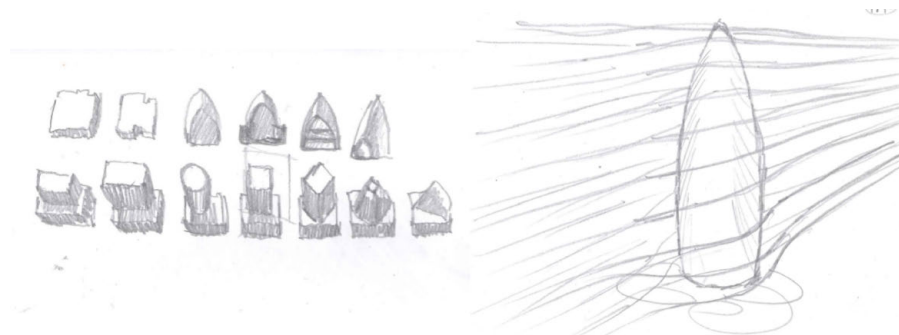
Figure 1.13: Development of the iconic commercial skyscraper in 30 St Mary Axe (2004) by Foster + Partners, during the early design stage. Left: several alternatives of designs for the project. Right: the tower shape was designed and optimised following results of CFD wind analysis to mitigate the wind speed level in the surrounding space. (Sketches elaborated by the author, based on (Massey 2013))

Moreover, one of the current challenges for wind analysis with visualisation techniques in the early design stage is to explore strategies using auxiliary elements for microclimatic

control in consolidated urban context, where it is not possible to modify the geometry of the building configurations. For these cases, designers need to analyse the interaction between wind flow and elements of protection, such as artificial windbreaks. This approach considers not only standard solutions, but involves an exploration in the early design stage of more complex and sophisticated designs for wind comfort in pedestrian areas. The microclimatic control of the space opens an exploration field for architects to develop wind control methods that involve efficiency and aesthetic designs (Figure 1.14). The digital wind visualisation techniques developed for architects should assist in the analysis of that complex level of design, from the early design stage.
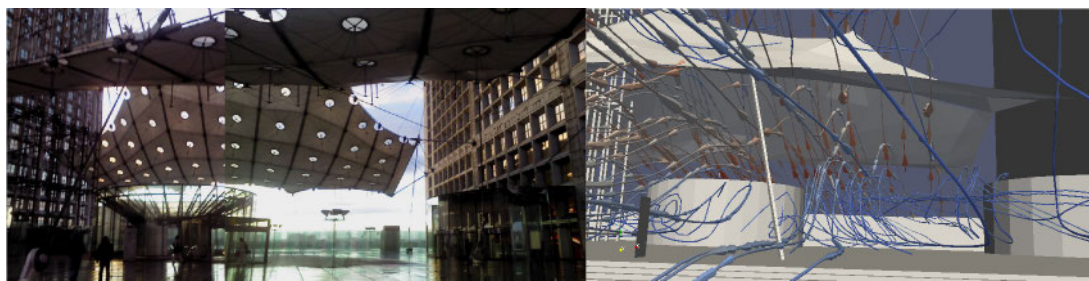
Figure 1.14: A sophisticated artificial windbreak for wind mitigation, in the public space, could require wind analysis from the early design stage. Left: windbreak of porous canopies with glass panels in the Grande Arche building (1990), Paris. Right: CFD visualisation of the wind below the canopies, in the terrace of the building. This experiment was conducted by me to analyse the wind conditions in the area of the building's entrance. (Source: author)

Currently, some architects have explored the use of complex design of membranes and porous meshes as auxiliary elements to control the wind comfort conditions in the space near buildings. This has been called a supplementary architecture, because it is seen as an overlapping layer that can be installed on buildings, creating transition spaces to mitigate outdoor conditions (Hensel 2013). The design of porous screens and porous morphologies by architects is presented in many cases as permeable structures and diffuse boundaries, which "operate through the opportunistic use of environmental gradient thresholds" (Hensel and Menges 2006; p. 18). A form-making process with this level of morphological complexity requires more sophisticated techniques of visualisation to be used by architects, if they develop wind analysis from an early stage of design.

Finally, it is important to mention that digital wind visualisation is not the only method associated to numerical wind simulation to analyse the wind dynamics and design strategies for wind comfort. Current studies based on the use of genetic algorithms (GA) with CFD have developed automatic methods of form generation (Malkawi et al. 2005) and building form optimisation for pedestrian comfort in the early design stage of building projects (Kim et al. 2011). This allows consideration of complex typologies without a direct analysis through visual methods. This approach of a full digital design process has received much attention in recent years. Although, some practitioners are skeptical of the implementation of fully digital form-finding techniques and parametric optimisation, because these simulation tools could begin to determine the character of architecture without human intervention (Naboni 2013).

1.3 Chapter outline

I develop as a progressive exploration through empirical observation, digital and physical experiments, the fabrication of two hand-made low-tech wind tunnels and physical models. The present text is a compilation of every stage of this study and it is the exegesis that complements the presentation of a project as the final result of my work.

This exegesis is structured in seven chapters and an appendix with additional graphical material from my experiments and copies of papers published:

- The first chapter (introduction) presents a review of an relevant literature about aerodynamic concepts, wind visualisation techniques, tools and the relevance for wind analysis in urban planning and design. The analysis of this literature defines the research questions and the scope of my study.

- The second chapter describes the work of the first investigation, with the evaluation of a first group of digital techniques for wind visualisation and the fabrication and testing of a low-tech wind tunnel for wind analysis in the space around regular closed building forms. This work presents outcomes from my personal experiments using these tools and observations of parallel activities with other users.

- The third chapter examines the work of my second investigation, around the use of wind visualisation techniques within the context of an urban configuration. These observations were focused on the performance of these techniques in a workflow for wind analysis on the scale of the urban context and the design of a small windbreak for wind mitigation. This investigation involved the work developed in an elective course conducted with the support of SIAL staff members.

- The fourth chapter is an interlude to present key ideas about the relationship between wind and design as strategy for a more sophisticated interaction. This section develops theoretical ideas and architectural references about architectural wind manipulation, to define the next context of application for wind visualisation with CFD-PST. This chapter develops some of the design concepts that are explored in the following two investigation projects.

- The fifth chapter presents the third investigative project: a preliminary exploration for a concept of windbreak screen with aerodynamic features. The work is about the experiments with wind visualisation techniques to study the adaptation of features in a single screen for wind mitigation and the design of a concept of windbreak deflector. In this chapter, new wind visualisation tools are tested.

- The sixth chapter presents the fourth investigation, a new approach for the design of a windbreak screen, adapted for a configuration of several membranes and installed in a tram stop. In this stage, the methodology considered wind analysis through numerical simulations and a process of physical experiments in an ABL wind tunnel.

- The seventh chapter presents a general discussion of the outcomes and findings. This discussion develops the main findings of each investigation stage. These findings refer to criteria that explain areas or issues for the work of wind visualisation by architects. It develops some strategies as suggestions to overcome the issues, improving the feedback from the programs to the designers. The chapter includes the limitations of the thesis and possible future research.

- The eighth chapter presents a short overview, and the summary of the main conclusions of my research.

- In the final part of this exegesis, an appendix gathers images of the projects developed through the investigations and copies of the five papers with works related with this research, that have been presented in the conferences of eCAADe2012[4], eCAADe2013, eCAADe2014, CAADRIA2014[5] and SimAUD2015[6](accepted for publication, April 2015).

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[4]Education and research in computer aided architectural design in Europe conference
[5]Computer-aided architectural design research in Asia conference
[6]Symposium on Simulation for Architecture and Urban Design

CHAPTER 2

First investigation: wind dynamics visualisation

2.1 Introduction

This chapter presents my first investigation to evaluate CFD-PST (computational fluid dynamics - performance sketch tools) and other techniques for rapid visualisation of main wind movement patterns around an isolated closed building form. These experiments are focused on the spatial context of pedestrian areas surrounding a building, where the digital wind visualisation techniques for the early design stage are applied to understand the main wind phenomena produced by the geometry of a building.

The chapter starts with a description of the visualisation techniques used in these experiments. It then, explains the different experiments conducted with these techniques and presents the results of rapid visualisation for regular and irregular building forms.

Some of these experiments were part of my work in the Designing the Dynamic Workshop, organised by SIAL in November of 2011. The results and findings of that experience were published in the eCAADe2012 conference (Salim and Moya 2012) and in the book *Designing the Dynamic: High-performance Sailing and Real-time Feedback in Design* (Burry 2013). A copy of these articles can be read in the appendix.

Investigation aim and criterion of evaluation

For this first investigation, the aim is to test different rapid visualisation tools to verify if an observer can easily identify wind movement patterns around a building. With this approach, I use different techniques of rapid visualisation in two groups of experiments: wind visualisations around buildings with a regular form (flat surfaces with edges) and an irregular form (curved and continuous surfaces).

In the literature about urban aerodynamics, presented in the introduction chapter, the main movements of the wind flow around regular geometries of buildings have been categorised based on the zone where they are produced (Figure 2.1). These classifications are very useful for an architect to identify these phenomena in the wind analysis of his project. Thus, the rapid visualisation and identification of these wind effects is one of the first tasks to evaluate these tools.
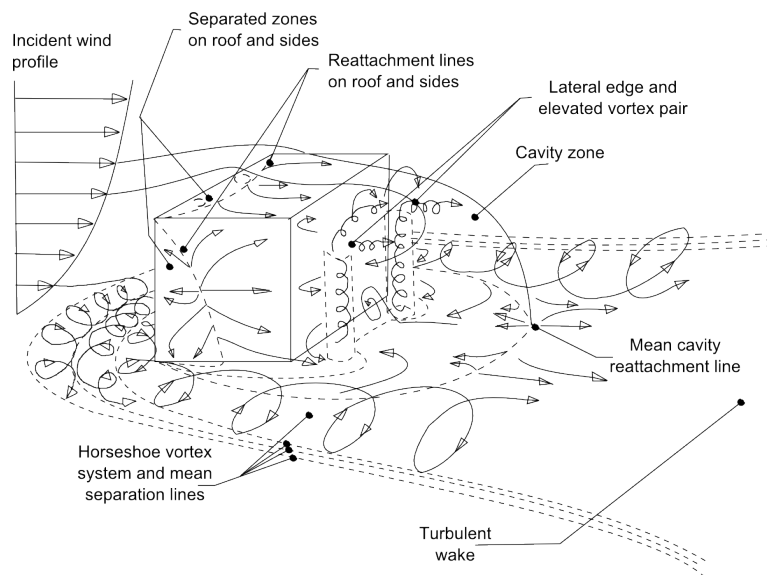
Figure 2.1: Diagram from wind engineering literature that shows graphical representations of the main wind phenomena around an isolated building with rectangular form. This list of wind phenomena is used as criterion of evaluation for the tool performance. (Diagram elaborated by author, base on (Hosker 1979))

As mentioned in the introduction, the visualisation of these wind movement patterns allows to designers elaborate strategies to mitigate the wind comfort issues in the outdoor environment near a building. For instance, installing auxiliary elements of protection

or adapting (during the design process) the geometrical form of a building project to reduce these negative effects. Many of the phenomena described in the image (Figure 2.1) produce accelerations of the wind flow at ground level, affecting the level of wind comfort in pedestrian zones (Peterka et al. 1985). Downwash effect, separation zones and vortex of airflow in the street are wind phenomena that increase the discomfort of pedestrian in public areas, building entrances and public transport stops. A good summary of these wind discomfort issues around a single building can be found in the Stathopoulos' work *Wind and Comfort*(2009).

Criterion of evaluation. Based on an image of wind flow pattern classification, the criterion of evaluation for these experiments considered a selection of typical wind phenomena as visualisation task for these techniques. The idea is to conduct a rapid visualisation, trying to identify these movements at the windward and leeward side of the building. The visualisation task is considered as "yes" for a technique if this can visualise the wind effect and display a representation comprehensibly. If the technique cannot display a clear representation, the task is considered as "no". Moreover, if the technique requires a complex process to visualise the phenomenon, it is considered as "difficult". Therefore, the tests are organised for each geometrical model of building (Table 2.1).

Wind Visualisation of Building with Regular Form

Building models	Wind visualisation tool	Wind visualisation test	
One and two buildings	CFD-PST Vasari	2D wind flow	3D wind flow
One and two building	Mini airflow tunnel	Fog test	Erosion test
One building with curved facade	Ind. wind tunnel	Bubble test	
Several buildings	JPIV	Vector field	

Table 2.1: Table of the experiments conducted in this first investigation, including several techniques of wind visualisation and the tests to visualise different wind phenomena around one and two simultaneous regular buildings.

For these tests of rapid wind visualisation, the techniques used were the CFD-PST software Autodesk Vasari and the open source program of optical analysis JIPV. As physical tools for wind visualisation: a mini airflow tunnel and an industrial wind tunnel were used.

CFD-PST program

Autodesk Vasari is a building design and analysis tool that integrates 3D modelling, energy analysis, solar radiation analysis and CFD analysis modules in the software. The software is designed to let users focus on the conceptual design phase (Autodesk 2013b).

The CFD module of Vasari is a virtual wind tunnel to simulate wind flow in real time with few parameters. This program can create 2D and 3D simulations of the wind flow and display information of wind velocity, temperature and pressure quickly. This method of simulation is mainly aimed at outdoor flows around single volumes (Anderson 2014). The visualisation process is simultaneous with the simulation using simplified representations of colour patterns, streamlines and isosurfaces (Figure 2.2).

Model
- Model Site Context
- Create Conceptual Mass Model
- Choos a Weather Station

Simulate
- Set Analysis Grid
- Wind Speed & Direction
- 2D vs 3D Analysis
- Run Simulation

Visualise
- 2D Slices horizontal and vertical
- 3D Volumetric Traces
- Point cloud & ISO Surf.
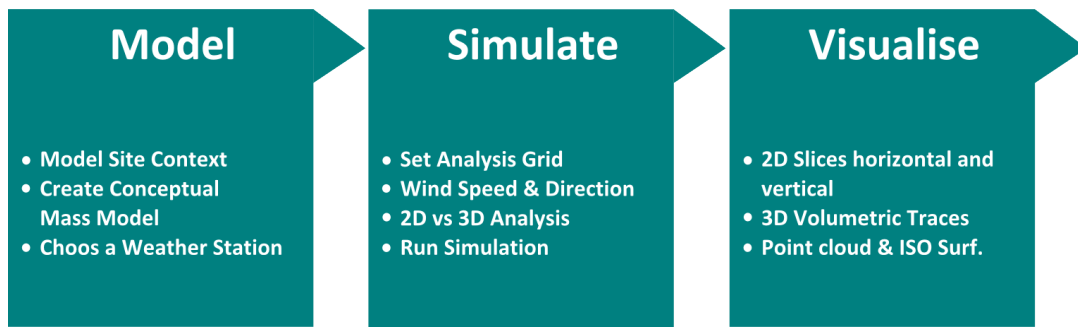
Figure 2.2: Diagram of Autodesk Vasari wind tunnel workflow. This software is a simplified CFD program of wind analysis for the conceptual design stage. (Author's diagram based on sustainabilityworkshop.autodesk.com)

The low-tech mini airflow tunnel for visualisation

To have an idea about a real turbulent flow of air around a building, I decided to build a physical mini airflow tunnel for these experiments, only for visualisation purposes. I had this idea based on two previous cases, referred to the literature review, where a low-tech wind tunnel was used for visualisation experiments during the early design stage of architecture projects.

The terms "low-tech" and "high-tech" tools classify the technologies used for visualisation of wind phenomena that are used in this research. The low technology is the opposite of high technology and refers to tools that do not require complex mechanisms,

do not involve automation, are low cost and made by oneself and are used for simple qualitative observation. In contrast, high technology means highly specialised tools, with an automatic process and generation of quantitative data (Figure 2.3).
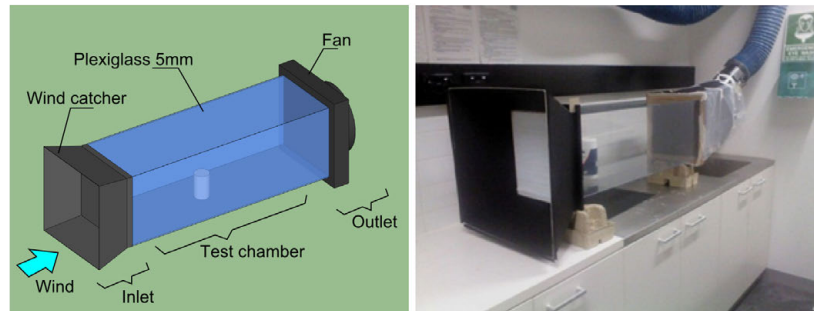
Figure 2.3: Design, construction and use of a hand-made mini airflow tunnel for wind visualisation of aerodynamic phenomena around isolated building models. Left: concept of hand-made mini airflow tunnel. Right: first version of the mini airflow tunnel. (Source: author)

The low-tech airflow tunnel was a version of a wind tunnel of low wind speed and open return design (air intake and exhaust are not connected to each other). It was a low-cost tool that required simple fabrication for hands-on experimentation. This mini airflow tunnel consisted of a $30\ cm \times 30\ cm \times 90\ cm$ transparent test chamber made with acrylic of 3 mm, a contraction section (cardboard extractor hood in black colour to avoid laser reflections), an anti-turbulence porous screen to produce a laminar wind flow, one fan to generate the wind flow and a fog machine for visualisation of the airflow. Additionally, 2D slicer laser devices and digital cameras to record videos and take photos were used on different occasions (Figure 2.4). As simple and rapid visualisation tool, other wind parameters used in wind tunnels are omitted, such as turbulence intensity or ABL effect.
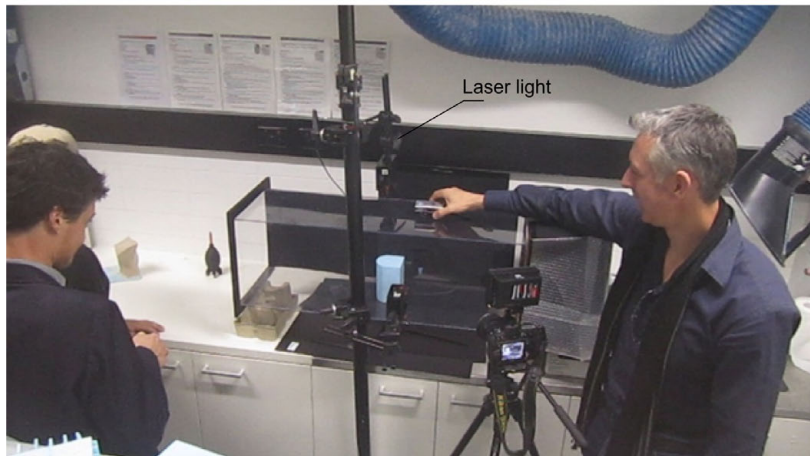
Figure 2.4: The mini airflow tunnel was built to be used in the Designing the Dynamics workshop, 2011. (Source: author)

As stated, a fog machine was used to visualise the flow of the wind inside the test chamber. It was necessary to use a dark area to work with laser devices for the experiments, which are used to visualise sections or slices of the wind flow movement. The speed of wind was around 1 - 5 m/s for some experiments, and 3 - 5 m/s for others. The condition of the velocity was to produce a clear visualisation and it was not related with the scale of the models.

Another technique of visualisation was to use talcum powder to print patterns of wind deflection (see Figure 2.13). This method basically uses the wind flow to drag small particles of sand, drawing the movement pattern flow around the models producing a footprint on the floor.

Particle image velocimetry technique (PIV)

The particle image velocimetry (PIV) is a digital technique to track the movement of particles using photographs, and it has been used for analysing images captured from wind simulations in industrial wind tunnels (Kompenhans et al. 1999). Its scope is mainly the visualisation of micro fluids; however, it has been used for visualisation with experiments of wind comfort (Dezso 2006). This technique of visualisation is mainly used in laboratories and there are no references of use for wind analysis in architects' design processes. But,

using open source software called JPIV[1] as the post-processing tool, a few sequences of images can be shot and analysed quickly. The idea is to test this technique for post-processing of physical experiments of rapid visualisation to evaluate its performance as a wind visualisation technique in the early design stage.

2.2 Visualisation of wind flow around regular building form

To test the visualisation techniques during the Designing the Dynamics workshop (Burry 2013), three groups of models with regular geometries were built: digital models for Vasari, blue-foam models for the mini airflow tunnel and 1:100 scale models for the industrial wind tunnel (Figure 2.5)
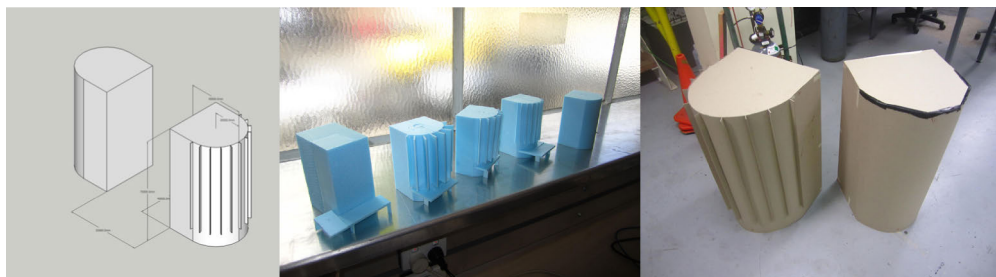
Figure 2.5: Digital and physical models of regular building forms for visualisation tests, using CFD programs, the mini airflow tunnel and a industrial wind tunnel. Left: CAD models. Middle: 1:500 scale models. Right: 1:100 scale models. (Source: author)

CFD-PST visualisation test

In the first stage of these experiments, Autodesk Project Vasari was used firstly to visualise the aerodynamic effects of the airflow around a single cube, and later to run visualisations for two cubes with flat and curve faces. The conditions of these experiments basically simulated the chamber of the mini airflow tunnel. Thus, the parameters of Vasari defined a "grid" (digital domain to set up in Vasari) with proportions of three times the height of the test chamber Moreover, the chamber had three times the height and width of the model (Figure 2.6). The velocity of the wind was similar to the experiments in the mini airflow tunnel (5 m/s) and was a laminar and regular flow, without an ABL effect.

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[1] www.jpiv.vennemann-online.de
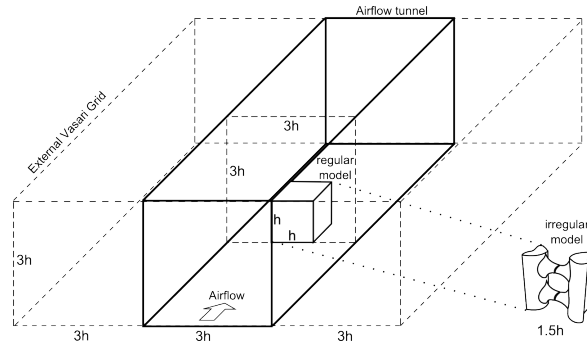
Figure 2.6: Digital domain set up of the experiments for the CFD-PST program Vasari. The domain in Vasari is a grid around a tunnel, similar to the mini airflow tunnel. The grid can only be adjusted in size, with low level of density. (Source: author)

The first observation is the differences visualised in the 2D simulation and 3D simulation produced by Vasari. The oscillating effect of the wake region in the 2D simulation is quite different from the literature references about 3D airflows (see works of Wisse (1988), Hosker (1979), Peterka (1985), Penwarden (1975) and Beranek (1984b)). To get a more similar movement pattern, it is necessary to refine the digital grid and to run a 3D simulation to visualise the classical elevated vortex pair at the leeward side of the cube (Figure 2.7). Similarly, when it is a 2D simulation, a lateral visualisation with vector fields shows two vortex areas in the wake region. When the experiment is a 3D simulation, only one vortex is visualised. At the same time, the reattachment line of the main wake cavity has different distances for each case (Figure 2.8). Moreover, the wind visualisations with the pattern of colour (to show intensity of wind speed) did not give a good representation of some effects, such as the change of the wind flow direction at the frontal zone of a building; the downwash flow effect and horseshoe vortex are difficult to identify, as well.

In a second experiment, the cube is changed for a cube with a curved face. Here, the separation zones at the top of a building with a flat façade and a curved façade are visualised, with their different profiles of deflection. The program could represent the vertical deflection of the wind on the building roof and the difference of velocity on the frontal façade. However, the differences in the horseshoe vortex, at the bottom of the buildings with flat and curve face, are not easy to observe or they are very mitigated, in these lateral visualisations (Figure 2.9).
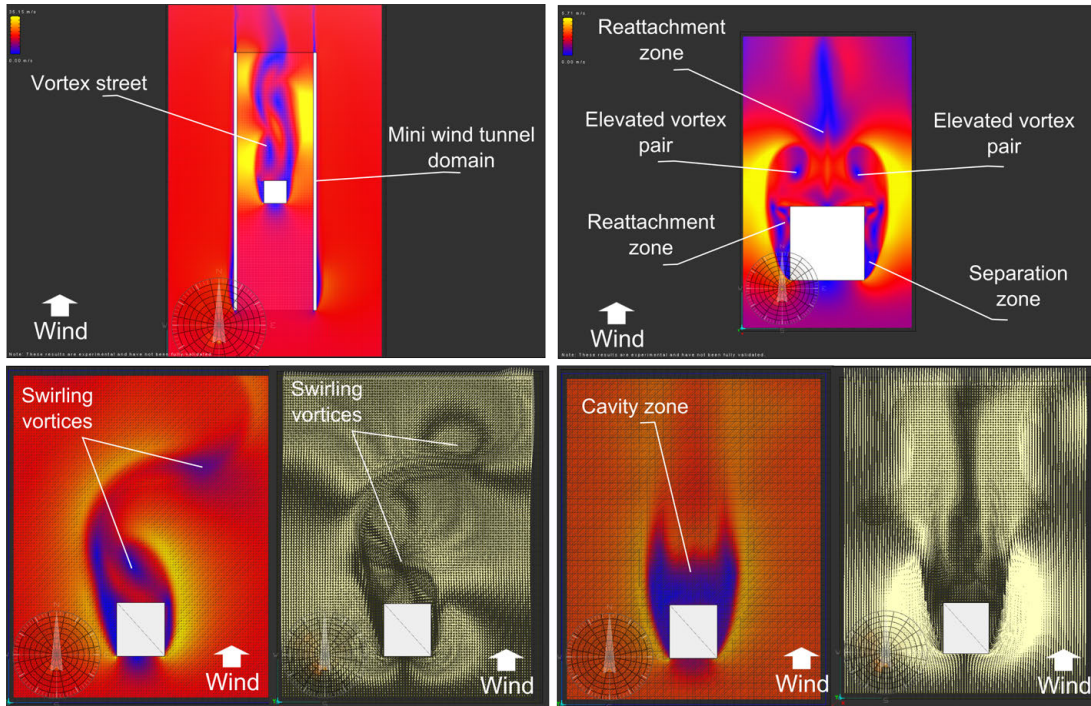
Figure 2.7: Digital visualisation of wind turbulences around a regular building with colour patterns and vector field (visualisation technique of scientific data) using the CFD program Vasari. Different parameters and conditions in the program can produce different outcomes. Left top and bottom: the program displays a 2D wind flow with an oscillating wake region similar to a vortex shedding. Right top and bottom: the program displays a 3D wind flow around the model, with symmetrical patterns of movement and turbulences. (Source: author)
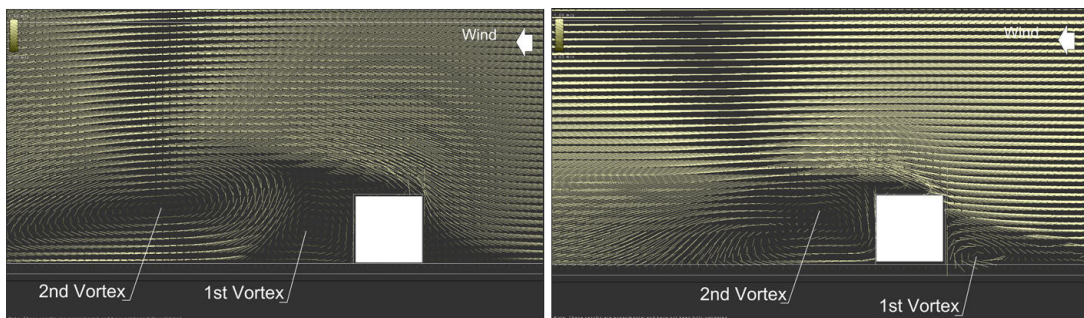
Figure 2.8: The program CFD Vasari can simulate 2D or 3D airflow to facilitate visualisation feedback. However, they show differences between lateral visualisation of wind flow turbulence, at the wake region of a building model (Peterka et al. 1985). The user must learn when to use each method. Left: vector field visualisation of a 2D wind flow. Right: vector field visualisation of a 3D wind flow. (Source: author)

In a third group of experiments with a wind flow around two buildings, it was difficult to see in the visualisations of colour patterns, the differences produced in the wind flow
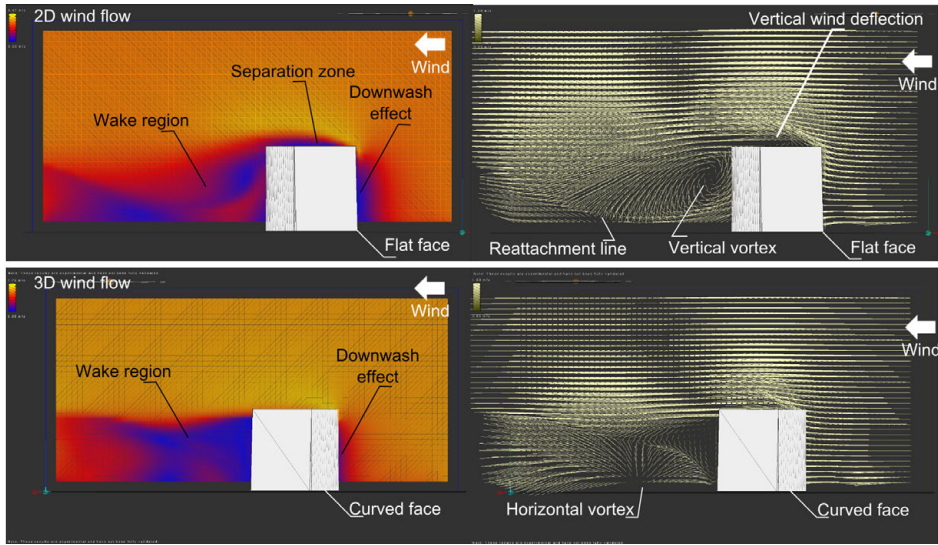
Figure 2.9: The CFD visualisation and analysis in the early design stage allows the identification of the main wind effects produced by the geometry of a building. The image shows a digital visualisation of 3D wind flow on two kinds of windward façades, with CFD Vasari. Couple at the top: a flat face on the building produces a vertical wind deflection on the roof of the building. Couple at the bottom: a curved face deflects the wind laterally, mitigating the deflection on the roof area. (Source: author)

deflected by flat façades and curved façades and the region of deflection at the bottom of these vertical surfaces. Also, the wake region behind the buildings can be very different in some cases compared with others; especially, when the influence of a building wake affects the area of a second building. For instance, the wake region behind a second building looks significantly larger than the first one (Figure 2.10), when both wakes should be relatively similar, if we compare with similar experiments in the literature.
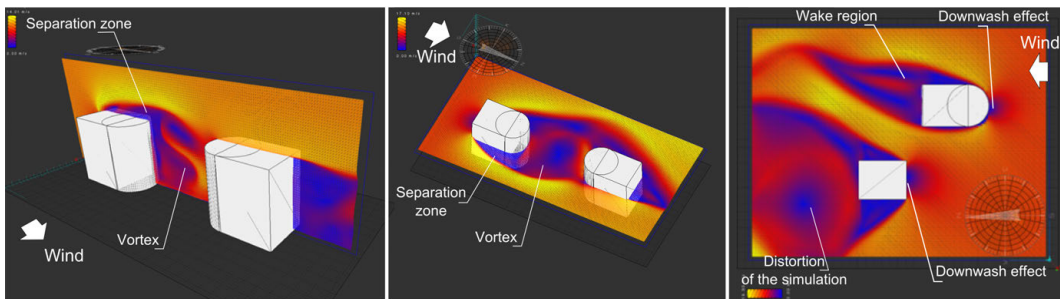
Figure 2.10: Digital visualisations of a 2D wind flow, between two buildings with CFD Vasari. Left and middle: The visualisation displays the turbulence between both buildings and the separation zones produced by a flat and curved windward façade. Right: when the size of the domain is to small, the visualisation is unclear. (Source: author)

Mini airflow tunnel: visualisation with fog technique

For the experiments in the mini airflow tunnel, blue-foam models representing buildings with similar geometrical profiles to the digital experiments were tested: single volumes of regular boxes, boxes with cylindrical faces and irregular faces, and groups of two volumes and four volumes in different configurations.

The general observations of this group of experiments, using fog to draw the motion of the wind and visualise wind movements, were focused on phenomena such as acceleration and direction of the airflow. During these experiments the observer interacted with the physical objects, moving the models to see new wind patterns.

In the physical experiments with an isolated building model, the behaviour of the turbulent wind region behind the models was clearly visualised (something that was more diffuse in the previous digital visualisations). For instance, the visualisation shows that the model with curved façade produced a smaller wake region and downwash effect than the model with flat façade. Also, the visualisation clearly showed how the separation zone and vertical deflection, on the top of the model, are more significant with a flat façade. However, even though the vertical movement of the vortex in the leeward side of the model is evident, it was difficult to identify a specific movement pattern in this turbulent region (Figure 2.11).

For the experiments with two and more building models, the multiple vortex zone of wind flowing between two buildings was observed with a high intensity of speed at the ground level, while the high area concentrated a low airflow speed movement. In the image it is visible the high turbulence between both building with the flat façades. In contrast, when the windward façade of the first building is flat, and the space between both building has curved façades, the turbulence regions are observed above both buildings. Finally, the visualisations with several buildings were not enough clear to identify specific wind patterns (Figure 2.12).

In general, in the visualisations with a vertical 2D slice, using a laser devise, the most common wind effects could be recognised: movement patterns such as the wind flow deflection at the top and sides of a building (separation zones).
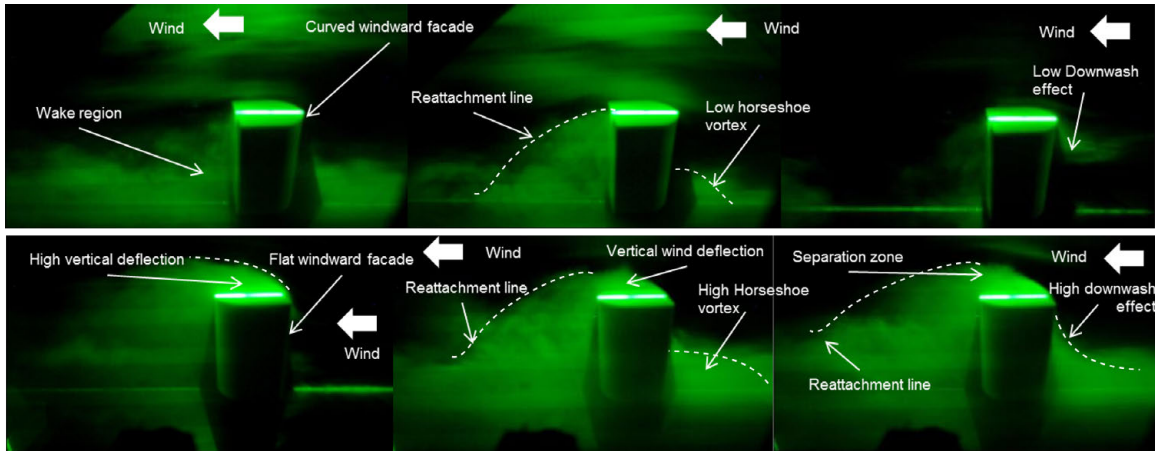
Figure 2.11: Visualisation of the main vertical wind effects around an isolated building model with flat and curved façade, using a 2D sheet laser light in the low-tech mini airflow tunnel. Top row: visualisation of vortex at front and behind of a model with curved face. Bottom row: visualisation of vortex at front and behind of a model with flat face. (Source: author)
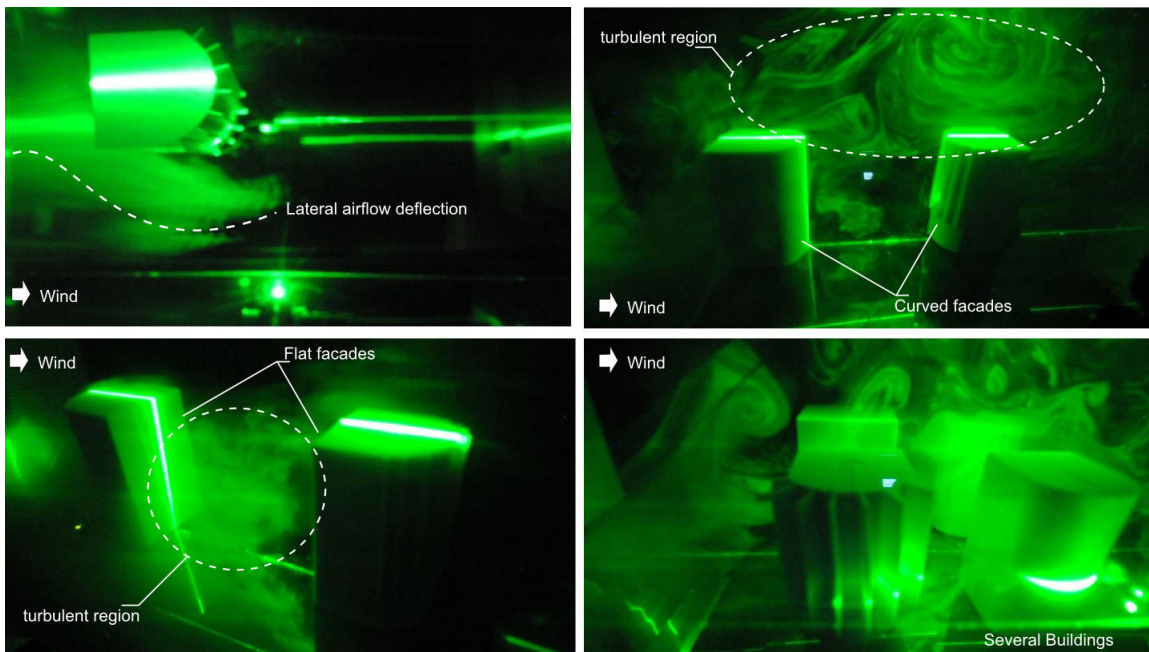
Figure 2.12: Several visualisations of vortices between building models, in the low-tech mini airflow tunnel. The physical visualisation displays first a global 3D image of the wind phenomenon. Thus, it is easier to select areas for analysis using 2D techniques of visualisation such as illumination with a sheet of green laser light. Top left: lateral airflow deflection. Top right: turbulent region visualised at the top of both buildings. Bottom left: turbulent region visualised between both buildings. Bottom right: turbulent regions between several buildings. (Taken from: (Salim and Moya 2012)).

Mini airflow tunnel: visualisation with erosion technique

After the experiments with fog emission, I conducted experiments using the erosion technique in the mini airflow tunnel, as a rapid wind visualisation method, to see the differences between wind patterns deflected with a flat building face and a curved building face. The tests considered only two buildings sharing the space of the test chamber. Again, for these experiments, calibrated wind parameters were not considered.

The visualisation showed two different conditions of the flow: wake regions and stream flows regions. The experiment showed regions with a high density of particles around of the windward face of each model. These zones represent the boundaries of influence areas or interaction zones between the flows produced around a building. This influence area shows the perimeter of airflow deflections, and a vortex region at the front of each building. Moreover, the areas with a greater density of particles represent the zones where two different movements of airflows meet (vertical and horizontal or two regimes of airstream). One interesting observation was the representation of two buildings with the interaction of wake regions. This means, the wake regions overlapped (Figure 2.13).
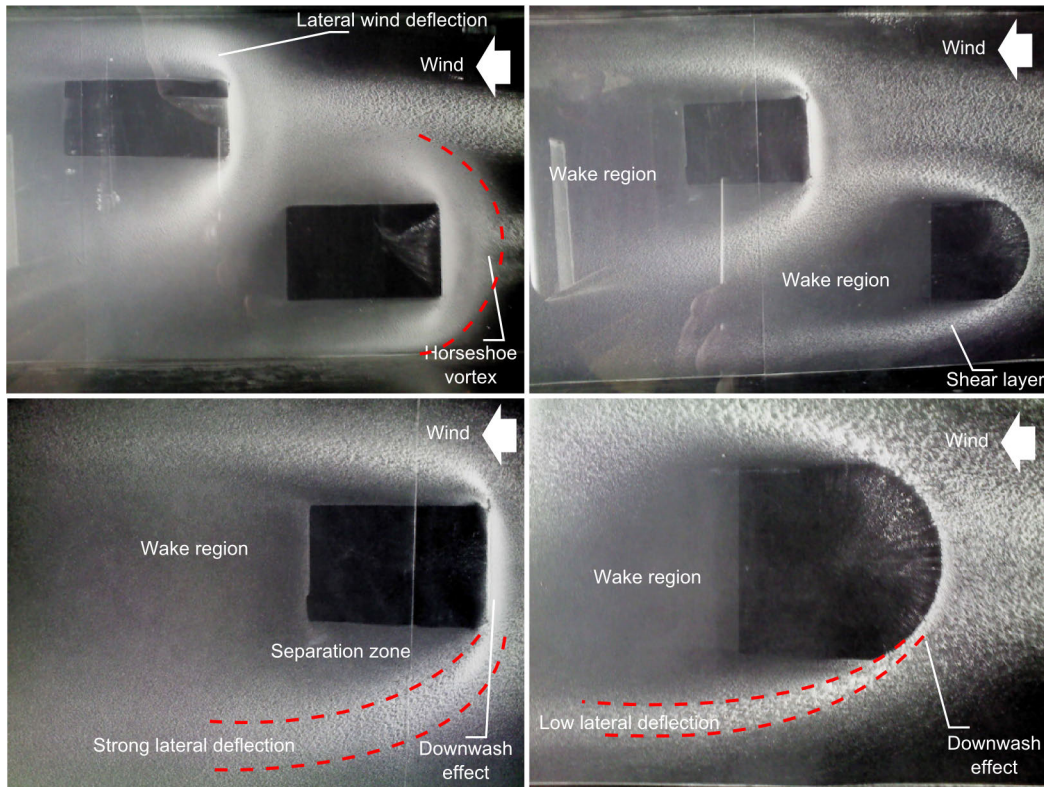
Figure 2.13: Visualisation of the main horizontal wind effects around a building model with flat and curved façade, using 2D patterns of particle erosion in the low-tech airflow tunnel test. This technique allows the identification of the area of deflection that produces strong speed airflows at the ground level, with an impact on the pedestrian comfort. (Source: author)

To know how this visualisation looks compared with a real wind tunnel experiment, I compared my rapid visualisations with cases referred to in the literature. The experiments of W. J. Beranek realised in the 1980s in Delft University of Technology present similar wind pattern regimes around two buildings (Figure 2.14). Beranek clarifies, about this kind of phenomenon, that the pattern is not affected while one of the buildings is outside of the influence area (Beranek 1984b). Another phenomenon observed was the shear layer effect being deflected on both sides of a building. The shear layer is a region of wind where there is an effect of entrainment of both stream flows: free stream and wake region (Aynsley et al. 1977). The rapid visualisations with erosion technique showed that this shear layer is thinner on a curved façade than a flat façade. Also, the curvature of this layer decreases with a curved façade.
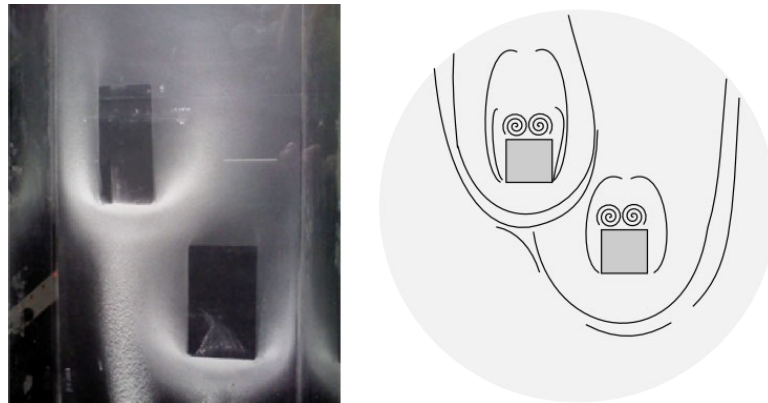
Figure 2.14: The visualisation produced in the low-tech mini airflow tunnel can be useful for preliminary analysis in the early design stage. Left: Low-tech airflow tunnel erosion test in the mini airflow tunnel. Right: from urban aerodynamics literature, streamline patterns for two wake interactions from an experiment of an ABL wind tunnel. (Diagram elaborated by the author, based on (Beranek 1984a))

In addition, these visualisations showed that the separation zones at the edges and sides of the façade were more significant on the flat façade (corner effect). A third phenomenon visualised in the test was a shear layer deflecting another wind gust coming from a second building (Figure 2.15). These rapid visualisations showed how two buildings can change the wind direction when the flow is deflected by a façade and is projected to a wake region of another building. This effect is because of the transversal connection between different pressure air masses, caused by the proximity of buildings (Gandemer et al. 1978).
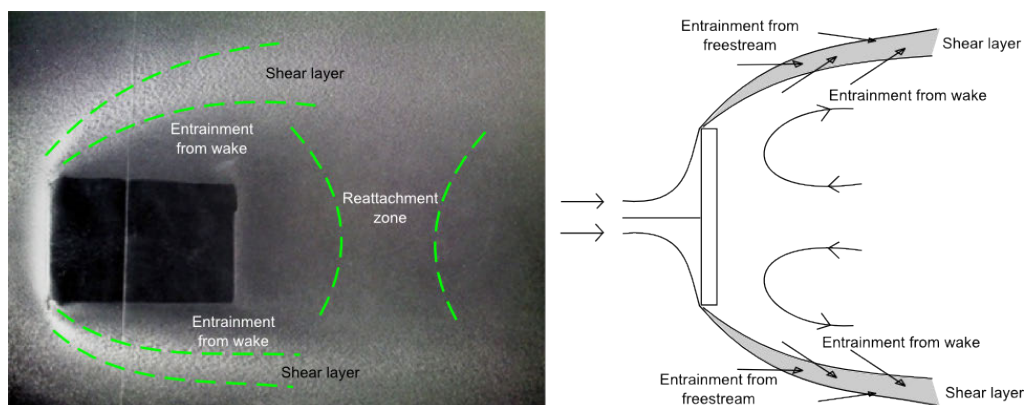
Figure 2.15: The empirical observation of the physical experiment explains the concepts developed in the literature. Left: Lateral wind deflections and thresholds between regions of wind (shear layers) visualised in the low-tech mini airflow tunnel. Right: explanation of the concept of entrainment of freestream and wake fluid into the shear layers, found in the literature review. (Diagram elaborated by the author based on (Aynsley et al. 1977))

ABL WT visualisation test

Experiments with the same geometrical design of models were conducted in the large-scale industrial wind tunnel at the RMIT Bundoora Campus. These experiments are referred to here as a reference technique of visualisation using a high-tech tool in a specialised aerodynamics laboratory. Therefore, this technology is not integrated in the architects' design process, like digital tools of analysis. This industrial wind tunnel has a test section that is 3 m wide, 2 m high and 9 m long, and it was set up with a barrier of horizontal timbers in the inlet zone to reproduce a wind flow velocity profile similar of the ABL, for 1:100 scale models. The conditions of wind flow in the wind tunnel were similar to previous experiments conducted in these facilities (see (White et al. 2012)). The model tested was the building with a curved face, which was observed installed directly on the ground and with a base to keep a gap at the bottom. The aim was to visualise the deflection effect of wind and turbulence at the top of the model, turbulent zones at the ground level around the model and acceleration of wind around the corners. The visualisation technique used a flow of bubbles for a visual representation of wind movement (Figure 2.16).
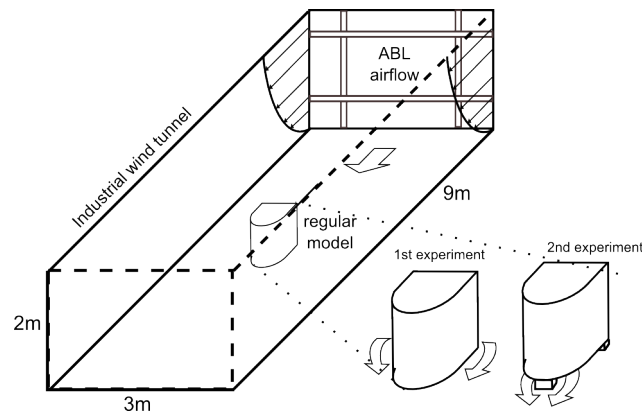
Figure 2.16: Experiments of visualisation of wind deflection at the top and bottom of a scale model, in the RMIT Bundoora Campus ABL wind tunnel. The experiments considered a model of a building with a flat and curved face, installed directly on the ground and a second experiment with a gap of 10 cm in the base. (Source: author)

Through this physical visualisation it was easy to identify the separation zone at the top of the model and the downwash flow in front of the façade. In addition, the visualisation of the vortex flow at the bottom of the façade was clearly observed. However, it was difficult to identify specific patterns of movements at the leeward side of the models, because the wind movement was very turbulent (Figure 2.17).
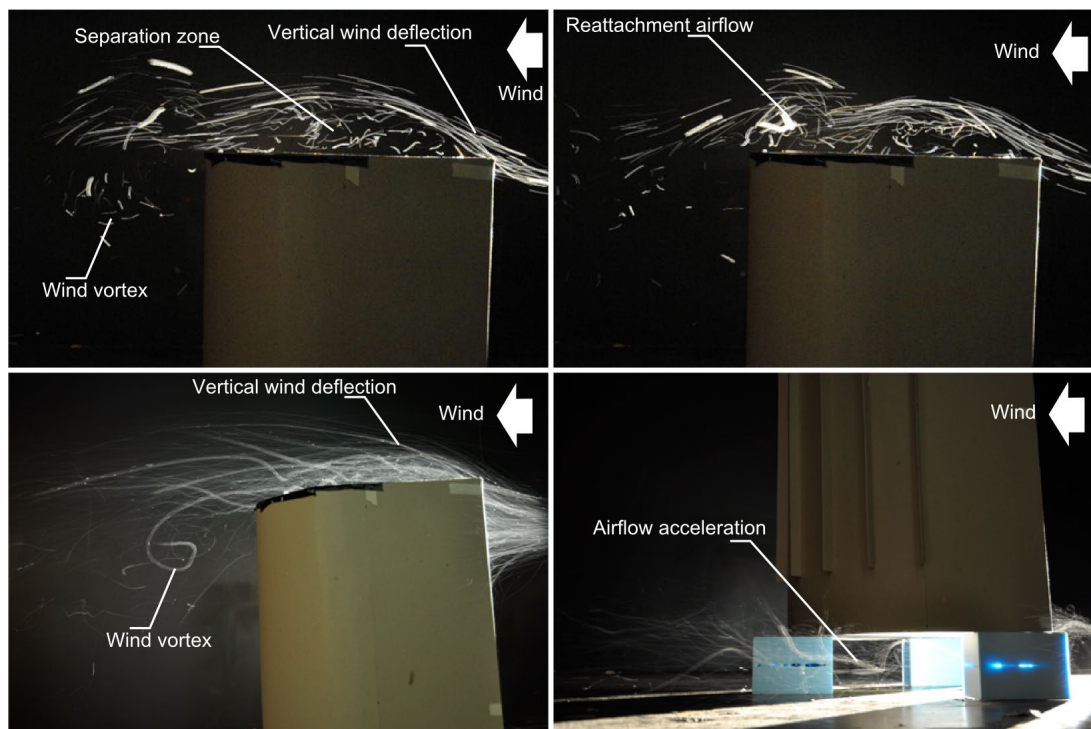
Figure 2.17: Visualisation of wind deflection at the top and bottom of a scale model, in the RMIT Bundoora Campus wind tunnel. This technique of visualisation is more accurate but not suitable in the early design stage. Top left and right: the effect of deflection at the top of the buildings has a region of reattachment that is missing in the mini airflow tunnel visualisations, because these experiments replicated ABL. Bottom left: visualisation of airflow deflection on the roof. Bottom right: visualisation of airflow passing through a gap at the bottom of the building with an acceleration effect. (Source: author)

If we compare the separation zone and the vertical deflection at the top of the model, it is possible to observe that there is a reattachment zone of the airflow at the opposite edge of the building. This effect is missing in the mini airflow tunnel visualisation and in the Vasari visualisations. In fact, the industrial wind tunnel experiment was set up with parameters that were omitted in the other techniques, because they do not fulfil those conditions for rapid visualisation. In this sense, architects in the early design stage do

not aim for real wind flow simulations, but rather for a visualisation of wind flow with different approximation levels.

PIV visualisation test

As a digital method of visualisation, for post processing of analogue images, JPIV was tested with photos from the experiments of the mini airflow tunnel, and the industrial wind tunnel. However, because the good performance of this technique depends on the clarity of the pictures, it was not possible to evaluate all the phenomena of the table. For the case of these experiments, it was possible to see in a few pictures the areas of high wind speed with representation of vector fields, showing intensity and direction of the flow.

For the mini airflow tunnel experiments, the PIV technique showed a vector field at the top of a building, where the wind flow deflection produced wind gusts to the leeward side of the model, with more turbulent movements. These visualisations allow the identification of the upward airflow zone behind the model and downward airflow regions around the model (Figure 2.18).

On the other hand, in the industrial wind tunnel, the technique allowed the visualisation of the downwash flow on the model's windward façade, the vortex flow at the bottom of the building and the turbulence of the wake region at the back of the building (Figure 2.19).

The JPIV software was an interesting tool to test the potential of digital visualisation of post-processed images for the early design stage. It can be argued that a visualisation using CFD software will generate similar results in a post-process, with graphical filter representations. However, an analysis using PIV post-process facilitates the comprehension of the movement of a flow, representing that movement as field of vectors with a grade of intensity for direction and velocity of the flow. This post-process was relatively easy and quick; thus, it is possible to use in the wind analysis of several design alternatives, if the facilities for physical experiments are available.
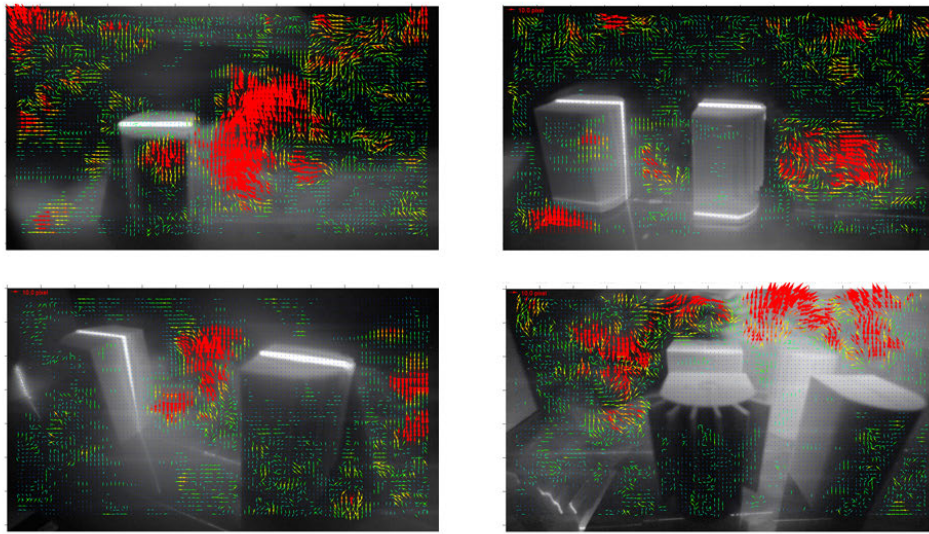
Figure 2.18: Experiments of wind visualisation in the low-tech mini airflow tunnel. Technique of fog and sheet laser light with post-processing of PIV, to visualise with vector fields the areas of turbulences behind and between models of buildings. Top left, right and bottom left: visualisation of turbulence in the wake region with vectors. Bottom right: visualisation of turbulence on the building roofs with vectors. (Source: author)
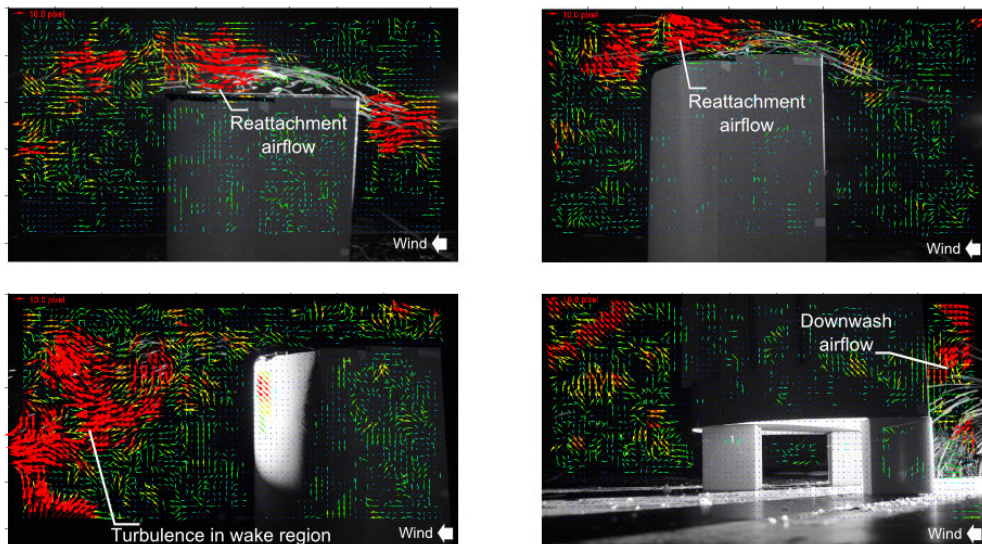
Figure 2.19: Wind visualisation in the ABL wind tunnel, using bubbles with post-processing of PIV. Visualisation of areas of turbulences behind and at the top of the models. Top left and right: visualisation with reattachment airflow on the roof with vectors. Bottom left: visualisation of turbulence in the wake region. Bottom right: visualisation downwash effect at the bottom of the windward façade with vectors. (Source: author)

(March 2015)

2.3 Visualisation of wind flow around an irregular building form

In general, the literature refers to wind analysis with examples of regular buildings, such as boxes or cylinders. However, there are cases where the building design has an irregular form; for instance, a new building concept designed for wind energy harvesting. For these cases, the movement of wind in the space is more unpredictable and difficult to identify. Thus, with the idea of observing the wind flow patterns interacting with a different and more complex building typology, I tested Vasari and the mini airflow tunnel as rapid visualisation tools, following the next program of tests (Table 2.2).

Wind Visualisation of Building with Irregular Form		
Building models	**Wind visualisation tool**	**Wind visualisation test**
One building	**CFD-PST Vasari**	2D wind flow 3D wind flow
One building	**Mini airflow tunnel**	Fog test

Table 2.2: Table with the techniques of wind visualisation used in this stage of the investigation, and the tests conducted to visualise wind phenomena around a building scale model with irregular form.

The visualisation test was focused to identify in the experiments the similar wind patterns described in the evaluation criterion. But also, two design strategies of this particular building were analysed. One strategy is the design to concentrate and accelerate the wind flow through a duct in the façade (one characteristic of this design is that the variation in the incidence angle of the wind flow will increase the intensity of the speed in the duct (Stankovic et al. 2009)). The second strategy is the design of the buildings that was planned to produce a low downwash effect to the ground.

The rapid visualisation for these tests mainly used Vasari filters of colour patterns for wind velocity intensity and isosurfaces filter. On the other hand, the test in the mini airflow tunnel used fog emission to visualise the airflow.

Aerodynamic building concept

The building chosen for the tests was an experimental concept of a building with integrated wind turbines, published in the book *Urban Wind Energy* (Stankovic et al. 2009). This

concept is a design of two towers connected with bridges, forming structural frames to support several horizontal axis wind turbine (HAWT). The whole design of this building has no edges, only curved surfaces for the towers' façades to catch the wind from different angles, avoiding separation zones and high turbulence. The building's façades work as a wind concentrator to increase the efficiency of the wind turbines (Stankovic et al. 2009).

Using pictures and photos, I created a digital model of a section from the original building design. This digital model was used to build a physical model with a 3D printer, to be used in the low-tech mini airflow tunnel. The dimensions of the model were chosen to facilitate the visualisation of air phenomena. Moreover, using the digital model, some CFD simulations were conducted using Vasari software, replicating the conditions of the mini airflow tunnel (Figure 2.20).
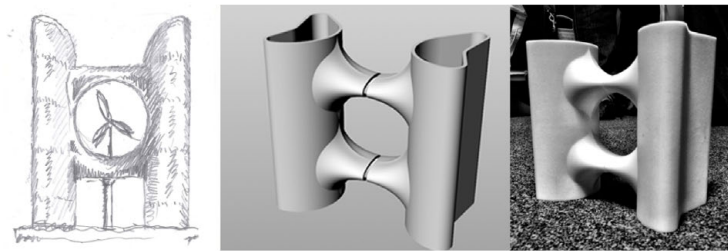
Figure 2.20: The concept of wind turbine integrated in a building is used as model of a building with irregular but aerodynamic form. Left: original prototype (Author's sketch based on (Stankovic et al. 2009)). Both images at the right: digital and physical reproductions for experiment with CFD Vasari and the mini airflow tunnel. (Source: author)

CFD-PST visualisation test

In the rapid visualisations with Vasari, the separation zones and accelerations of wind flow were easy to identify. This rapid visualisation allows the observation of the airflow accelerating through the building as one of the main design strategies of this building concept. However, the wind flow visualisation did not show a variation of the wind speed when the angle of incidence of wind changes (a rise of wind speed through the building's concentrator is mentioned by Stankovic and Cambell (2009) when the wind direction is 45°). Another interesting observation is the extension of the wind flow after passing the duct and being projected to the wake region: when the wind has a variation of incidence

angle from the building axis, it produced a longer airstream in the wake region than wind flows perpendicular to the building. Finally, the rapid visualisation shows how the downwash wind flow on the windward façade is lower than a bluff building, similarly to the horseshoe vortex at the bottom of the building, which looks very attenuated (Figure 2.21).
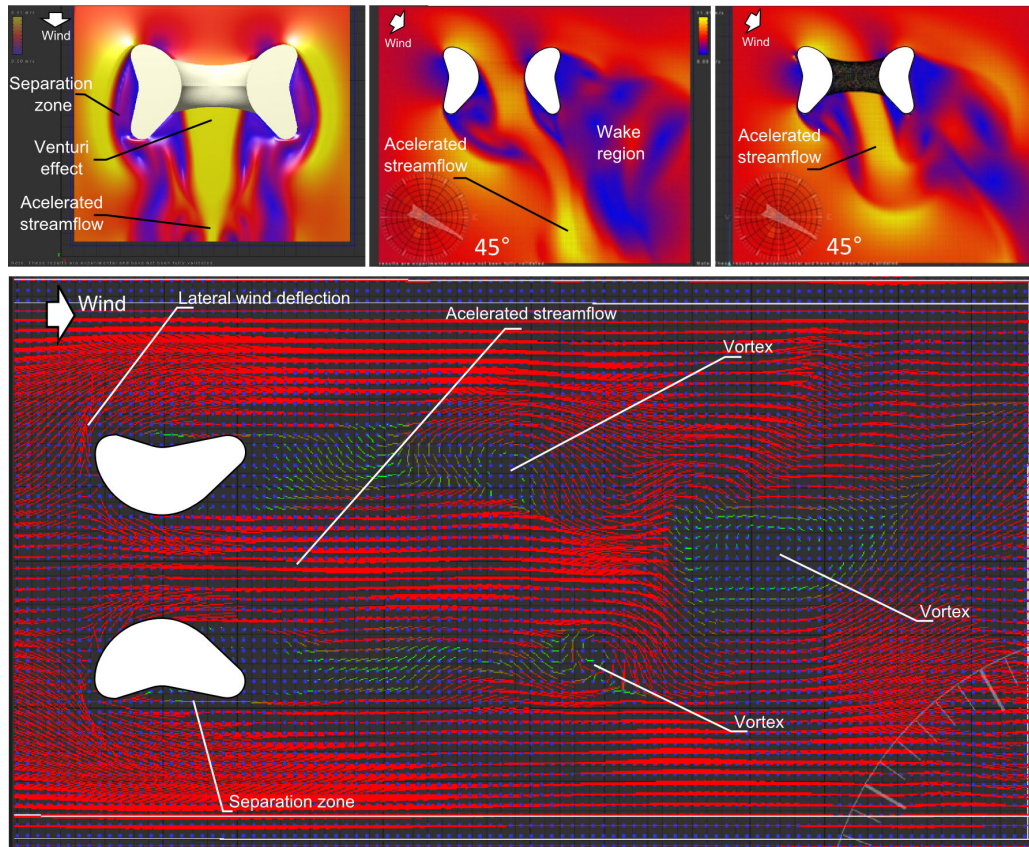
Figure 2.21: CFD visualisations of the acceleration effect of wind produced by the building frames and lateral deflections, with a horizontal 2D slice generated by Autodesk Vasari. Top left: air acceleration produced by a perpendicular wind flow to the building. Top middle and right: larger stream flow of air produced by a 45° wind. Bottom: visualisation of vector field with areas of vortex in the wake region, behind the building. (Source: author)

Moreover, the visualisation shows the separation zones on the roof and the sides. They are clearly visible and easy to identify. The wake regions behind each tower present a clear group of vortices, one of them a vertical vortex in the base of the tower. Furthermore, behind the bridges of the building is observed an upward wake region with a strong vertical airflow deflection (Figure 2.22).
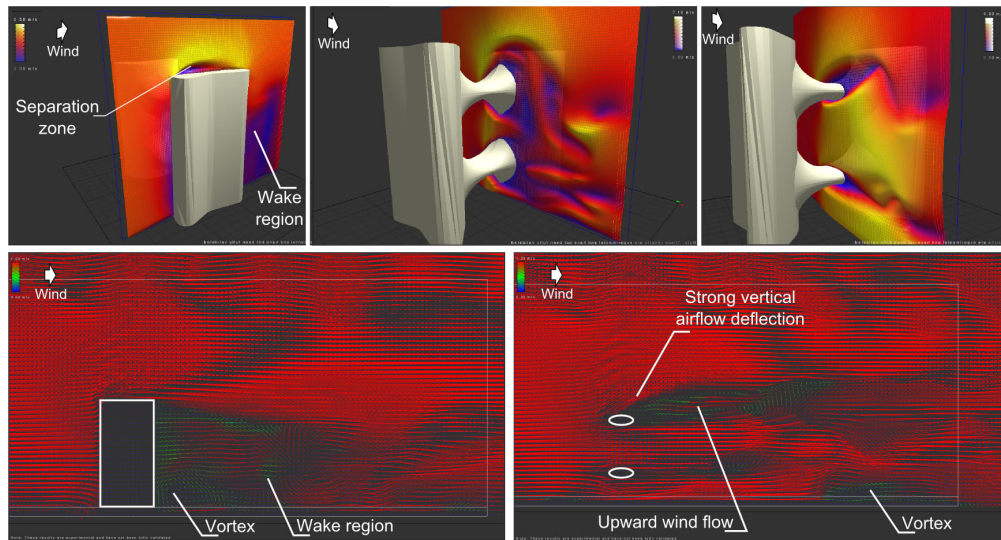
Figure 2.22: CFD visualisations of the acceleration effect of wind produced by the building frames, with a vertical 2D slice generated by Autodesk Vasari. Top left: separation zone of wind at the top of the building, which is less pronounced than a regular building form. Top middle and right: wake region with an oscillating pattern of vertical movement. Bottom left: vertical vector field visualisation of wake region behind one of the building's towers. It shows the vortex of airflow at the base of the tower. Bottom right: vertical vector field visualisation showing the upward wakes produced by both building's bridges. (Source: author)

However, the rapid wind visualisation using representation of isosurfaces in Vasari (graphical representations that are not frequently used by architects) presents an image of regions as surfaces or clouds that is difficult to understand, because is controlled with dimensionless parameters that are not directly related to velocity intensity of pressure (Figure 2.23). However, the idea of a 3D visualisation of the wind dynamics is useful to understand zones of wind as thresholds. The problem with this method of visualisation is that the user must set up the parameters of the boundaries to generate these thresholds. This requires a pre-knowledge of the phenomena to calibrate a useful representation with this technique.
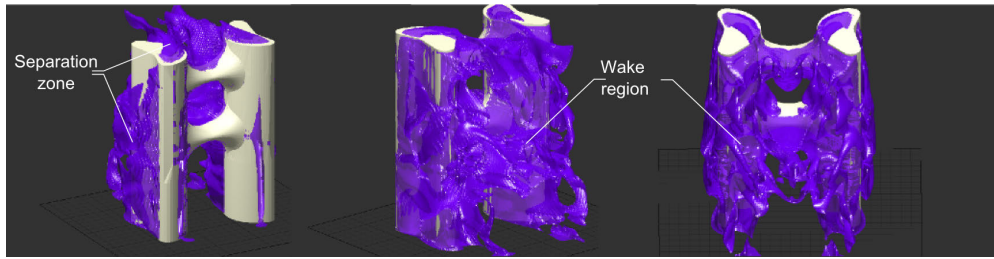
Figure 2.23: Several 3D isosurface visualisations of the wake region, produced by Autodesk Vasari. This display provides a more global visualisation of the wind phenomenon, but it is difficult to set up and requires more time for rendering. (Source: author)

Mini airflow tunnel visualisation test

In general, the rapid visualisation experiments in the low-tech mini airflow tunnel presented several clear wind phenomena at the leeward side of the building (wake region), that were easy to identify.

Like the digital experiments, the first wind effect identified, with fog visualisation in the mini airflow tunnel, was the Venturi effect at the centre of the accelerator duct. It is visualised in the gap between the towers and at the ground level, too. This acceleration of air is projected to the wake region and it is easy to identify this effect as the main pedestrian discomfort issue for this design of building. However, an interesting effect that was not observed in the previous Vasari visualisation, but clearly observed in the mini airflow tunnel, is a lift effect on the wind flow when it flows through the duct to the wake region (Figure 2.24).
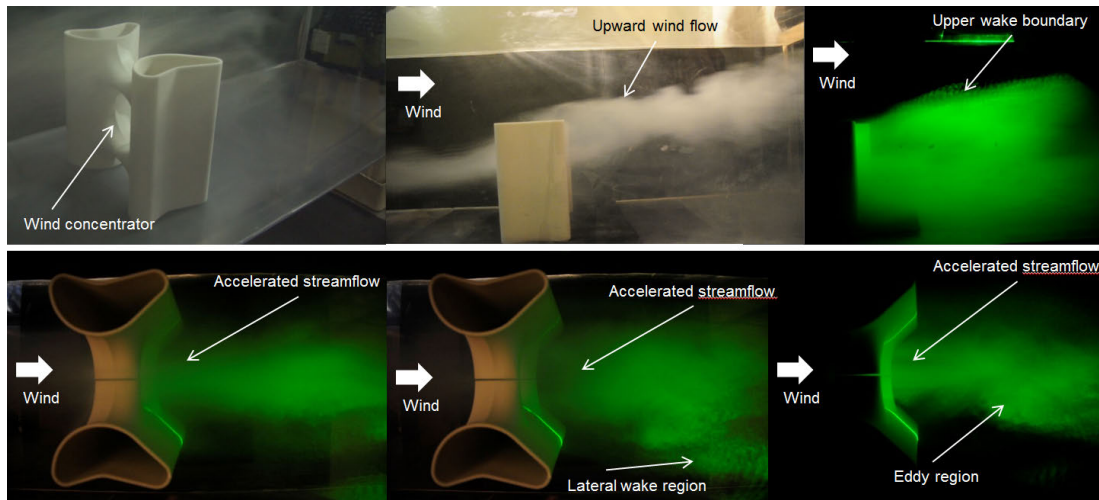
Figure 2.24: Several visualisations conducted in the low-tech mini airflow tunnel with the aerodynamic building. The aim was to visualise a global image of different wind effects. Top row: visualisation of upward wind flow in the wake area behind of an irregular building. Bottom row: visualisation of eddy area and accelerated wind flow in the wake region behind of an irregular building. (Source: author)

Another phenomenon observed was the wind deflection around the tower bases (horseshoe vortex). The wind was visualised flowing attached to the surface, because of the curvature of the façades. Thus, it is easy to consider the separation zones as less significant, because the curvature of the windward façade mitigates the downwash effect (Figure 2.25).
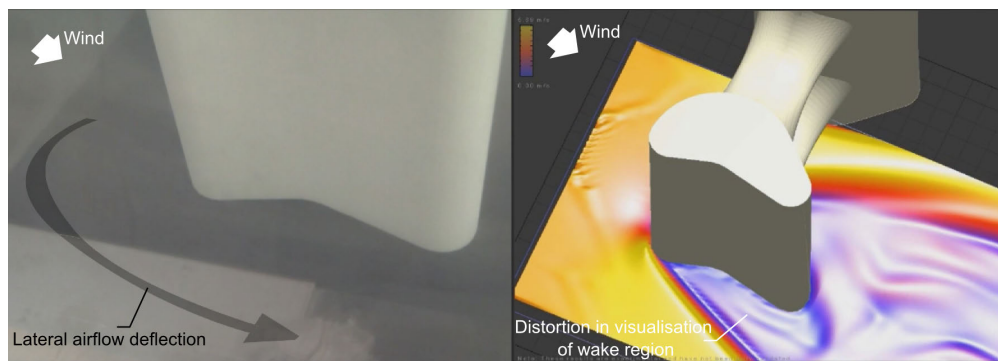
Figure 2.25: Comparison of visualisations conducted in the low-tech mini airflow tunnel and CFD Vasari: Horizontal wind deflection and separation zone at the base of the building model with curved façade. The region of airflow deflection was more evident in the mini airflow tunnel, while the Vasari visualisation present a distortion because of the small size of the domain.

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Finally, behind the model, the visualisation showed a double wake zone of turbulence with opposite vortices directions. While, a traditional building has two main areas of vortices at the leeward side, this building with two towers produces two vortex areas for each tower with opposite wind flow directions (Figure 2.26). The zone of the wake region (eddy area) also looks longer than a wake region produced by a traditional building. Perhaps this increase in the area of the wake is caused by the acceleration of the wind flowing through the central frame and the ventilation gap at the ground. Probably these airstreams push back the return flow in the wake area, increasing the extension of this region.
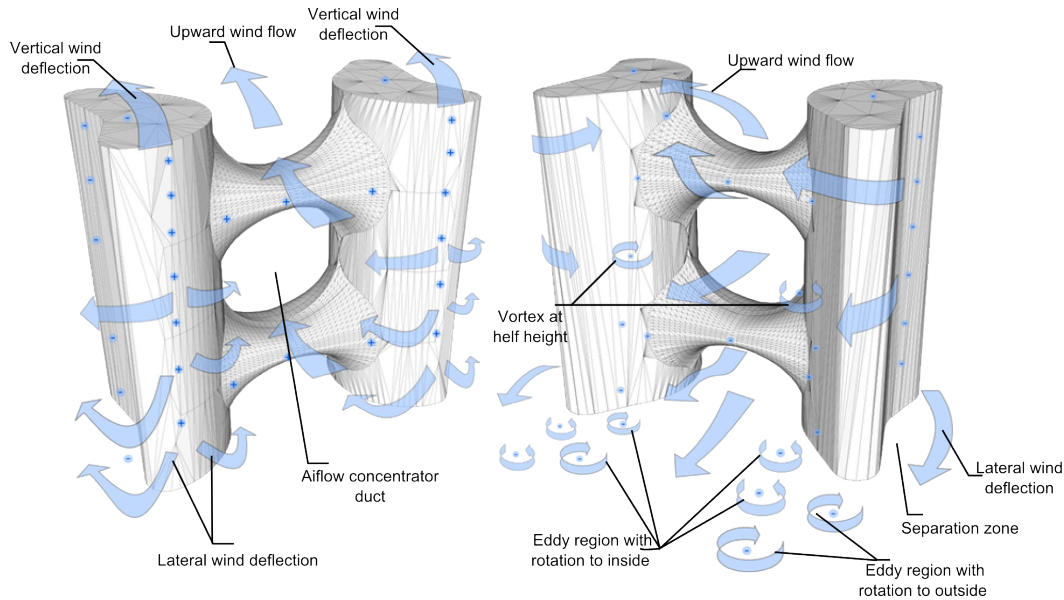
Figure 2.26: Diagram of wind flow around the building model, after observations with the low-tech mini airflow tunnel: the diagram shows the main vectors of wind directions, circular arrows as eddy areas, and the estimation of possible air pressure areas with "+" and "-" symbols. (Source: author)

2.4   Summary

At the end of these experiments of quick wind visualisations with the physical tools (mini airflow tunnel, industrial wind tunnel) and CFD-PST software (Vasari), I was able to obtain some preliminary findings of these techniques used for rapid wind visualisation in the surrounding space of a single building with flat and curved façades, the spatial config-

uration of two buildings and around an isolated irregular building design. A summary of the evaluation results for these tools can be found in the following tables (Table 2.3 and Table 2.4).

Wind Visualisation Building with Regular Form

Wind phenomena	Vasari 2Dflow	3Dflow	Mini airflow tunnel	Ind. wind tunnel	JPIV
Visualisation Downwash flow	no	yes	yes	n/a	yes
Visualisation Horseshoe vortex	no	yes	yes	yes	yes
Visualisation Separation zones roof	yes	yes	yes	yes	yes
Visualisation Lateral separation zones	yes	yes	yes	n/a	n/a
Visualisation Elevated vortex pair	no	yes	no	n/a	n/a
Visualisation Leewarside reattachment	Difficult	Difficult	yes	n/a	n/a

Table 2.3: Table of evaluation for several techniques for quick wind visualisation and the more relevant wind phenomena around a regular form building (see glossary for definition of terms). In general, the visualisation of the movements of vertical wind vortex and the downward deflection of wind at the windward side of the building are missing in the 2D flow visualisation generated by CFD-PST program Vasari. In the same way, it is difficult to identify the boundaries of the turbulent region at the leeward side of the building, which have irregular patterns in 2D flow visualisation with Vasari. On the other hand, physical experiments (mini airflow tunnel) allow a clear visualisation of the main wind phenomena at the windward side of a building.

Wind Visualisation Building with Irregular Form

Wind phenomena	Vasari 2Dflow	3Dflow	Mini airflow tunnel
Visualisation downwash flow	difficult	n/a	yes
Visualisation of horseshoe vortex	difficult	n/a	yes
Visualisation separation zones roof	yes	yes	difficult
Visualisation separation zones sides	yes	yes	n/a
Visualisation venturi effect	yes	no	yes
Visualisation acceleration in wake area	yes	dificult	difficult

Table 2.4: Table of evaluation, including several techniques of wind visualisation and their performance to quickly visualise different wind phenomena around an irregular form building (see glossary for definition of terms). The CFD-PST program Vasari shows clearly horizontal movements of airflow (lateral airflow deflections) and regions of high and low wind speed, but patterns of vertical airflow movements are more difficult for a quick identification. On the other hand, the mini airflow tunnel is a tool that can visualise clearly the vortex of wind at the bottom of the building and the effect of acceleration through the gap of the building.

From this investigation, the main outcomes that can be summarised are:

- The visualisations based on numerical simulations, using the CFD-PST program Vasari, showed that the outcomes can be easily distorted because of some parameters are not well set up. These distortions may lead to a wrong interpretation by the user. The first parameter is the visualisation of 2D and 3D wind flow simulations. Both methods can produce different movement patterns of wind around a building. However, a visualisation of a 2D wind flow could be more dissociated to a building form than a 3D wind flow, because the first case does no consider the three dimensions of an obstacle and some wind phenomena are missing such as vertical movements at the bottom of the building (Table 2.5). This does not mean that 2D wind flow is not useful for rapid visualisation, but if the user is not aware about the differences, the interpretation of phenomena could be extremely difficult and misleading. Moreover, a second parameter that can produce distorted visualisations is the fact that the dimension of the domain or grid in Vasari can produced larger distortions in the visualisation.

		Wind Analysis Around Single Building Models	Wind Analysis Around Multiple Building Models
Quick visualisation 2D wind flow:	horizontal movement visualisation :	No simetric wind patterns / no observation at the ground level	Clear visualisation of channel effects and other horizontal wind movements
	vertical movement visualisation:	Clear visualisation of vortex	No clear visualisation of deflections
Slow visualisation 3D wind flow:	horizontal movement visualisation:	3D wind patterns and phenomena at ground level	Clear visualisation of channel effects
	vertical movement visualisation:	Visualisation of phenomenon such as downwash effect	Clear visualisation of vortex and canyon effects

Table 2.5: Table with the visualisation issues related to 2D wind flow simulation, generated with CFD-PST Vasari.

- In general, the CFD-PST program analysed (Vasari) is more focused on visualising linear stream flows. Thus, the tables of evaluations show that the visualisation of phenomena most easy to identify are the areas of separation zones at the top and sides of the models. The standard parameters of visualisation in the program display automatically these representations that facilitate the rapid identification of this group of wind phenomena. These regions show strong accelerations of wind at

the same time that lateral deflections of the flow. In contrast, the visualisations of vertical downward flows and vortices such as horseshoe vortex require more parameters of post-processing and are more difficult to observe. A possible effect of this is when the user does not have a theoretical knowledge about these phenomena: he or she could underestimate these wind phenomena in analysis.

- The visualisation using both physical and CFD-PST techniques present different process of visualisation. With the mini airflow tunnel the process was: 1) physical model elaboration; 2) global 3D visualisation of the wind flow; and 3) several 2D visualisations of local areas around the model for progressive analysis. In contrast, with the CFD program Vasari the analysis process was: 1) digital model elaboration; 2) 2D visualisation of an area around the model; and 3) final comprehension of the global wind flow (after several 2D visualisations or a 3D visualisation). These two different analysis processes present different orders of stages and different timing, the first one more suitable for a user without a theoretical background like designers and architects, because that order of stages (from 3D to 2D) facilitates the comprehension of wind phenomena.

- Another finding is the potential for PIV techniques to be integrated in the early design stage for preliminary wind analysis of physical experiments (when photographs are available). This post-process generates new graphical representations with fields of arrows that can help to visualise the movement direction of the airflow. Currently, open source software is available and the post-process has been simplified. Then, it can be set up to analyse and provide outcomes quickly as a part of the wind visualisation in design process. However, the use of this tool for analysis should be done with relatively accurate simulations. In this sense, maybe the use of this technique could be useful for visualisation in the real spatial context.

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2.5   Conclusion

This chapter has presented an investigation about rapid visualisation of aerodynamic phenomena around buildings with techniques of physical and CFD-PST visualisation.

Through two groups of empirical tests, with models representing buildings with regular and irregular forms, it was possible to evaluate the method of visualisation used by CFD-PST programs such as Autodesk Vasari, to display and assist in the identification of the more common wind phenomena around a building. These cases tested represent an area of application for these tools of wind visualisation: the analysis of wind flow around isolated building masses.

The work gathers evidence about rapid visualisation method using CFD-PST, which requires a more complex process to visualise vertical movement patterns of the wind, because a simple display of these phenomena does not show them clearly. This can affect the comprehension of designers about the global phenomenon around a building. The spatial three dimensions of a wind flow are not clearly visualised with the tested CFD-PST programs. In contrast, the rapid visualisation with the mini airflow tunnel provided a more comprehensible visualisation of the global 3D wind phenomena.

Through the cases and experiments, these works with parallel observations resulted in several findings that suggest a new approach:

- This investigation visualised how a group of buildings change the movement patterns of the wind. However, these observations were focused on local visualisation of a single building and not as part of any design process involving different scales and designs. Thus, a task for the next investigation is to evaluate rapid wind visualisation in a workflow and in a design process.

The next chapter describes a group of studies about wind visualisation techniques applied in the design process of an architectural windbreak, installed in an urban context, with local wind issues of discomfort.

CHAPTER 3

Second investigation: flexing wind

3.1 Introduction

This chapter introduces the second investigation of my research: an evaluation of CFD-PST (computational fluid dynamics - performance sketch tools) for rapid visualisation of the main wind movement patterns through a large built environment and around an artificial windbreak, in a local context of Melbourne. The studies developed here represent the second spatial context for wind analysis by visualisation tools: the urban configuration.

The sections refer to the methodology designed for this investigation, the main observations about a workflow with physical and digital tools to develop a windbreak design, the main outcomes from my observations and some new lines of action for the next stages of the research.

Some experiments in this stage were conducted during an elective course in January of 2013, with the support of SIAL and the assistance of Dr. Flora Salim and PhD candidates Mani Williams and Kamil Sharaidin[1]. The results and designs developed in the elective course were presented in the eCAADe 2013 conference (Moya Castro et al. 2013) and the CAADRIA 2014 conference (Moya Castro et al. 2014b). Papers with the complete explorations can be found in the appendix of this exegesis.

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[1]This project and their documentation and publication of results was approved by the RMIT Human Research Ethics Committee, project title: Flexing Wind elective course, project number: CHEAN A-2000822-1-13, Investigator: Flora Salim.

Investigation aim and criterion of evaluation

Based on the outcomes of the first investigation, I formulated the following question: What limitations of rapid wind visualisation techniques are present in a design workflow and how do they affect the design process?

The idea of testing wind visualisation techniques in a workflow is because a workflow considers several stages with different scales and aims. If, in the first investigation, the aim was to visualise a group of phenomena around a building, without any other design purpose, for this investigation the aim was the evaluation of the visualisation techniques through different requirements that are involved in the development of a concept design. Thus, the structure of this design process was to work with two wind visualisation techniques to analyse wind conditions in an urban context (large scale); and the analysis of a concept for an architectural windbreak for wind mitigation (small scale) (Li et al. 2007) (Figure 3.1).
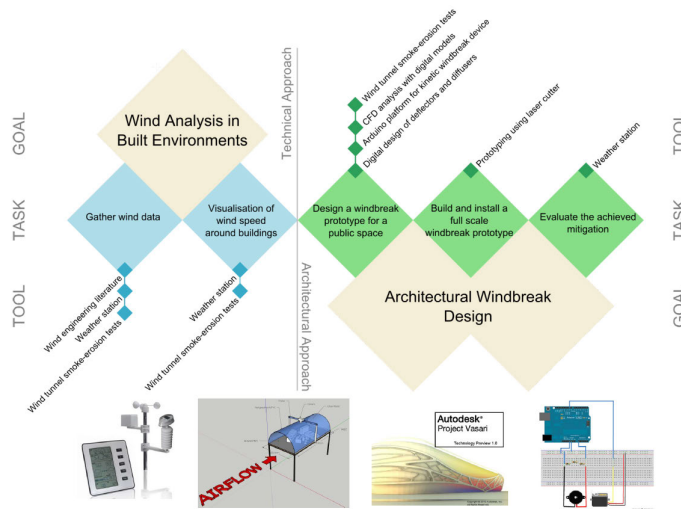
Figure 3.1: Design process workflow with stages, tasks and wind analysis tools. One of the aims was to evaluate CFD visualisation and a mini airflow tunnel for wind analysis through a two contexts: large urban context, small local context. (Source: author)

As a result of the evidence from the first investigation, I selected two tools for the work in this investigation. These tools were the CFD-PST program Autodesk Vasari and a new version of the mini airflow tunnel that I built for this purpose.

These tools must visualise phenomena of wind dynamics that have two dimensions of

movement in a built environment: vertical and horizontal. In the vertical dimension, the mechanism that produces changes in the flow direction and accelerations is the pressure distribution on the building façade. The horizontal dimension is the wind flow affected by buildings shapes and the urban configuration, producing changes in the wind flow pattern, because of the pressure differences between the low pressure wake region and the high pressure at the windward side of the building (Aynsley et al. 1977).

The idea is to identify some of the more common wind phenomena produced by the urban configuration. The target, on this occasion, is to identify the wind patterns associated with discomfort issues in pedestrian areas, based on a classification of urban aerodynamic phenomena: channel effect, row effect, wake effect (Figure 3.2) (for explanation of these concepts see (Gandemer et al. 1978)).
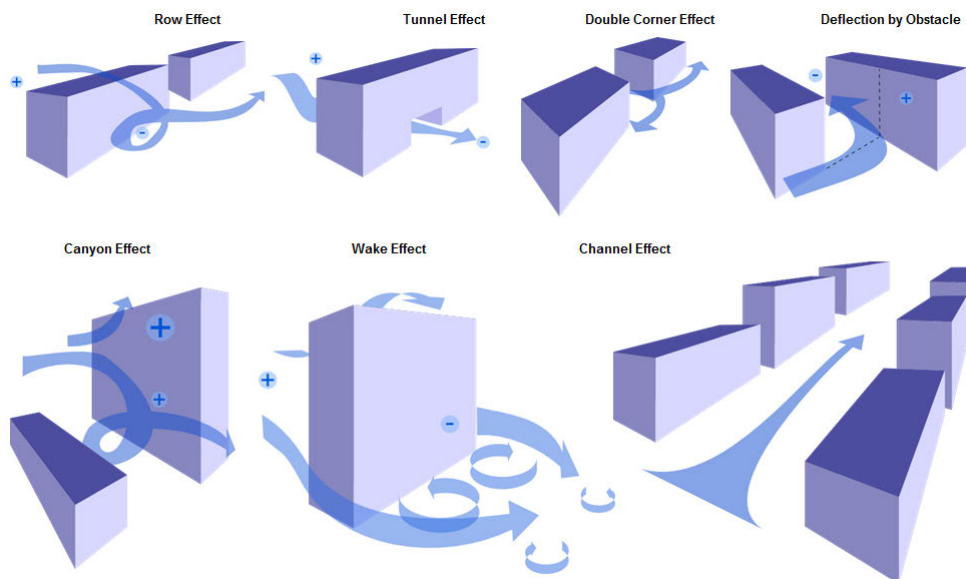
Figure 3.2: The literature has already classified the main wind movement pattern through an urban configuration. One of the purposes of visualisation techniques in the early design stage is to facilitate the identification of these phenomena. (Source: author)

Criterion of evaluation. The criterion to evaluate the performance of these techniques was different from the previous investigation. In this case, the tools were used for rapid airflow visualisation of two dimensions: a large urban scale (to identify wind discomfort areas) and a small local scale (to analyse wind patterns around windbreak concepts with

porous structures and non-porous surfaces)(Figure 3.3). For each wind visualisation test, the aim was to identify the main wind effects associated with urban contexts and the windbreak design. Thus, a good result is the identification of as many as possible wind phenomena. The evaluation exercise considers the action taken during the design workflow (Table 3.1).
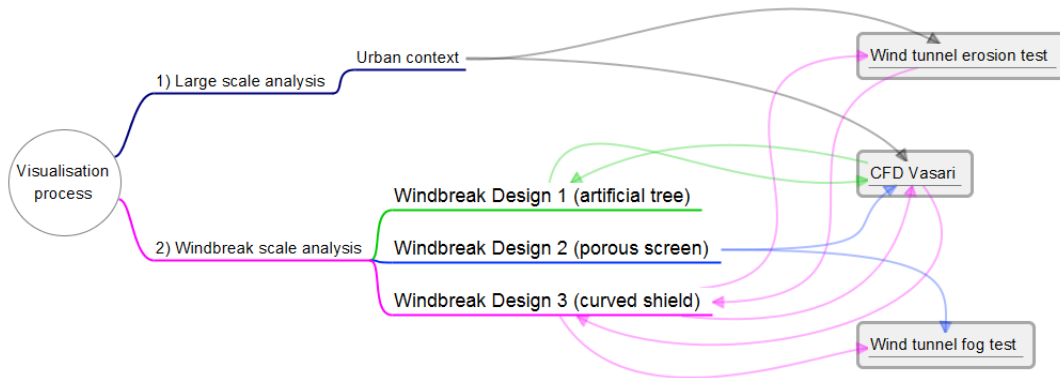
Figure 3.3: Structure of the wind visualisation process for this second investigation with two wind visualisation tools: Mini airflow tunnel and CFD-PST Vasari. The tools allowed useful and continuous feedback except for the second design, because the analysis did not provide useful visualisation (Source: author)

Building model	Wind visualisation tool	Wind visualisation test
Large scale built environment	CFD-PST Vasari	Vis. horizontal airflow movement /Vis. vertical airflow movement
Large scale built environment	Mini airflow tunnel	Erosion test to visualise high speed regions near buildings
Three architectural windbreaks	CFD-PST Vasari	Vert. wind deflection/ Hor. wind deflection/ Protection region
Three architectural windbreaks	Mini airflow tunnel	Wind protection region (wake region)

Table 3.1: Table with the wind visualisation tools evaluated in this second investigation, and the program of wind visualisation tests conducted for a model of large urban context and three small architectural windbreak models.

Low-tech airflow tunnel (second version)

For this investigation, a second version of the low-tech airflow tunnel was built. This time, the design was adapted for a rapid visualisation using an erosion technique. For that reason, the wind tunnel was designed with only one part as test section, without the diffuser or concentrator section. The test chamber of the airflow tunnel was a semi cylindrical tunnel built with a curved sheet of transparent acrylic (width: 900 mm, height:

450 mm, length: 1550 mm). This size of the chamber was planned to accommodate different models sizes, including a 1:500 scale model of the city area. The aim was to reproduce airflow effects in an urban configuration of streets with low and tall buildings. The wind was produced with a fan in a box with a screen to generate a relative laminar flow (Figure 3.4). Similar to the first version, this low-tech airflow tunnel was for basic visualisation of airflow phenomena. The urban wind conditions such as speed, turbulence intensity and the ABL effect were omitted to facilitate a simple operation.
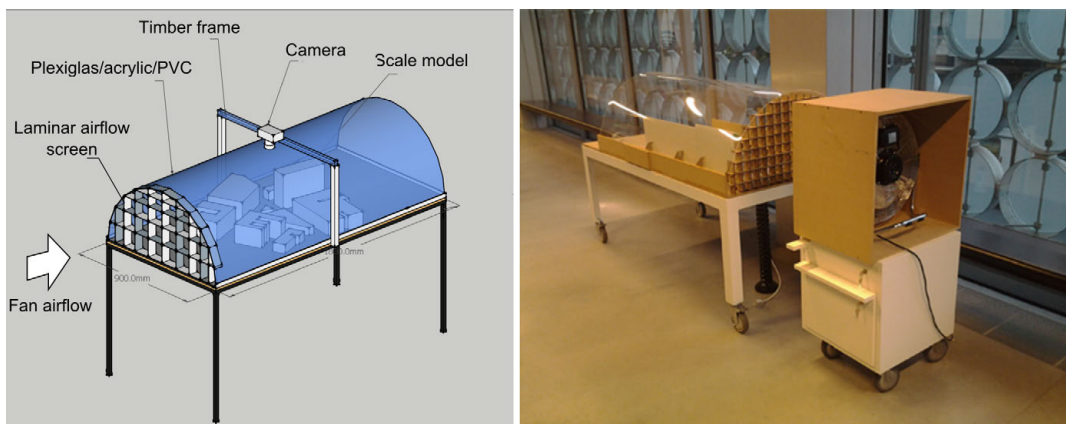
Figure 3.4: Second version of the low-tech mini airflow tunnel built for the elective course. The purpose of this mini airflow tunnel was for only visualisation, but with a dimension for models of urban configuration of buildings. (Source: author)

3.2   Wind visualisation through a built environment (large scale)

For the first group of experiments the aim was to analyse the wind through a built environment. The context explored was the surrounding area of the Design Hub Building, in the central business district of Melbourne (Figure 3.5).

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Figure 3.5: Urban area of study for the workflow in the business district of Melbourne. The areas in cyan are the zones with high wind velocity at the ground level. (Source: openstreetmap.org CC BY-SA)

As an exercise of analysis and representation, wind maps were elaborated using real data from a weather station. These graphical maps represented the pedestrian space into wind regions with gradual transition between them. This first approach allows the comprehension of the diffuse boundaries between wind speed regions or areas of comfort and discomfort in the space (Figure 3.6). Mapping is a register of the environmental dynamics useful to conduct an analytical observation of it (Hensel and Menges 2006). Therefore, I think that wind maps represent the ideal outcome of a wind visualisation process, for a spatial context where an architectural intervention is planed (e.g. a windbreak).

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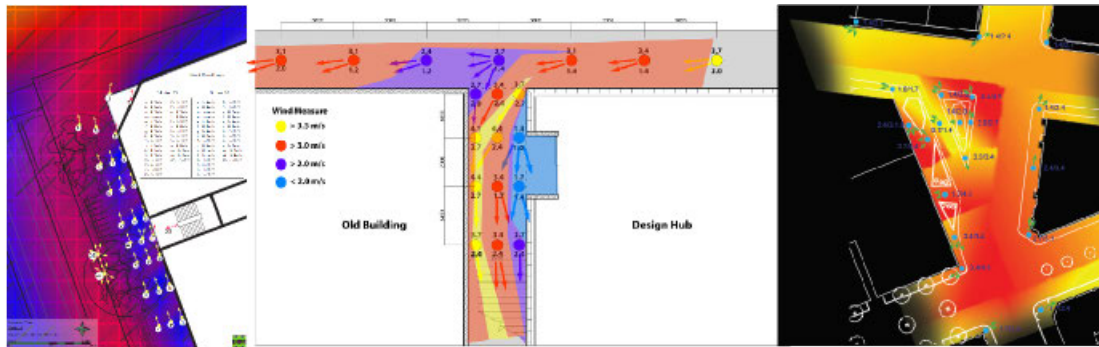
Figure 3.6: Three versions of wind maps showing wind intensity on three different places with high wind intensity in the urban area, elaborated by teams of designers, after observations on site and wind visualisation using CFD Vasari and the mini airflow tunnel. (Source: (Moya Castro et al. 2013))

CFD-PST visualisation

With Autodesk Vasari, the wind behaviour in the built environment was visualised, using a digital model of the city, with the buildings and streets of the areas around RMIT's city campus. The parameters of wind speed and wind direction used in these CFD simulations were taken from climate statistics[2].

The first experiments of visualisation showed effects of wind acceleration between buildings and along the main streets (Figure 3.7). With these visualisations areas of stream flow of wind in narrow spaces such as lanes and high wind speed regions in the cross of Swanston St and Franklin St were identified, where the wind has been reported as strong during several visits to that place. However, this scale of visualisation does not show other patterns of wind at the areas around corners. Previous researchers have already studied different wind movement patterns around corners with accelerations and deflections that can explain the constant intensity of wind at those places, even with wind from different directions (Kastner-Klein et al. 2004, Savory et al. 2004). However, those effects are missing in these visualisations with Vasari. For instance, because of areas of low pressure in some streets, the wind should produce divergent flows at each crossroad. But the visualisation only shows the main flow without effects on the other streets.

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[2]www.bom.gov.au
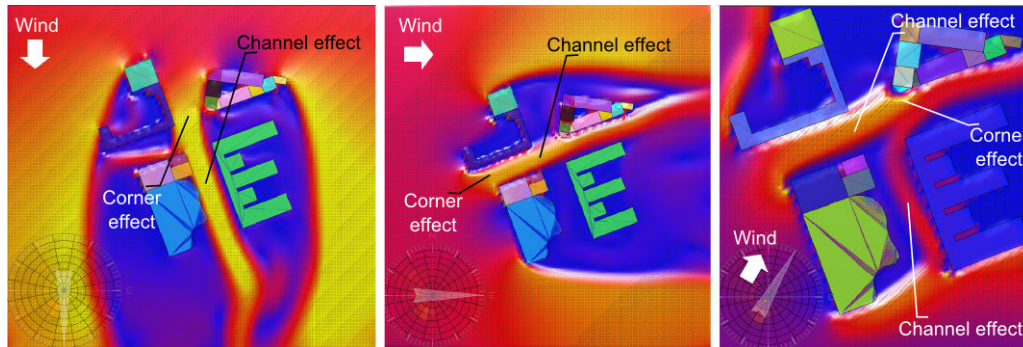
Figure 3.7: 2D wind visualisation of horizontal stream flows with different directions, through a large scale built environment, using CFD Vasari. The visualisation does not show patterns of wind flow at the local scale (around corners) and conditions of the wind flow can not be saved for a new visualisation with different scale. (Source: (Moya Castro et al. 2013))

In contrast, another group of experiments was conducted to visualise the wind conditions at the leeward side of a group of tall buildings. In a visit to the site, it was observed that behind these high buildings the wind had an unconformable level. The literature has discussed the pedestrian comfort issues in areas near to tall buildings (entrances) where they are affected by high wind speed (Hutchinson 1978, Gerhardt and Kramer 1986). However, the preliminary visualisation with Vasari did not provide a quick identification of possible wind phenomena associated with this issue (Figure 3.8). In general, in this wake region it is difficult to identify wind phenomena such as airflow speed intensity, comfort level or wind direction without a more accurate post-process of several visualisations.
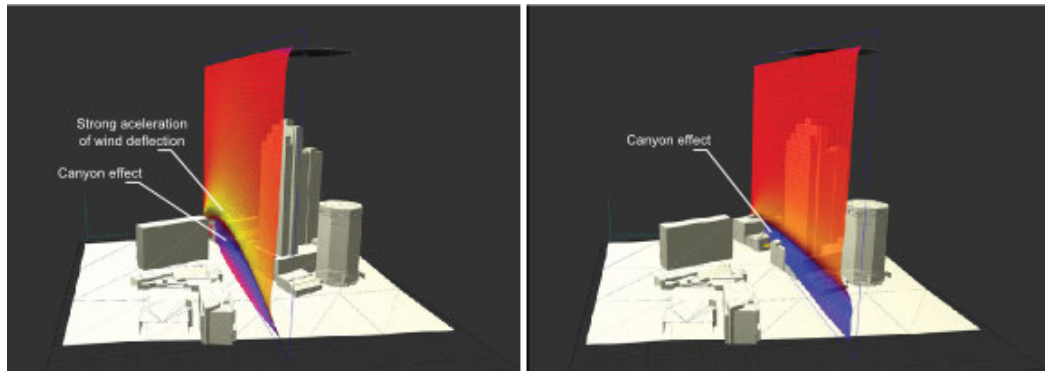
Figure 3.8: Several 2D wind visualisation of vertical wind deflections and wake region near the tall buildings in the area of study, with CFD Vasari. It is extremely difficult to visualise the 3D phenomenon of the wind through 2D slices, especially at the local scale. It is necessary to create a composition with different format of visualisation to have a more complete image of the wind dynamics behind these buildings. Left: canyon effect with strong vertical wind deflection. Right: canyon effect with less vertical wind deflection. (Source: (Moya Castro et al. 2013))

At the same place, a second visualisation was conducted with a different graphical representation (streamlines), which is provided by the program Vasari. This visualisation allowed one to see the patterns of lateral wind deflection around the buildings and in some moments the turbulence at ground level (Figure 3.9). This visualisation allows observation of the movement of the wind around corners. However, it was not possible to define the region of discomfort that was observed before in the place. Only a general appreciation can be stated: a turbulent condition of that region, but without a clear idea about the intensity of wind speed. Anyway, it is possible to visualise the downward movement of the flow after passing the group of buildings.
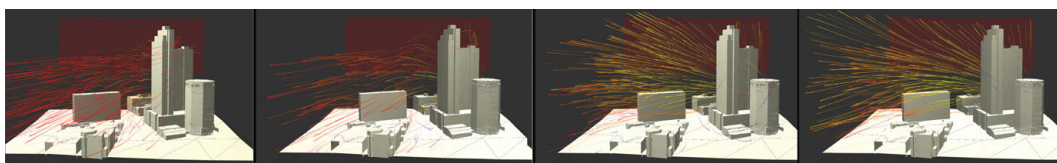
Figure 3.9: 3D wind visualisations of wake region near tall buildings, with CFD Vasari and streamlines filter. Each screenshot shows the airflow at different levels: from the ground level to the upper level of the building. The wind is observed moving around corners in the first screenshot, something missing in previous 2D visualisations. However, speed conditions are not appreciated, yet. (Source: (Moya Castro et al. 2013))

CFD-PST Vasari generates rapid wind visualisations that can be categorised into

three degrees for their complexity and for the nature of the phenomena displayed. The more basic phenomena visualised can be considered as a first degree (horizontal visualisations), the second degree refers to vertical visualisations that present more complex wind phenomena (vertical air vortex) and the third degree, which display 3D visualisations of wake regions. However, something that is not evident is the visualisations as partial and independent representations of a complex and global phenomena. This method of visualisation with partial images might produce a dissociation between the first, second and third visualisations, that could make it more difficult to identify the phenomena by an architect who does not have a previous knowledge of this kind of wind phenomena (Figure 3.10).
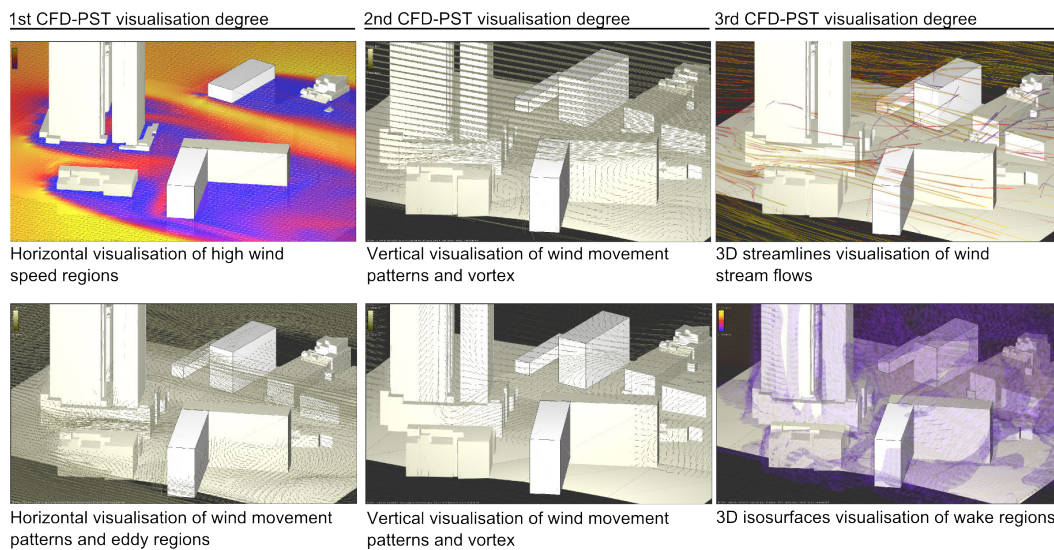
Figure 3.10: CFD-PST Vasari generates rapid wind visualisations that can be categorised into three degrees. The visualisations are partials and displayed independently, producing a dissociation between 2D vertical and horizontal, and 3D visualisations. Left column: horizontal visualisations that are the standard display showing more common phenomena such as regions of wind speed around buildings. Middle column: the second grade of visualisation refers to vertical visualisations, that show more complex wind phenomena, such as vertical vortices of wind. For this reason it is necessary to display several slices with different positions for a more complete visualisation. Right column: third visualisation degree with 3D wind visualisations that shows spatial thresholds of wake regions or the development of stream airflow. This kind of visualisation is the most complex to be generated in Vasari. (Source: author)

In general, the digital visualisation at a large scale (urban context) using CFD-PST Vasari was useful to identify several places with channel effects through the city configu-

ration. This means, the areas where wind flow is accelerated along the space of the street. These phenomena were clearly visualised affecting the main façades and pedestrian areas around RMIT buildings. However, other details or phenomena are missing, such as the acceleration points in the corners and intersections of streets. On the other hand, the visualisation shows wide areas as wake effects. These are areas of turbulent movement of wind (wake regions) but it is difficult to analyse the wind intensity or movement patterns in those regions with this visualisation technique.

The rapid visualisation of a wake region, which is an area of turbulent wind with a vortex of airflow, produced by the low pressure behind the buildings, allows the observation of the direction of the airflow at the bottom of the building to visualise the wind pattern in the pedestrian area and entrance of the building. This kind of visualisation is not automatically displayed by the program, and it is necessary additional post-process to see it (Figure 3.11).
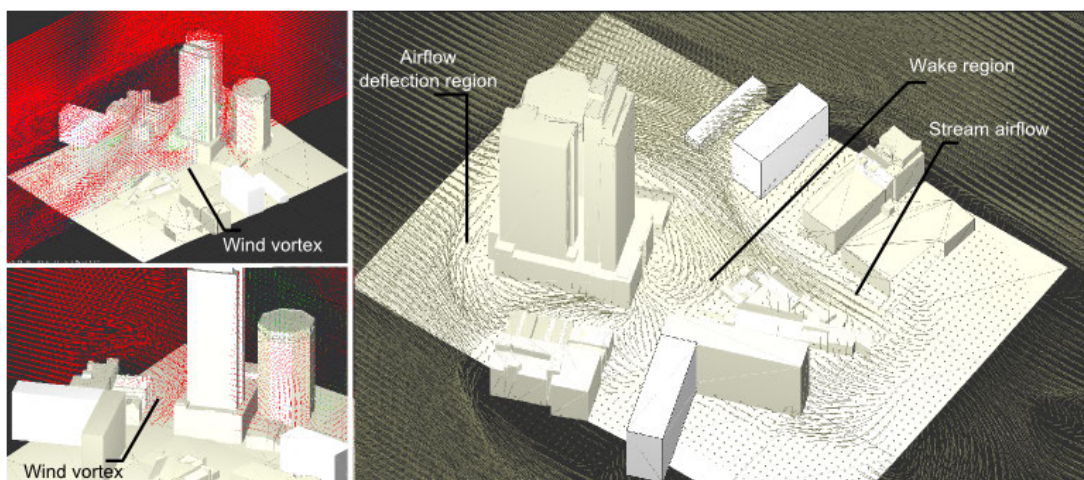
Figure 3.11: 2D wind visualisation of wake region near tall buildings, with vector field using CFD Vasari. To have an idea of the wind movement around the model it is necessary to display several slices with different positions. The wind is observed moving in an airflow vortex at the bottom of the buildings and in the street. Top: deflection effect of the wind around the base of the building. The airflows to the building gate. Bottom left: visualisation of the vortex produced behind the building. Bottom right: visualisation of the canyon effect produced on the street, between the tall and a short building. (Source: author)

For this case, with a field of vectors, the flow of wind to the entrance of the building and the confluence of two main areas of deflections is observed. In addition, the group

of low buildings near the tall buildings facilitated the generation of a vortex effect on the street. All these phenomena affect the area at the bottom of these building, with high wind speed stream flow at the entrance area of the building. The visualisation supports the consideration of a strategy for wind mitigation, which is a windbreak design explained in the paper "Pneumosense project" (Moya Castro et al. 2014b), in the appendix (Figures 3.15 and 3.16). However, for these analyses it was necessary to repeat the simulations for a model in a local scale, with a relative similar wind conditions, because the previous outcomes are not possible to automatically export and extrapolate for the new visualisations.

Mini airflow tunnel visualisations

On the other hand, the difficulties with the visualisation of wind in the wake region, near a group of tall buildings and near corners, made it necessary to repeat the experiments using the mini airflow tunnel. The area was analysed with a technique of particle erosion, which is used (in more accurate experiments) for wind comfort analysis in industrial wind tunnels (Dezso 2006). The idea was to identify the possibly vortex in the region of the wake, near to the building to validate the condition of wind and define a strategy for a windbreak design. A model of the buildings was built and installed to test in the wind tunnel.

The visualisation technique using erosion showed a region at the bottom of the building that was eroded. This effect means there is a downward wind flow affecting that place with significant velocity, producing a vortex of air in front of the building. This idea is coincident with the observations in the site.

Another test with erosion visualised the movement of wind flow along a space simulating a channel effect along a street. This visualisation was effective to identify the turbulence near of the building façade in a space that is similar to a channel, and it was effective to visualise airflow phenomena that were missing in the digital visualisation, such as the deflection of wind in the area near the corners (Figure 3.12).

Through these exercises of airflow visualisation it was possible to notice which phe-

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Figure 3.12: Visualisation with erosion test in the mini airflow tunnel to see the area of turbulence at the bottom of the buildings. Left: large-scale city model installation in the mini airflow tunnel. Middle: area of erosion showing the high wind speed region at the bottom of tall building. Right: experiment in the wind tunnel to visualise the wind flow and channel effect with accelerations at the corners in a space similar to a local street. (Source: author)

nomena are not being detected, because of the scale of the digital models. These missing effects are the acceleration zones in the vicinity of the corner area and the vortex on the bottom of the façade. Using the mini airflow tunnel with erosion and fog techniques it was possible to identify these effects of deflection and to elaborate strategies for the next stage: the development of a concept design for a windbreak screen.

3.3 Wind visualisation around an architectural windbreak (small scale)

With the aim of designing an element of mitigation of the wind in a local site, the wind visualisation techniques were used with new requirements: different scale and complex

design elements for pedestrian areas (Jal 2003). The visualisations were performed for two main strategies of windbreak concepts: non-porous deflector and porous structures. The images presented here are the final result of propositions for a windbreak concept, after a design process involving the techniques of wind visualisation and analysis in the design process (Figure 3.13). The details of these designs are explained in the papers "Flexing wind" (Moya Castro et al. 2013) and "Pneumosense project" (Moya Castro et al. 2014b), in the appendix.
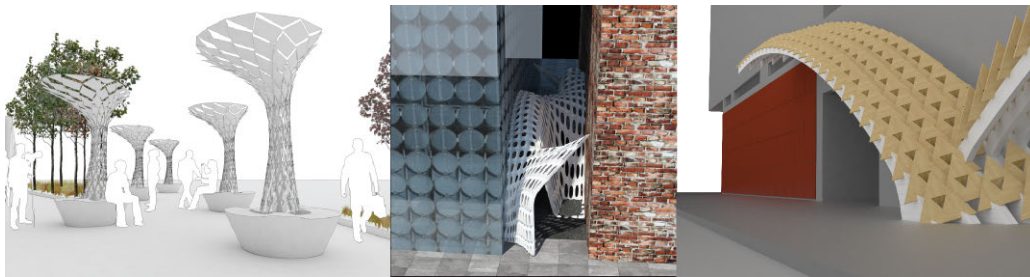
Figure 3.13: Three final versions of artificial windbreak concepts designed for wind mitigation in the public space. These projects require a local scale context to conduct wind visualisation with CFD programs. Left and middle: the Pneumosenser project and the Lyrebird project are concepts for designs with porous surfaces. Right: the Milk.Crate.Break Project, an arch design concept with a non-porous surface. (Source: (Moya Castro et al. 2013) and (Moya Castro et al. 2014b))

A porous screen and non-porous shield were considered as the main passive strategies to change the local wind flow condition in the sites, with the challenge that these strategies should also produce low disturbance levels in the surrounding space. The strategy of porous structures or skins was based on geometrical patterns of holes with variation of density to produce regions of protection at the leeward side of the windbreak (Gandemer 1979). This avoids strong deviations of the air from the free stream wind flow. Moreover, the deflection of wind by a design based on a concept of a non-porous surface was analysed with different positions and profiles for a curved structure oriented to the prominent wind direction on the street.

These windbreak concepts represent the current challenge for wind visualisation in the early design stage. The idea of these tests was to develop a design based on wind effects, using the wind visualisation techniques to see the interaction with the wind, analyse the

performance of the concept and make adaptations to run a new visualisation. Thus, a double visualisation of the phenomena (physical and digital) was the method of evaluation of the design features and their optimisation (Figure 3.14).
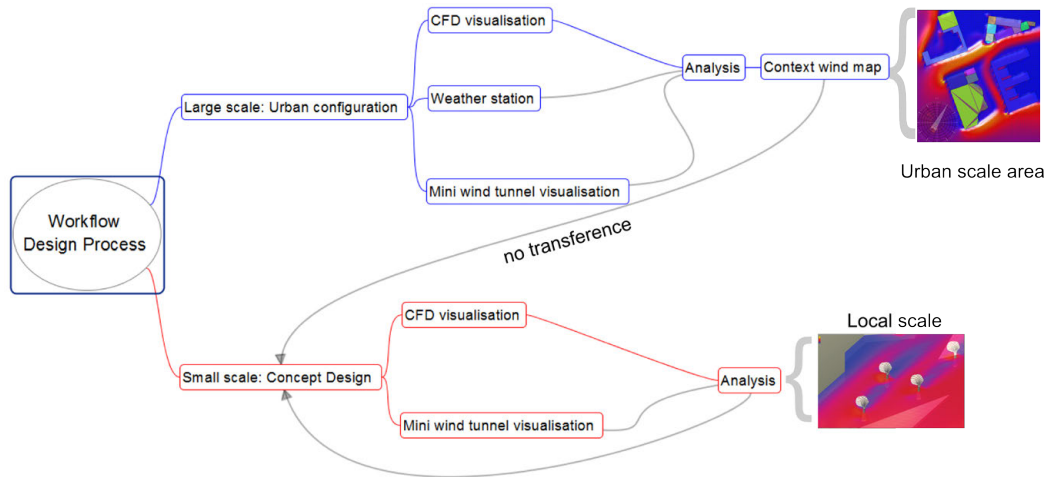
Figure 3.14: Workflow with two scales of context to conduct wind visualisation (large urban scale and small local scale) in an early stage of the design process. The CFD-PST Vasari is a component in the process that cannot share parameters and outcomes between both scales of visualisations. Each stage must run independent simulations and visualisations. (Source: author)

As explained before, the criterion to evaluate the performance of these tools was to verify if the visualisation allows the identification of a phenomenon.

CFD-PST visualisation

The original CFD-PST visualisations test, for one of the windbreak concepts, had the intention of analysing the porosity patterns for the skin of a structure with different densities. However, the visualisation of the porous screen does not display a representation for the condition of a protection region with enough clarity or with a format to evaluate the comfort level produced (Figure 3.15). In addition, the previous outcomes from the large-scale wind visualisations were not possible to be automatically imported in the new visualisations. Thus, these models of porous screens were tested with very simplified wind conditions observed from the previous visualisation test.

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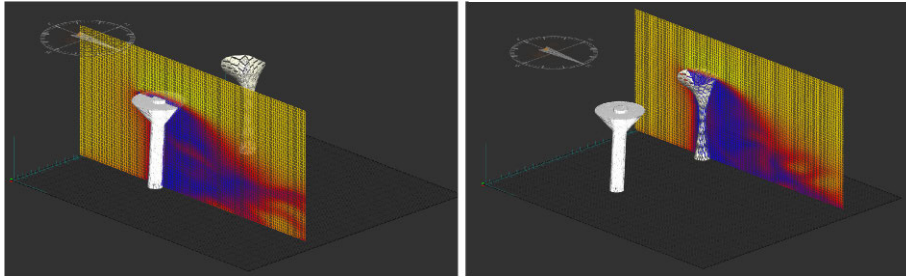
Figure 3.15: 2D vertical visualisation of a wind speed around porous structure and non-porous structure for a windbreak with cylindrical form (Pneumosenser project), using CFD Vasari. The visualisation fails in analysing the performance of these designs, because it does not show a clear difference between both wake regions. Left: wake produced by a non-porous structure. Right: wake produced by a porous structure. (Source: author)

The second wind visualisation test considered a group of porous structures. The aim was to optimise the number of structures and the space among them. Testing with different arrangements of these structures, the optimisation was an arrangement of windbreaks to create a space of low velocity (unified wake region) with enough space for traffic of pedestrians. For instance, it was observed how when the windbreaks are closer to each other the area of low velocity increases in size (Figure 3.16). The visualisation helped to define the distance and number of structures to produce this comfort region.
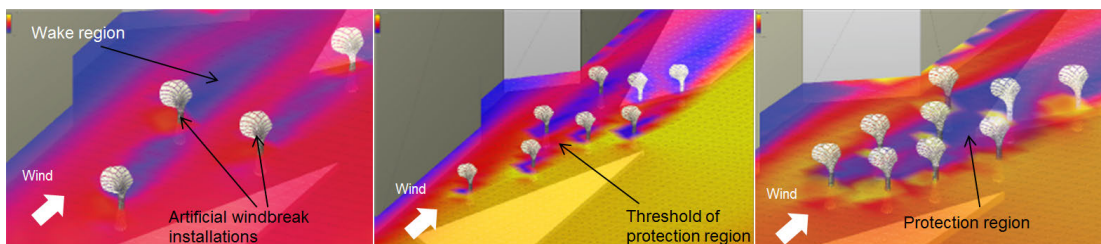
Figure 3.16: 2D horizontal visualisation of wind speed for the Pneumosenser project, using CFD Vasari. The wake produced by each windbreak (blue area) was used to define the best arrangement of windbreaks. This means, the structures were moved to produce a unified wake region around the group of windbreaks. (Source: Moya Castro et al. 2014b))

With the digital visualisation of wind on a porous screen (skin for one of the windbreak designs) the region of low velocity at the leeward side of the skin was difficult to interpret (Figure 3.17). It was observed that the screen produced a region with several stream flows that did not allow identification of a pattern of movement, wind velocity intensity or comfort factor. For the case of windbreak screen, previous studies have defined a region of

protection, behind the screen, with semicircular boundaries (Raine and Stevenson 1977, Pescaru et al. 2011). In the visualisation of porous screens the effect was an area that does not represent these thresholds or a similar boundary profile. These representations of the wake region do not allow identification of the protection factor in the leeward side of the screen. For this reason more options like the variation of density in the porosity are difficult to compare.
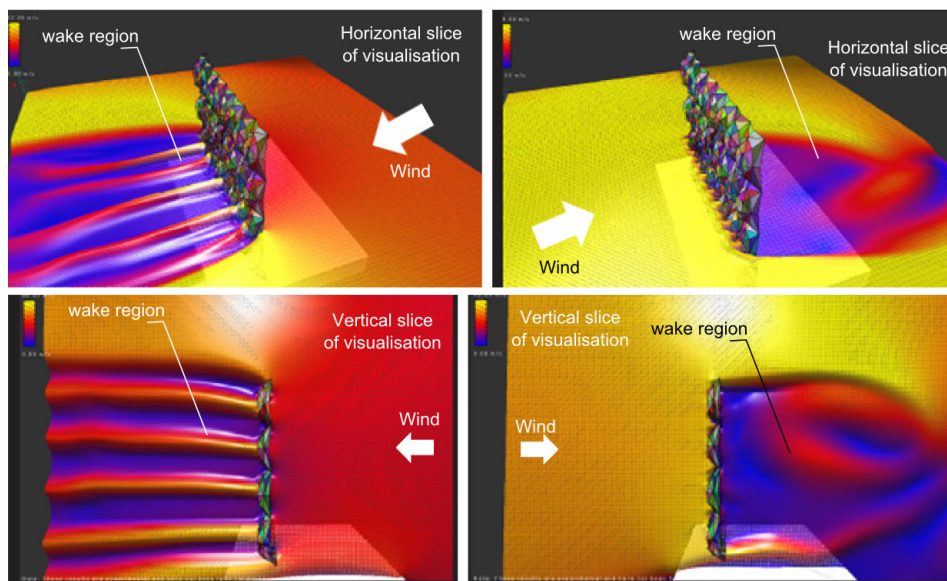
Figure 3.17: Vertical and horizontal 2D visualisations of wind speed, generated with CFD Vasari, to analyse the mitigation and protection region produced by a porous screen of the Milk.Crate.Break project. However, the two horizontal visualisations (top images) and the second couple of vertical visualisations (bottom images) show different patterns behind the screen that do not allow the evaluation or comparison between mitigation effects produced by these porous surfaces. (Source: (Moya Castro et al. 2013))

In contrast, we focused on the CFD visualisation with a non-porous surface, verifying the deflection effect of wind produced by the structure. For this case, trying to keep the high velocity above the structure, several positions and shapes of a shield were tested. The intention was to deflect the wind but avoiding accelerations of wind from the structure to the surrounding area. The final result, after several visualisations, was to choose a double curve structure (Figure 3.18). For this case, the wind visualisation was useful to compare the possible design options and make changes in the model for an optimisation that facilitated the deflection of wind.
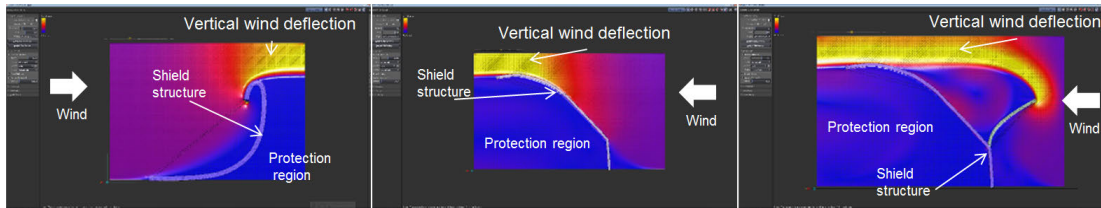
Figure 3.18: Vertical 2D visualisations of wind speed generated with CFD Vasari, to test three different profiles of non-porous structures for the Lyrebird project. The visualisation of the vertical deflection and wind speed intensity regions are useful to identify the third design (right image) as the best to resist the overload of the structure by the pressure of the airflow. (Source: (Moya Castro et al. 2013))

Mini airflow tunnel visualisation

In this stage of the design process, the visualisation in the mini airflow tunnel using the erosion technique was used mainly to test the grade of deflection generated by structures with non-porous surfaces. The aspects that were visualised with several shapes were the level of curvature in the structure, the size of the structure and the option of using a double curve as structure. The visualisation showed the main differences between structures with a low projection from the façade and those with a significant projection from the façade. In the same way, a single curvature and a double curvature were evaluated to see which provides enough protection (Figure 3.19). In general, these experiments of wind visualisation were clear enough to have a clear idea of the efficiency of the windbreak design in the context of the street.

On the other hand, the wind visualisation with fog technique in the mini airflow tunnel was used to observe the mitigation of the wind speed when the flow passed through porous screens or porous membranes. However, the rudimentary method of fog visualisation was not useful to compare the level of mitigation provided by each porous screen or porosity density (Figure 3.20).

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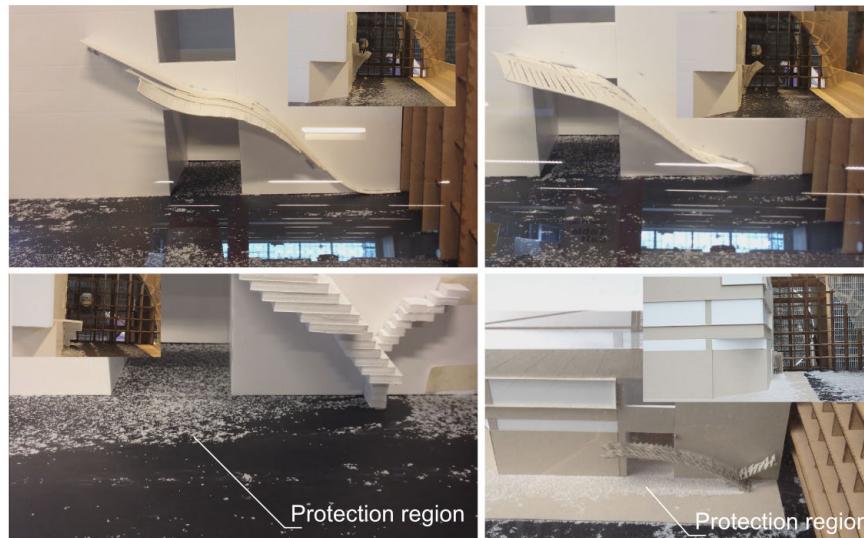
Figure 3.19: 2D patterns of horizontal airflow deflections visualised with erosion technique in the mini airflow tunnel, for four options of the shield project. The design alternatives of double arch (bottom left and right images) produce a better area of wind speed mitigation and protection for the entrance area of a building. (Source: (Moya Castro et al. 2013))

Figure 3.20: 3D visualisations with fog technique in the mini airflow tunnel (the images are not very clear). Both images show the visualisations conducted to evaluate the mitigation effect produced behind a porous membrane concept of the Pneumosense project. (Source: (Moya Castro et al. 2014b))

3.4 Summary

The intention of this investigation was to evaluate to what extent rapid wind visualisation techniques in a process of workflow facilitate the identification of wind phenomena to support decisions in the design process. The outcomes of this work can be summarised in a group of main points for each stage of this workflow. The next tables show the evaluation results for each tool and task (Table 3.2 and Table 3.3).

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Large scale urban site visualisations (E=easy) (D=Difficult)		
CFD-PST Vasari visualisation	**Wind phenomena observed**	**Incidence in the EDS**
Visualisation horizontal wind movement	E)Areas of high speed streamflow D)Horizontal airflow deflection E)Low airflow speed regions	Identification of area conditions and orientation of the windbreak structure.
Visualisation vertical wind movement	D)Vortex in Canyon effect	
Visualisation of wake regions	E)Wake regions with low wind speed	
Mini airflow tunnel visualisation	**Wind phenomena observed**	**Incidence in the EDS**
Erosion tests in large scale visualisation	E)High wind speed regions near facades E)Vortex of downward airflow near facades	Selection of the site for the windbreak and orientation of the structure.
Erosion tests in local scale visualisation	E)Channel effect and turbulent airflow in the street	

Table 3.2: Table with the evaluation of the tools during the analysis of wind conditions in a large urban scale model. In general, the visualisation of horizontal movement of wind is easily observable using CFD-PST Vasari, allowing the identification of several wind phenomena; however, some of them are difficult to observe, such as the direction of the horizontal airflow movements, because they require setting up additional methods of visualisations. In general, these observations facilitated decisions in the early design stage of the architectural windbreaks design process, such as the identification of strong wind directions and the decisions about the best strategy for the design and orientation of the windbreak. On the other hand, the vertical movement of wind is more difficult to observe with CFD-PST and fewer phenomena are identified. Therefore, a strategy for the design of windbreaks was not possible to elaborate.

Concept of porous windbreak structure		
CFD-PST Vasari visualisation	**Wind phenomenon observed**	**Incidence in the EDS**
Visualisation horizontal wind movement	Low wind speed region	Improvement of windbreak group configuration to increase protection region
Concept of porous windbreak screen		
CFD-PST Vasari visualisation	**Wind phenomenon observed**	**Incidence in the EDS**
Visualisation wake and protection region produced by windbreak	Low speed and turbulent wind region	It was not posible a evaluation of protection levels
Mini airflow tunnel visualisation	**Wind phenomenon observed**	**Incidence in the EDS**
Fog tests	Turbulent wake region	It was not posible a evaluation of protection levels
Concept of windbreak shield		
CFD-PST Vasari visualisation	**Wind phenomenon observed**	**Incidence in the EDS**
Visualisation Vertical wind movement	Vertical airflow deflection	Change from structure with single curve to barrier with doble curve
Mini airflow tunnel visualisation	**Wind phenomenon observed**	**Incidence in the EDS**
Erosion tests	Wake region behind the barrier	Modification of the barrier design to keep a projection region avoiding airflow deflections to the footpath

Table 3.3: Table with evaluation of tools and results of performance for wind visualisation in a small-scale context and windbreak design (analysing windbreaks with porous and non-porous designs). In this case the tests were more specific and the wind phenomena observed were more focused. However, the rapid CFD-PST visualisation of wind speed intensity in the protection region of windbreak with porous screens was very confused and difficult for evaluation and decisions. In contrast, the rapid visualisation of the wake area produced by a group of porous structures was useful to estimate a level of protection associated to the arrangement of the group of windbreaks. In addition, the rapid CFD-PST visualisation of local vertical wind deflection and the mini airflow tunnel visualisation of protection regions produced by a shield structure was clear enough to define the structure as a shield with a double curvature and the best position on the footpath.

Therefore, for visualisation in the large urban scale (built environment) it is possible to state:

- In a CFD-PST visualisation in the large urban scale, generated by Vasari, the outcomes cannot be exported or extrapolated to conduct new visualisations with a different scale. It was necessary to manually elaborate a wind map to establish an analysis for further experiments. Thus, the CFD-PST is a component in the workflow that must be set up each time if the scale of the analysis moves from an urban context to a local context. In this sense, the findings from a first analysis are difficult to fully extrapolate in a second visualisation.

- In a CFD-PST visualisation, the preliminary analysis made with Vasari allows identification of the phenomenon of channel effect, horizontal deflections and wake effect between buildings. In contrast, for other phenomena that are generally present in urban contexts, it is not easy to visualise them in a first moment. For instance, the effects of wind produced around street corners (accelerations, deflections, vortex) are missing at this visualisation scale (for these cases new simulations are required to get a better visualisation). In contrast, the physical visualisation of the phenomena in the low-tech airflow tunnel, using techniques of fog and erosion, showed some patterns of turbulent flows near buildings. The particle movement showed patterns of small vortices in some areas near building faces and around corners. This was a missing phenomenon in the digital visualisations with CFD software.

- CFD-PST provides three degrees or level of visualisation. The first degree for visualisation of horizontal wind movement patterns, the second degree for visualisation of vertical wind movements and a third degree for 3D wind movements. It is observed that first degree of visualisation allows the identification of several wind phenomena in the large-scale context, while the second degree is more suitable to visualise wind patterns around the windbreaks. The third degree of visualisation could be more efficient evaluating zones of protections at the leeward side of windbreaks. However, I found a level of dissociation between these grades of visualisation because they display partial and local areas of wind phenomena. In this sense, a more logical

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order of visualisation should consider the third degree as the first stage in a process of observation by the users, to facilitate the comprehension of partial horizontal and vertical visualisations of wind patterns.

- The elaboration of wind maps for local wind conditions is considered as a valuable exercise of simultaneous analysis and representation. Mapping wind in a site is useful to conduct an analytical observation of the airflow characteristics within the space that can be graphically communicated by designers, incorporating architectural language with the wind data. The wind maps elaborated in this project present the ideal outcome of a wind visualisation process that can be incorporated as an additional function in wind analysis software for architects.

Secondly, for visualisation in the small scale of the design process for a conceptual windbreak:

- The CFD-PST visualisations with Vasari, for one of the designs, based on a porous strategy of cylindrical windbreaks, performed very well in the optimisation process of a group of these windbreaks. The idea of using the wake region as region of low wind speed was the criterion to test several arrangements of a group of windbreaks. The best position for these structures was defined when the group of windbreaks generated a unique wake area of low wind speed.

- Using digital visualisation for the development of porous windbreak concepts, it was observed that the work with designs based on strategies of porosity was limited by the difficulty of analysing the wake region generated by porous screens. This makes it difficult, in the design process, to explore and compare optimisations of the designs, such as changes of porous density. The generation of analysis with comfort factor or protection is not automatically resolved for this program.

3.5 Conclusion

This chapter has presented an investigation about preliminary and rapid visualisations of airflow around windbreaks, for local issues of pedestrian discomfort. Several tests

were conducted to evaluate rapid wind visualisation techniques, to study airflow in urban context and small scale mitigation strategies. This was a process of a workflow to develop and optimise conceptual designs of windbreaks.

As a result of these tests and observations, I found that wind visualisation between different scale contexts and for porous structures presents issues of continuity and logical association between wind phenomena that make more difficult a rapid feedback in a fluid workflow that includes wind visualisation in the early design stage. I concluded that these techniques requires a protocol or methodology to create a logical sequence of visualisation and methods to extrapolate results in a comprehensible format (wind map) to facilitate the transition between large-scale to small-scale visualisation. This is a limitation for a rapid comprehension of causes and effects of wind in a built environment. Moreover, the process of optimisation for designs based on porous surfaces, using wind visualisation, requires graphical representations with analysis of conditions for protection areas. The factors of protection or comfort are necessary to compare the performance of a design concept, but this kind of information is not available in CFD-PST programs such as Vasari.

At the end of this second investigation these conclusions define a new question: how rapid wind visualisation techniques evaluate the performance of a windbreak with more sophisticated aerodynamic features? This question will be developed in the next investigation project.

In the next chapter, I make an interlude to explain some ideas about wind visualisation and analysis and how it has been used as a design strategy for some architects. The concepts developed in the next chapter are the basis for defining the following area and context of application for wind visualisation and the origin of the experiments in the next investigation stage.

Interlude: design strategies with aerodynamic features

4.1 Introduction

Throughout this research, two previous investigations have evaluated the techniques of wind visualisation for rapid feedback in the early design stage, developing experiments of wind visualisation for two scenarios: the first is the analysis of aerodynamic phenomena around isolated buildings and the second is the analysis of wind phenomena through urban built environments. However, the exploration of sophisticated strategies to interact with wind by architects could include architectural designs with aerodynamic features that require analysis in the early design stage, as well. This chapter works as an interlude, presenting architectural examples of designs with aerodynamic features. The intention is to define these examples as a third scenario of projects for wind analysis. At the end of the chapter, the studies of Jacques Gandemer are presented as general classification of geometrical configuration for these aerodynamic features; these can be used as based of designs to compare and improve concepts of architectural windbreaks. In addition, some ideas from this classification are explored in further experiments.

The concept of an architectural strategy for wind mitigation and its relationship with the design is developed in the following sections; the concepts of an aerodynamic slot and a porous membrane are shown as sophisticated examples of design features intended to

deal with wind phenomena and provide human comfort. This relationship between wind and architecture is presented in the next section, where three architectural projects are analysed; they were designed in the same geographic context and with similar intentions (to build a wind shelter). For this reason, I used them as a reference to analyse the differences between architects' ideas, projects strategies and the phenomenon of wind when it is affected by aerodynamic features of a building. The comparison between the projects *Escuela Naval* (Valparaiso, 1956-57), *Hospederia del Errante* (Ritoque, 1995) and *Las Piedras del Cielo* (Ritoque, 2012) allows the identification of some theoretical differences between approaches in this field.

Finally, the chapter explores other studies of windbreaks and their aerodynamic features, as a possible knowledge field to support the development of better design strategies for wind interaction. This knowledge is found in Jacques Gandemer's work about windbreaks and wind comfort. In the section on aerodynamic components, a group of features is selected to develop a concept of wind barriers designs. This last section gathers a classification of geometrical screens associated with aerodynamic effects, to propose basic design parameters for architectural windbreak designs for pedestrian shelters.

4.2 Architectural strategies for wind interaction

Aerodynamic fins and slots on roofs

One strategy to explore wind interaction and architecture was developed through a design process involving wind visualisation from the early design stage. The concept explored was an architectural innovation developed in the 1950s: aerodynamic slots integrated in building roofs. That is the case of the design strategy proposed in the project of an architectural competition for a Chilean Naval Academy Building, developed but never built by Francisco Mendez and the School of Architecture UCV[1], in Valparaiso, Chile (1956) (Ureta Morande 2007). This project proposed a deflector fin integrated on the roof of a group of buildings to produce an accelerated layer of wind, which was projected to

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[1]Universidad Catolica de Valparaiso

the leeward side of the buildings, above the courtyards to enlarge the protection effect (Figure 4.1).
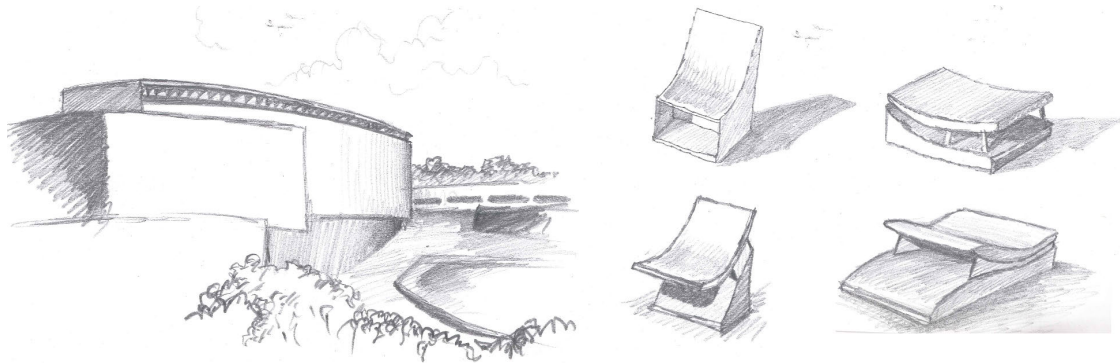
Figure 4.1: Buildings of the *Escuela Naval* project (1956) with aerodynamic features as strategy for wind discomfort mitigation in the outdoor environment. Left: buildings with the aerodynamic slot on the edge of the roof. Right: several experimental concepts of fins designed for the slot system. (Author's sketches based on (Ureta Morande 2007))

This layer of accelerated air separated the free-stream flow from the recirculating region, at the top of the buildings, increasing the protection area in the courtyard, behind the building (Figure 4.2). The idea was applied in other structures of the project to configure a large protected zone. The wind phenomenon produced was named "vault of wind" (Ureta Morande 2007), as a reference to a dynamic projection from the physical roof on the leeward side, to provide protection to pedestrians in playgrounds and the courtyard. Even though the project was never built, this concept was considered innovative for its time (Grillo 1960). However, the literature about strategies of wind mitigation in outdoor environments does not mention cases using a similar strategy.

One interesting thing about this project is how the slot system was developed. Using techniques of wind visualisation in a mini wind tunnel, the team explored the effect of the "vault of wind", testing different designs of fins and positions to study the effect of airflow deflection. Independently of how accurate these wind simulations were (the studies were conducted in 1956), the important thing is that the wind visualisation aided architects to develop and optimise the concept.

The wind flow, projected as an accelerated layer of air from aerodynamic slots, enlarged the protection area, and it is an improvement compared to the normal upward
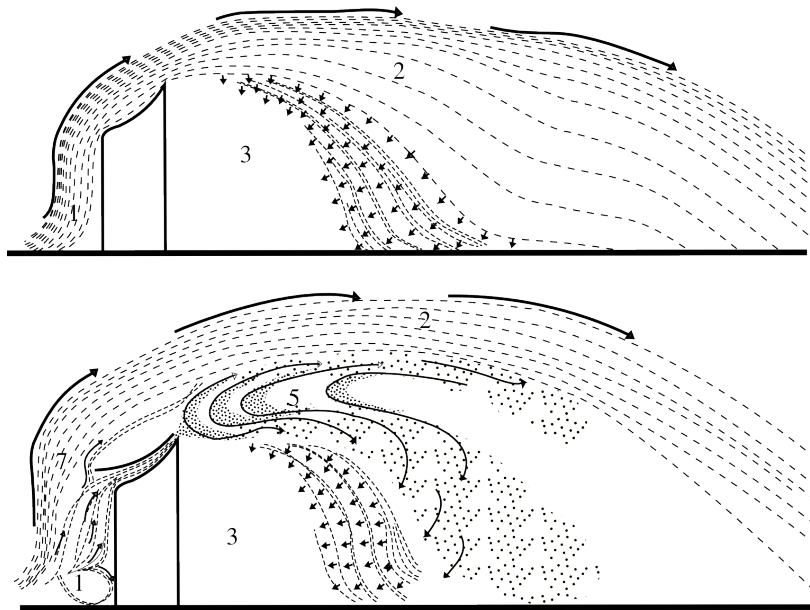
Figure 4.2: Sketch of study from the *Escuela Naval* project (1956) showing a comparison between the vertical wind deflection produced by a building. Top: vertical deflection and wake region behind a building without an aerodynamic slot. Bottom: the building with the fin and slot system produce a larger wake as protection region at the leeward side. (Author's sketch based on (Ureta Morande 2007))

deflection produced by a building. A strategy of a building, working as simple wind barrier, can be seen in the project of Byker Wall[2] in the Byker district of Newcastle upon Tyne, England (Figure 4.3). That building, built in the 1970s, formed a protection wall that blocked off the North Sea winds and isolated the center of a community from rail and roadway noise (Brown and DeKay 2000). However, this project with a long building barrier does not consider any slot system on the building's roofs. Thus, for the case of Byker Wall, the protection regions depend only on the size of the long unbroken block, while in the case of *Escuela Naval* project, the outdoor shelter effect depends on its aerodynamic slot system and the "vault of wind".

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[2]The Byker Wall is the name of a long unbroken block of 620 maisonettes designed in 1968 by architect Ralph Erskine and the assistance of Vernon Gracie, to replace old Victorian slum terraced housing. The construction took place between 1969 and 1982.
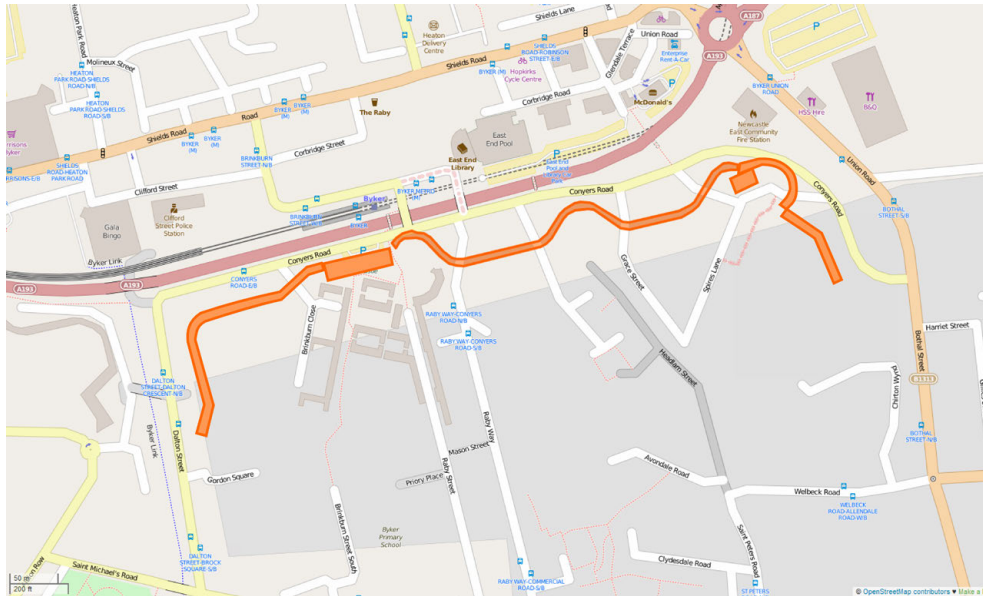
Figure 4.3: Map of the Byker Wall in the Byker district of Newcastle upon Tyne, England (taken from openstreetmap.org CC BY-SA). This group of buildings was designed considering the strategy of vertical wind deflection for wind discomfort mitigation. However, this strategy is less sophisticated and effective than *Escuela Naval*, because there is no slot system on the building roofs as an aerodynamic feature.

The use of aerodynamic features on buildings can be found in other architectural references. In fact, an auxiliary fin/slot on a building roof, but with other purposes, is installed on the GSW headquarters building (1999) in Berlin (Soares Goncalves and Mitie Umakoshi 2010), which is considered as example of an environmentally responsive architectural design. This building has, on the top of its 22-storey slim slab, a structure similar to a wing to provide shadow on the terrace and is a passive method of ventilation of the tower. On the other hand, buildings with gaps and holes on the façade, like the concept of a skyscraper design for building-integrated wind turbines (BDSP project WEB, 2000) (Stankovic et al. 2009), are examples of designs where the wind is manipulated through the architecture to produce an aerodynamic effect (airflow acceleration). However, although both structures are aerodynamic features of these buildings, the use is focused on the natural ventilation system or the acceleration of wind flow for wind power harvesting (Irwin et al. 2008). They are not designed to provide conditions of wind comfort in the surrounding public space (Figure 4.4).
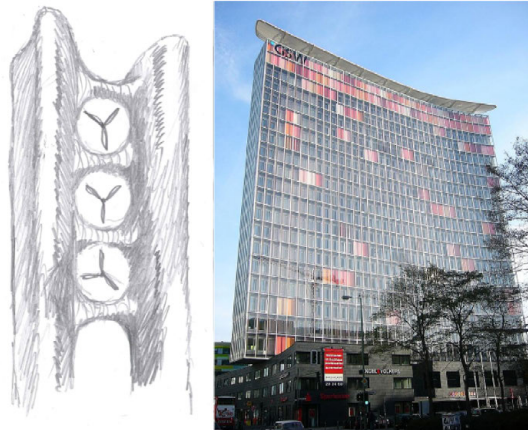
Figure 4.4: Other buildings with gaps or slots to interact with wind have been explored by architects and engineers, but these designs are not for outdoor environment wind comfort. Left: concept of a building with accelerator gaps for wind turbines (2000) (Author's sketch based on (Stankovic et al. 2009)). Right: Sauerbruch Hutton-GSW Building with a fin at the roof (from Hyde 2003, CC BY-SA 2.0).

Furthermore, wind visualisation in the design process to explore the effect of wind acceleration by aerodynamic slots integrated in buildings was a strategy used for the Manuel Casanueva's project *Hospederia del Errante* (1995), Ritoque, Chile (Casanueva 2003). This experimental house was built by students as a pedagogical activity to explore materials and passive systems of climate control (sun and wind), being supported by the Chilean government scientific agency[3] (Moya Castro 2000) (Figure 4.5).
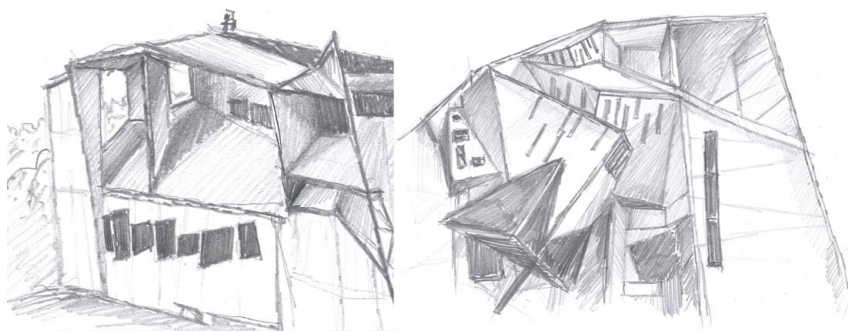
Figure 4.5: The concept of slot as aerodynamic feature of a house, to control outdoor environment wind conditions, is the strategy explored in 1995 by Manuel Casanueva in the experimental project *Hospederia del Errante (1995)*. Left: front view *Hospederia del Errante*, Ritoque, with two slots or gaps for wind acceleration. Right: lateral view of the slot system that project the wind flow to the backyard. (Source: author's sketches based on (Casanueva 2003))

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[3]FONDECYT project-1941189 http://ri.conicyt.cl/575/article-20168.html

The passive design of this project to deal with wind can be seen in the south façade, that was built with two slots or gaps to deflect and accelerate the predominant south-west wind to the backyard zone, increasing the protection area on that side. The effect of the roof pitch in the length of the leeward eddy area for a building is already well known (Melaragno 1982). However, the inclusion of wind accelerator slots is an additional method to extend the wind deflection and the protection region in the backyard without increasing the pitch height of the roof. Moreover, other parts of the building were designed to deflect the wind, creating separation zones to avoid strong movements of air in the areas of the gates at the north façade. In addition, the south side of the house presents parts of the façade with gaps working as diffusers to channel the wind flow through the façade. The approach for the design of each section of the façades in this project was to facilitate the movement of the airflow, avoiding turbulence in the outdoor space around the building.

However, Manuel Casanueva did not name this wind effect with the clarity of the authors of *Escuela Naval*, when they called the wind effect produced by the slots "vault of wind". He did not specifically identify this phenomenon with an architectural definition. Because of this, the wind phenomena in the *Hospederia* are more diffuse as an architectural concept. Probably the project, resolving several environmental factors at the same time, caused a simplification in the observations and definitions of these wind effects. It is a different approach to *Escuela Naval* and their focus on a specific wind phenomenon.

Nevertheless, the methodology to incorporate wind analysis in the design of the *Hospederia* was similar to the *Escuela Naval* project. The design process included from the beginning several tests of wind visualisation with a mini wind tunnel. These preliminary explorations qualitatively evaluated different geometrical configurations of the project, sections of deflector façades and roofs, and possible designs for the slots to define their final form in the south façade (Arce Moreno 2006) (Figure 4.6).
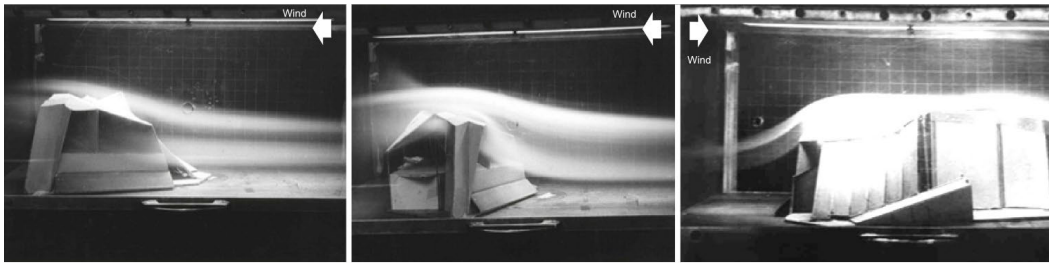
Figure 4.6: Wind visualisations of the slot system performance in the *Hospederia del Errante* (1995), in a mini wind tunnel, using fog technique. The wind analysis of *Hospederia del Errante* project was conducted from the beginning of the design process, testing different concepts of the project's façades, to develop a aerodynamic design for a sophisticated interaction with the coastal wind. (Source: author)

Porous screens as architectural strategy for wind protection

Architects have been exploring more permeable structures and façades to increase the interaction between climate and design. The surfaces and boundaries have become more porous and transparent, where the wind can pass through the structures and not only move around. Ventilation systems using passive structures to collect and regulate the indoor environment with air and temperature from outside have a history. However, the point here is the use of porous surfaces to be filtered by the wind. This strategy involves a different approach to how to visualise the airflow if preliminary analysis is required. This kind of design is part of a scenario in which more sophisticated strategies are being developed. Porous surfaces or membranes are architectural elements to interact with the wind on the inside and outside of consolidated buildings or temporal structures. That is the case of the Jean Marie Tjibaou Cultural Center (1998) by Renzo Piano, with façades designed in response to different wind speearly design stage and directions, to improve and adjust the indoor ventilation of the Center (Buchanan 1993). In contrast, the Windshape pavilion (2006), designed by nARCHITECTS and a group of students, is an ephemeral and auxiliary structure of several porous meshes that was installed near the Marquis de Sades castle in Lacoste. This space for meeting and exhibition dynamically changed with the wind, creating an oscillating space and an outdoor environment with diffuse boundaries (ArchDaily 2008) (Figure 4.7).

Figure 4.7: The design of permeable structures to interact with the wind flow, in a more sophisticated way, is a current field of exploration by architects, that requires working with wind analysis tools in the early design stage. Left: Jean Marie Tjibaou Cultural Center, designed by Renzo Piano, 1998 (taken from Waters 2003 CC BY-NC-ND 2.0). Right: Windshape pavilion by nARCHITECTS, 2006 (Author's sketch based on (Arch-Daily 2008)).

Similar to the last case, auxiliary elements are required for mitigation of wind discomfort in consolidated contexts of buildings. Currently, design for outdoor microclimates integrates experimentation with new architectural forms. In the book *Morpho-ecologies* (Hensel and Menges 2006), students of the Architectural Association School presented different designs with complex porous morphologies, and simulations of prototypes under wind interaction. These examples can be interpreted as a typology of designs for more refined strategies to interact with wind.

It is evident that the complexity of the geometric configuration of these designs awakens an interest about their behaviour when these are affected by environment factors. Unlike a normal flat and opaque wall, curved surfaces and, especially, porous surfaces produce different aerodynamic phenomena around them. Generally, prototypes of porous surfaces and structures (in some case with organic aesthetics) have a condition of permeability that is particularly sensitive to wind flow patterns. Regardless of structural aspects considered in their conception, such as wind load, many of these designs are presented as elements able to reduce the airflow speed when it passes through them, similar to flat porous screens working as windbreaks.

One interesting thing in the examples in the book *Morpho-ecologies*, is how wind

visualisation was used to aid in the development of morpho-exploration concepts, without practical applications. This book presents several pictures with CFD visualisations of complex morphological designs, and their hypothetical aerodynamic performance. For these wind visualisations of prototypes, the tests were performed in conditions of idealised wind simulation (with few parameters). The intention was only to visualise the dynamics of the environment interacting with preliminary concepts for theoretical design experiment (Hensel and Menges 2008a) (Figure 4.8).
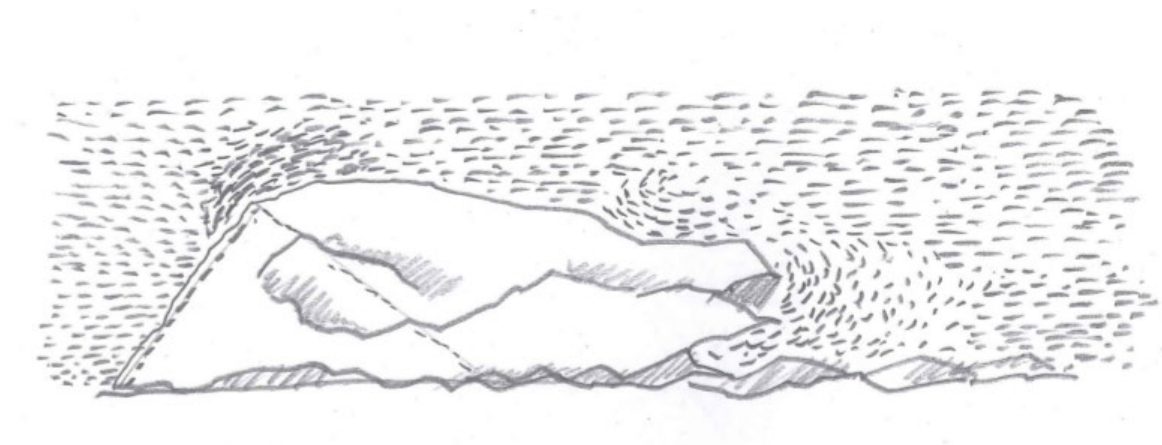
Figure 4.8: CFD visualisations of vertical wind deflection, distribution of pressure zones for the design of a porous structure prototype from the book *Morpho-ecologies*, edited by Michael Hensel and Achim Menges. The wind analysis is presented as part of the design process to develop porous structures that can increase or mitigate the wind speed. (Author's sketch based on (Hensel and Menges 2006))

The porosity in a screen or membrane is one passive design strategy that has been explored by architects. Because of their flexibility, tensioned membranes or meshes are one of the simplest concepts of auxiliary porous elements for microclimatic control. In a context where the urban configuration is already consolidated, meshes installed in the space around buildings "have great potential to be used in circumstances in which lightweight solutions to spatial arrangement and environmental performance are required" (Hensel and Menges 2008b; p. 75). They can be adapted with multiple grades of modulations with good response to the adaptation of space and wind conditions. "Arraying smaller membrane patches reduces horizontal wind-loads and the local acceleration or deceleration of airflow" (Hensel and Menges 2008b; p. 77).

Currently, Michael Hensel and Achim Menges 2011 have explored these kinds of morphologies. As example of a current porous morphology design, the project *Las Piedras del Cielo* (2012) is an interesting case for analysis (Hermansen and Hensel 2012). This project was built in the coastal zone of Ritoque by a group of masters students from the Oslo School of Architecture with the supervision of Michael Hensel, Christian Hermansen and Eduardo Retamales Fernandez (Hensel 2013). Basically, it is a small shelter that consists of a podium made with pieces of wood with embedded spaces and nine light tensioned membranes as a roof (Figure 4.9). The shelter unit has a configuration of volumes and surfaces to provide a permeable space with a reasonable protection from wind (the shelter contains a fireplace in the middle of the deck). This open configuration of boundaries was thought appropriate for the strong Pacific coastal winds. Thus, the membranes of the roof were not a continuous surface to avoid high gradient of wind pressure and the deck design helps to reduce the turbulence that could produce erosion effect on the sand around the shelter. This project builds an internal wind flow (a flow between deck and roof) as a balance among pressure, turbulence and sheltering factors.
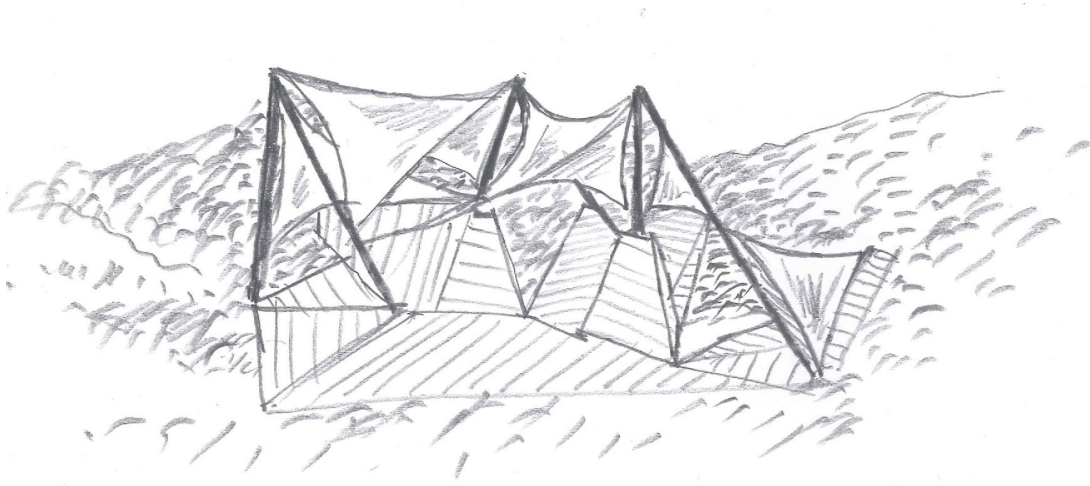
Figure 4.9: Membranes as permeable boundaries as design strategy for a shelter: *Las Piedras del Cielo*, Ritoque, Chile (2012) (Author's sketch based on (Hensel 2013)). The porous condition of a structure is considered as strategy of wind mitigation, but it is a strategy that does not explore other aerodynamic features.

However, the wind analysis of this project shows a strategy focused on mitigation of the wind speed within the shelter, avoiding distortions in the wind flow around the

membranes (accelerations). This is an opposite approach compared with previous cases of aerodynamic slots in *Escuela Naval* and *Hospederia del Errante*, where the propositions work with the phenomena of acceleration and deflection with an architectural purpose. *Las Piedras del Cielo* is a project that does not explore architectural intentions with the wind dynamics, trying to produce controlled effects, such as the "vault of wind". It is only an effect of wind speed mitigation (Figure 4.10).

Figure 4.10: CFD visualisation of *Las Piedras del Cielo* (Author's sketch based on (Hermansen and Hensel 2012)). The wind is not deflected by the membranes, only a condition of porosity is observed as mitigation of wind speed.

Architectural approaches for wind

This group of projects has different authors, different times and different scales. However, their similarities are several and they allow the establishment of wind as the main factor in their designs. Other similarities are: the design process involving analysis based on aerodynamic visualisation; the geographical context (Chilean region of Valparaiso) and its prevailing weather conditions of coastal winds; and their architectural program of shelter for outdoor environments. All these factors allow the comparisons with a theoretical idea about a wind-responsive architectural type and interaction with wind dynamics.

Considering the similar geographical context, environmental factors and experimental

approaches, these three projects represent several topics about the relationship between architecture, aerodynamics and wind comfort. The cases of *Escuela Naval* and *Hospederia del Errante* develop a concept where the function of an architectural element is based on a part of the project. Both projects have aerodynamic parts where the wind is specifically manipulated: deflector, slot, accelerator and so on. Those parts have a specific function, like components. For the first case, this component had a clear inspiration on an aerodynamic element which is a wing profile or fin; and for the case of *Hospederia del Errante*, Manuel Casanueva developed an abstraction process to integrate curved forms as deflectors and accelerators to the architectural elements in the building, but with a specific configuration for each façade, to deal with different wind directions. On the other hand, *Piedras en el Cielo* was conceived totally from the prototype form. It *expresses* the action of wind filtration with the whole body of the design, based in the property of a permeable surface and flexible membrane. This last strategy with these membranes also keeps a protection area in the shelter, but without installing walls.

If we take these three projects, they can represent an evolution where the idea of the wind, as a manipulation from the building form, has progressively disappeared. This idea is the use of wind to define an outdoor space. The accurate denomination of a "vault of wind" to identify a space of protection, that is built with a deflected layer of airflow in the *Escuela Naval* project, is a definition that gradually disappears in Manuel Casanueva's project (where he did not define any architectural spaces of protection based on wind), and it is completely absent in the case of the strategies developed in the project *Piedras en el Cielo*. This idea of calling aerodynamic phenomena with architectural names represents a refined vision that considers the wind as an extension of the architecture.

Extended thresholds

Authors have speculated about "dynamics" as a concept to explain the fluctuating nature of environmental factors like temperature, light or wind. This fluctuating condition of environments is the current challenge for design (Whitehead 2013). This is the case of pedestrian areas near buildings and their local wind phenomena, where the dynamics of the

wind overlaps with the dynamics of the pedestrian and other urban activities. From the perspective of wind comfort and because of the diffuse, gradual and fluctuating boundaries of regions with different levels of wind intensity, these pedestrian areas are identified as regions with a shelter parameter (Wisse 1988).

The artificial windbreak designs (auxiliary screens or membranes), installed in pedestrian zones, are mainly based on two parameters, the size and porosity. Even if their morphology is regular or complex, when they consider porosity, these screens try to produce a simple filtering effect to the leeward side, mitigating the wind speed (Li et al. 2007). For instance, in the book *Morpho-ecologies* (Hensel 2013) the pictures about wind analysis show visualisations of wind flowing through the designs, that do not look different to effects produced by flat porous screens or natural windbreaks. This means, there is no original proposition in the way that architecture manipulates the wind dynamics; they keep their design as a simple barrier with a filtering effect of wind. In other words, for designs with porous morphologies and their performance to produce controlled regions of comfort, the question that remains is whether the aerodynamic effects of these artificial windbreaks represent an evolution from normal performance of other windbreak alternatives such as vegetation screens.

An architectural definition for a wind effect is useful to understand phenomena that are projected from architectural elements. For instance, the term "thresholds" is a definition used to explain the complexity of an architecture to control "dynamics" regions with gradual transitions. The term "extended thresholds" is postulated by Michael Hensel about microclimatic indoor environments, as an extension of the comfort limits from physical walls (Hensel and Hensel 2010, Hensel 2013). Similarly, the expression is also useful to denominate a gradual control of comfort in an outdoor environment, provided by external auxiliary elements, such as artificial windbreaks.

4.3 Architectural windbreak for pedestrian comfort

The same approach to wind interaction and architecture can be applied to external elements installed in the outdoor environment, around pedestrian areas. To facilitate the

analysis of designs with aerodynamic features I chose to work with small elements near buildings rather than large structures covering a whole façade of a building. However, I think that these thoughts are applicable to architecture at a larger scale.

Wind shelters

The wind shelters represent a field of architectural exploration to investigate the relationship between wind and design in urban contexts. In general, the concept of wind shelter is based on the shield effect of a wall or screen, which produces a limited area of protection. The main challenge for designers is the unpredictable directions of the wind. To achieve this, some strategies consider a rotating structure, such as the case of the Blackpool Swivelling Wind Shelters (2006), by McChesney Architects and Atelier One, in Blackpool, England, where the shelter works as a sail, rotating with the prevalent wind to keep a protection effect (RIBA 2006). Another example of shield effect by a wind shelter design is the Winnipeg Skating Shelters (2011), by Patkau Architects, in Winnipeg, Manitoba (ArchDaily 2011). Here, a group of shelters made by sheets of plywood works as envelopes, keeping a comfort region at the centre of a circular perimeter of protection (Figure 4.11).
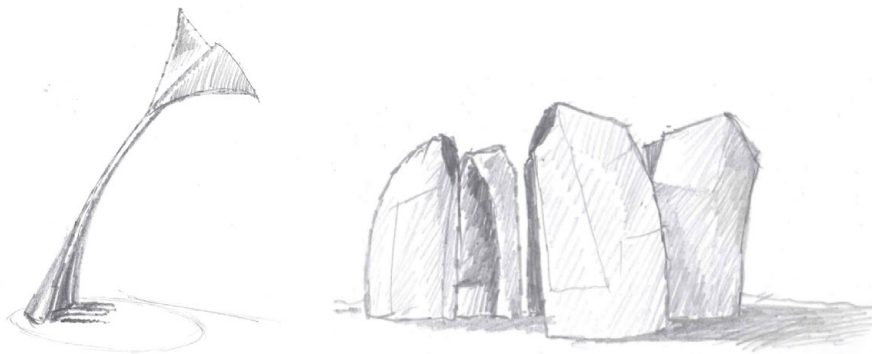
Figure 4.11: Architectural examples of wind shelters as basic protection shields. Left: Blackpool Swivelling Wind Shelters (2006). Right: Winnipeg Skating Shelters (2011). (Author's sketches based on (RIBA 2006) and (ArchDaily 2011))

On the other hand, with a design exploration based on wind analysis during the design process, it is possible to study and test shelter structures less closed and lighter but with

best wind performance. One example is the prototype of a canopy developed as part of the initiative CFD-ARCH (2012), by SUTD-MIT International Design Centre (Kaijima et al. 2013). Their authors states that "the objective of this research initiative was not to extend knowledge in the field of CFD but to find ways of utilising CFD to support early stages of the architectural design process, where many critical decisions, including those pertaining to the building performance are made" (SUTD-MIT 2013; p. 1). The geometry generation, for a passive cooling canopy design for a bus stop, was based on airflow analyses with several canopy concepts, with a final result of a refined, light and sophisticated canopy structure to keep a threshold of comfort in a bus stop (Figure 4.12).
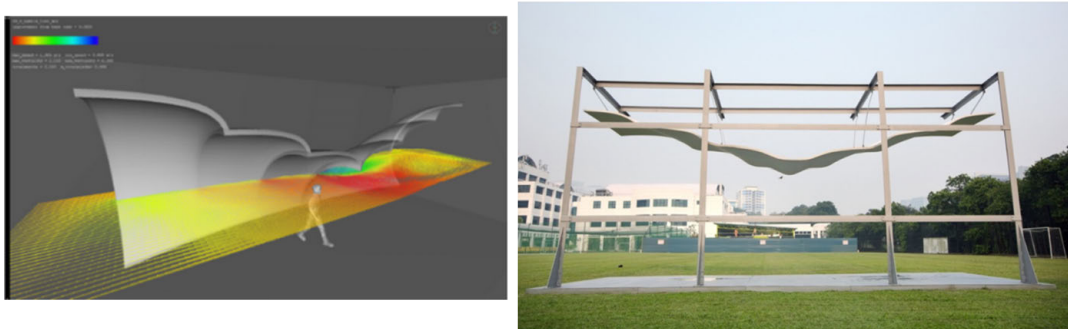
Figure 4.12: Initiative CFD-ARCH (2012) by SUTD-MIT International Design Centre. Left: wind analysis for a prototype of passive cooling canopy. Right: final design of the canopy for a bus stop. (Taken from (Kaijima et al. 2013) and (SUTD-MIT 2013))

A windbreak in the Grande Arche

"Thresholds" is a useful definition when it refers to regions of wind comfort in an outdoor environment. The auxiliary elements for microclimatic control in pedestrian areas, produce protection regions with thresholds of wind speed as boundaries.

Local wind phenomena in outdoor environments near buildings can generate discomfort issues in pedestrian areas. In the literature reviewed, the standard strategies to prevent or ameliorate these issues cannot always be implemented, when for each case, the causes and effects of wind issues depends on many local factors, such as the geometry of the building or the built environment configuration. This problem becomes especially significant when the urban context is not considered during the design stage; that is, the

case of urban context where the configuration of the city and the geometries of buildings are already consolidated. Thus, a strategy to deal with the local wind environment is to use artificial windbreaks, based on porous screens, near buildings.

I started to consider the idea of wind flow manipulation using artificial windbreaks, during a visit to *The Grande Arche* in Paris (Johann Otto von Spreckelsen, 1989). *The Grande Arche* is the central and iconic building of La Défense, the major business district, to the west of Paris city, France (Edwards 2011). The design of *The Grande Arche* is an approximate shape of an open cube (108 m width, 110 m height, 112 m depth) with one aperture orientated to the "Voie Triomphale" urban axis. The inner space of the arch is accessible for pedestrians by a stair on the bottom bevel of the structure. Here there are several glass pavilions and other elements, installed for protection of the main entrances of the lateral buildings. Additionally, there are two membranes as suspended canopies and a barrier of glass panels at the west aperture of the building (Figure 4.13).
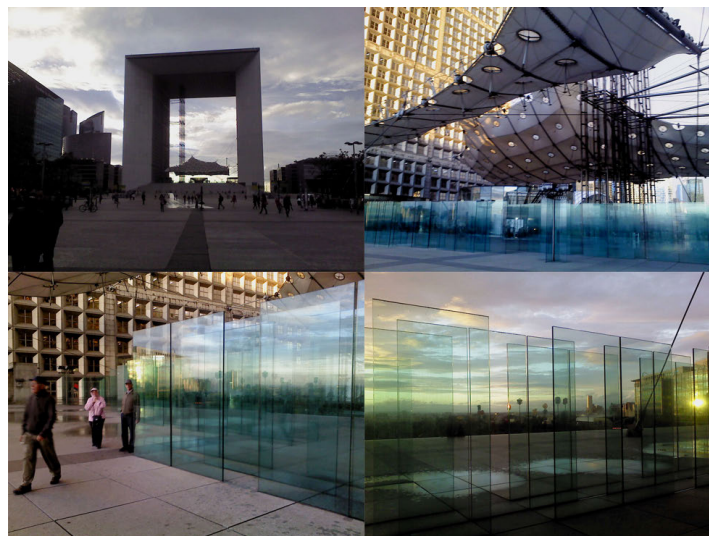
Figure 4.13: Glass panels as screen and membrane canopies are used as an artificial windbreak for pedestrian comfort in the *Grande Arche* (1990), Paris, France. (Source: author)

These glass panels caught my attention. It is a glass wall working as windbreak. This barrier comprised a line of 3 m high panels, all of them arranged in groups of parallel rows. These panels are not a continuous wall; the position of them forms a screen with several layers and gaps. The screen is completely transparent and the gaps allow the traffic of

people.

The windbreak was designed to mitigate the wind speed in the inner space of the arch when wind comes from the west. When the wind flows, it is accelerated when it passes through the inner space of the building. The geometry of this building produces a similar effect to a duct, where each aperture is framed by a bevel face producing strong deflections of wind to the inner space and at the ground level (Figure 4.14).
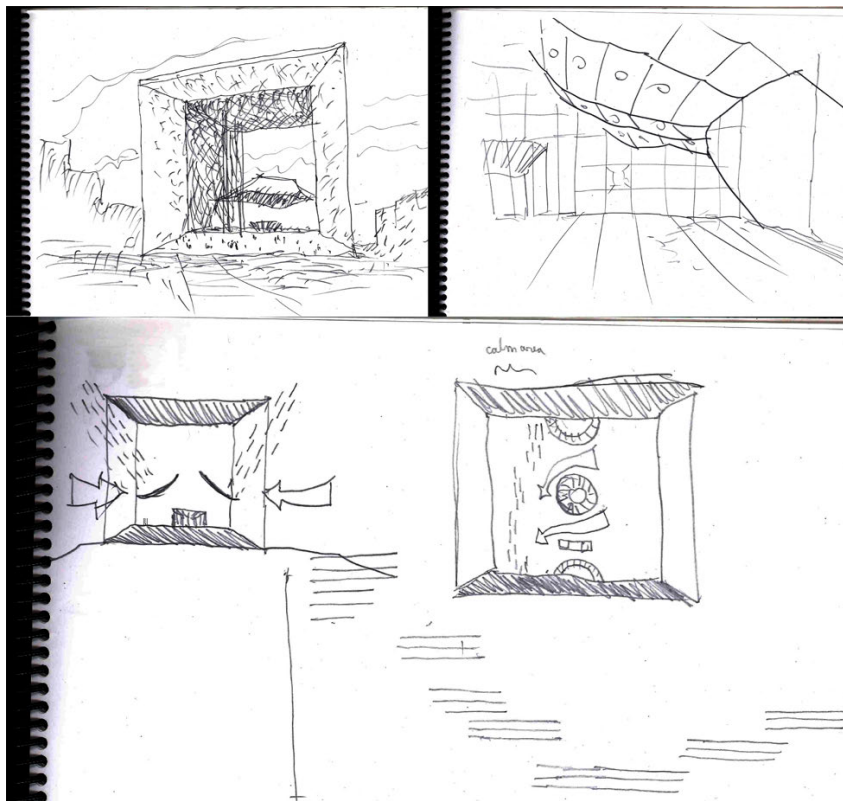
Figure 4.14: Observations on the site of the windbreak system in the *Grande Arche*. The drawings show how the canopies protect the rain that is drawn inside by the wind. (Source: author)

Thus, it is possible to understand that each element of this artificial windbreak is intended to create thresholds, where the boundaries between the inner space and the outdoor environment conditions are gradually manipulated and mitigated. However, not all these thresholds work efficiently as mitigation. Even though during my visit it was not possible to measure the wind speed in that space, I felt uncomfortable for several moments due to the intensity of wind. On the day of my visit, a strong wind flowed from

the east to the west, while steady rain was falling on the city. The wind flowing through the arch dragged the rain to the east entrance area of the central walkway (where there was no windbreak), while the wind flowed very strongly at ground level. This produced an uncomfortable situation for the pedestrians that had to avoid the strong airflow near gates of the office building, and the wet floor of the terrace entrance (Figure 4.15).
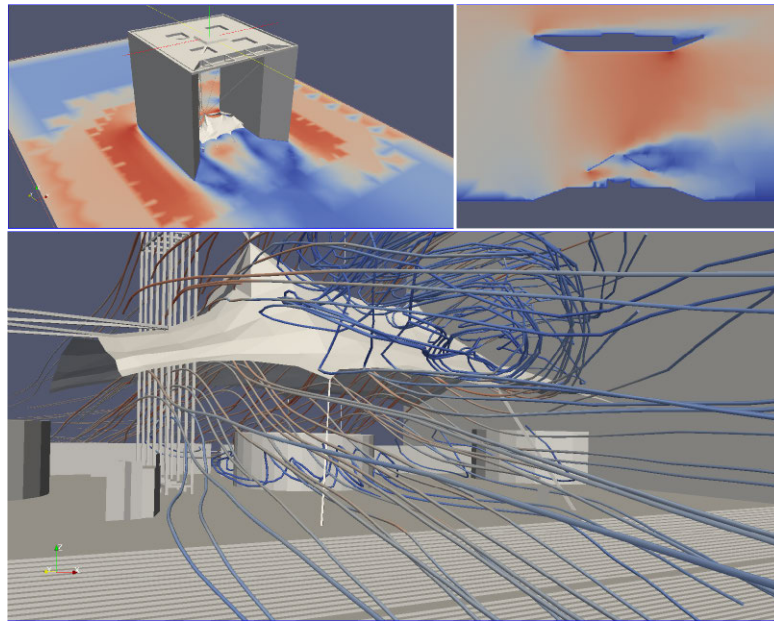
Figure 4.15: Rapid CFD-PST visualisations of wind thresholds inside of *The Grande Arche* building, with ODS-Studio (wind velocity = 5 m/s, no ABL condition). The visualisations show the wind acceleration inside of the building and below the canopies affecting the entrance of the building. Top right: horizontal 2D visualisation of the wind in the terrace of the building. Top left: vertical 2D visualisation of the building section showing the roof and terrace profile. Bottom: 3D visualisation of the wind flow that is a wind acceleration threshold in the west entrance. Here, below the canopy, it produced a discomfort area by a downward deflection of airflow. (Source: author)

Aesthetic and materiality in a windbreak

The visit to this building provided me a short period of observation of a full scale windbreak, and a question about the relationship between auxiliary elements, their aesthetic condition in the public space and their aerodynamic performance.

In this case, the transparent material of the windbreak is seen as mitigation of the negative visual impact of the barrier size in this pedestrian area. For a screen that is a

windbreak, the height is crucial to extend its protection area, but at the same time, it could produce a negative visual impact in the public space.

This problem is an aesthetic matter, and the transparent material is an option to deal with it. However, from an aerodynamic point of view, the condition of the screen has not been altered. Even though the transparent wall is an aesthetic solution (low visual impact), its aerodynamic condition is similar to a normal opaque wall, in that it is not the best design for a windbreak (Gandemer 1979). The aesthetics of a windbreak could be an aerodynamic matter. This means modifying the aesthetics of the windbreak form to improve its aerodynamic performance. For instance, porous screens can produce a better protection factor than a non-porous wall, without generating significant wind acceleration at the top of the barrier or strong turbulence at the leeward side. If the form is designed following aerodynamic rules, the height and the negative visual impact could be reduced.

This relationship between screen size and visual impact of a windbreak can be considered as an aesthetics interpretation. Thus, if the aerodynamic condition of a windbreak has to consider an aesthetic parameter, this aesthetic condition could be an aerodynamic feature. For this research, aesthetics is defined as the design integrating features to improve its aerodynamic effect, reducing the dimension (height). Specifically, an aesthetic factor for the aerodynamic design of a screen will be to decrease the height of the wind screen below the level of the human head, keeping the performance the same as for a taller windbreak.

This challenge could be an architectural matter that involves a sophisticated design to work with the aerodynamic properties of a screen. The development of these strategies must start from the early design stage, where the techniques of wind visualisation will assist architects in their preliminary explorations.

4.4 Artificial windbreak screens

Windbreaks for wind protection

The artificial windbreak in the *The Grande Arche* has a similar purpose to a natural windbreak that is strategically planted with an orientation perpendicular to the wind,

working as a screen (with an additional grade of flexibility and porosity). A windbreak should provide a very good area of protection at the leeward side (low wind speed) up to 10 times the height of the barrier (Melaragno 1982). Usually, an artificial windbreak is a timber fence that can be portable and is used to protect the livestock. Its design considers gaps between each timber paling, so the porosity density is 25-30% and includes a slope to facilitate a deflection of wind (Figure 4.16).
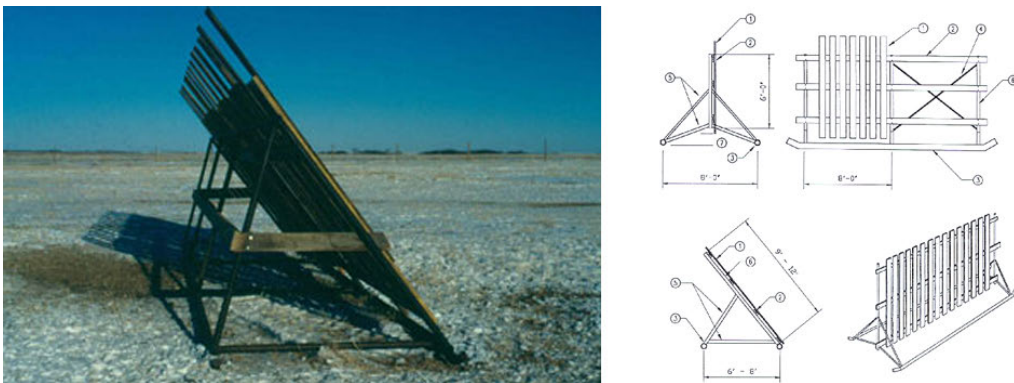
Figure 4.16: Artificial porous fences as windbreak screens for wind protection of livestock in farms (Kuhns 1998, Lin et al. 2006). The slope and porosity of the fence increase the protection region produced by a screen (DeWalle and Heisler 1988). These are basic aerodynamic features of these structures for wind mitigation. (Source: http://www.agriculture.gov.sk.ca)

For urban environments, windbreaks are used to mitigate local wind effects, especially when these affect the levels of human comfort. Natural and artificial windbreaks are used in many cases, although the use of natural windbreaks is more frequent because of their porous condition and aesthetic or ecological value (Gandemer 1979).

As mentioned before, the development of light structures with a grade of porosity, such as tensioned membranes, has been suggested for designs to mitigate and control environment conditions of sunlight and wind. However, architectural solutions based on a more complex design of auxiliary screens, such as porous membranes, neearly design stage a design approach that improves how they filter or mitigate wind. I found that the aerodynamic studies of Jacques Gandemer about artificial porous screens and their aerodynamic features can be used to determine ways of manipulating wind conditions and wind mitigation methods, with membranes and porous structures.

Jacques Gandemer's work

The studies of Jacques Gandemer about artificial porous screens and other wind-mitigating features explored different configurations of fences used as windbreaks (Gandemer 1981). These studies, realised with wind tunnel experiments, evaluated several possible barrier designs and the protection factor produced, respectively. After several tests, screens with a 20-30% of porosity density were found to have the best performance to provide a protection factor, defined as the biggest region with a low wind speed (Figure 4.17). In general, the main parameters found by Gandemer to define the performance of a porous screen are the porosity density, the height of the barrier and the length (Gandemer 1979). These few parameters have some limits on their performance to keep a protection area behind the barrier if their dimensions are changed, being the optimal characteristic for a flat porous screen: $2.5 \ m \leq h \leq 10 \ m; 0 \leq \emptyset \leq 50\%; 20 \ m \leq L \leq 120 \ m$ (Pescaru et al. 2011).
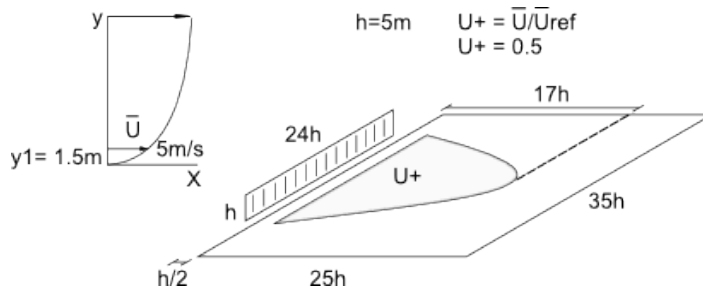
Figure 4.17: Diagram that shows Gandemer's experiment of a screen with 20% of porosity and the isocurve of mitigation behind the screen. With these experiments, conducted in a wind tunnel, Gandemer elaborated a classification of screens with different aerodynamic features and the region of wind mitigation produced for each case. (Source: author, based on Gandemer's studies)

Aerodynamic features of windbreaks

However, Gandemer also found that some auxiliary features produce particular aerodynamic effects when these are integrated into the porous screens, increasing the area of protection at the leeward side of a barrier. These features can be fins, slots, gaps, variation in the porosity density, irregular edges or parallel screens. In fact, some of these features (Figure 4.18) are similar to the roof system developed for the project of *Escuela*

Naval; the slot is an aerodynamic feature designed to generate similar effects as the guiding fins for porous screens studied by Gandemer.

Types of windbreaks used				scale h=5m, L=120m							
Model num	sketch	porosity	comments	Model num	sketch	porosity	comments	Model num	sketch	porosity	comments
BV 2		0%	reference: the wall	BV 9		70%		BV 16A			canopy
BV 3		47%	homogen distribution	BV 10		45%	same porosity as BV 3	BV 16B			canopy
BV 4		20%	homogen distribution	BV 11			ventilation the wake by upstream dynamic	BV 17A			spring-board
BV 5		sup 40% inf 100%	ventilation of the wake at the base	BV 13			superelevation by the upstream dynamic	BV 17B			
BV 6		sup 0% inf 100%	ventilation of the wake at the base	BV 14			combination BV13-BV6, BV11	BV 18			complem to BV 11

Figure 4.18: Types of windbreak screens studied by Gandemer. Each design is considered as an aerodynamic feature that changes the protection region produced by a simple porous screen. (Source: author, based on (Gandemer 1979))

The analysis of Gandemer's work allows the identification of three main design parameters for windbreaks: the size of a barrier, the nature of the screen surface (porous or non-porous) and the auxiliary aerodynamic features. Basically it is a group of elements to extend the protection area produced at the leeward zone of a flat porous screen of 20% of density.

Different features have different impacts on the protection factor behind the porous screen. If they are strategically integrated they can be used to affect the wind flow and control the protection region. For instance, these features generate flows, which in lateral sides of the region, delay the backward flow of the free-stream wind. This effect can be intensified with curved fins working as deflectors (Figure 4.19). On the other hand, ventilation at the bottom of the screen produces a flow that is opposite to the wind flow vortex with a direction to the screen. This ventilation is represented by a simple gap in the screen or high density of porosity at the bottom of the barrier.

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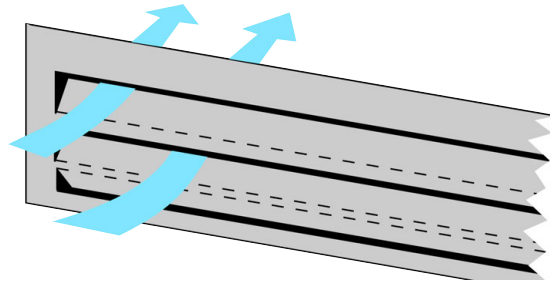
Figure 4.19: Windbreak screen with aerodynamic fins and slots used in the wind tunnel experiments by Gandemer. This aerodynamic feature has similarities with the concept of building with fin and slot designed for the *Escuela Naval* project. (Author's sketch based on (Gandemer 1979))

Gandemer classified with basic sketches the possible configurations of these windbreak screens, and their aerodynamic effects on the protection region (Figure 4.20). I think that it is a valuable source of design rules and knowledge of geometrical patterns of screens and aerodynamic effects. This can be used for design of more sophisticated elements than simple walls, to interact with the wind. I chose four features as more significant for further experimental analysis: graduated pattern of porosity, auxiliary curve deflector, double slot of acceleration and parallel screens.
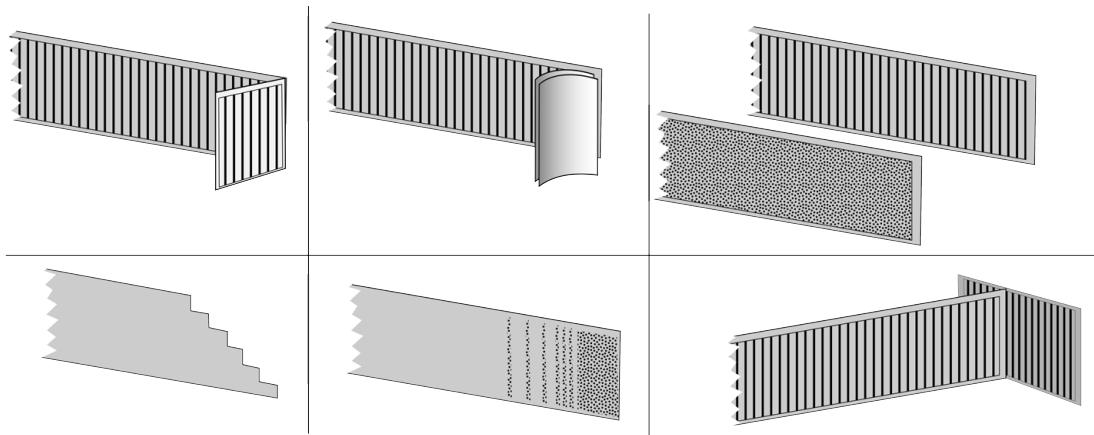
Figure 4.20: Other Gandemer's experiments of windbreak screens and aerodynamic features. Top row: porous screen with lateral screen, porous screen with lateral curved deflector and two parallel screens. Bottom row: lateral edge with zigzag pattern to mitigate lateral air deflection, variation of porous density to mitigate strong lateral deflection and perpendicular short screen for similar purpose. (Author's sketch based on (Gandemer 1979))

Aerodynamic features for design strategies

The aerodynamic features were selected and divided into two groups. The first group represents the features explored by Gandemer that improved the protection factor of a porous windbreak: the porous screen with 20% of porosity; the porous screen with lateral deflectors with double slot system and the group of parallel porous screens (Figure 4.21).
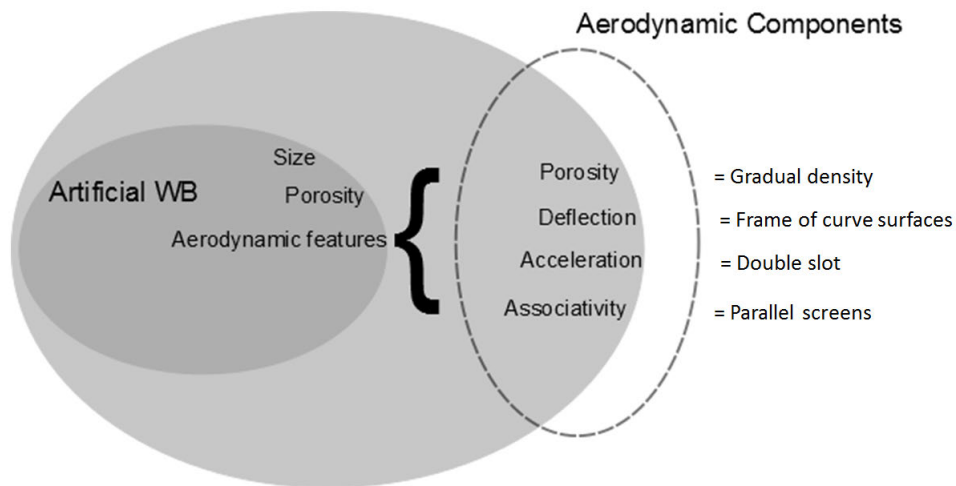
Figure 4.21: Classification of the main parameters of aerodynamic features of a windbreak screen for further experiments of wind discomfort mitigation. (Source: author)

A second group of models considers two variations based on the use of curved surfaces as deflectors with a double slot system: the first variation is a porous screen with 20% porosity and horizontal deflectors with a double slot system; the second variation is a porous screen with horizontal deflector and convex deflector above the barrier.

The further experiments using this group of windbreak features will have two goals. First, these experiments will show if it is possible to use these aerodynamic features in a different context and scale: auxiliary membranes for mitigation of wind issues, in local outdoor environments of cities. The second goal for this group of experiments is to verify if the variations of these features will work to improve the performance of an artificial windbreak for a pedestrian space; this means, models using horizontal deflectors and convex deflectors that can increase the vertical upward wind flow at the top of a barrier. If this final option is possible, the height of a barrier can be reduced, without affecting the area of protection.

4.5 Summary

Through this chapter I have developed some ideas about the challenges that architects are addressing in the design of strategies to work with wind. For instance, to resolve pedestrian comfort issues that must be analysed by architects with wind visualisation techniques in the early design stage, to develop more sophisticated strategies of mitigation.

- In the first part of the chapter I present some non-standard architectural strategies to manipulate the wind, such as the aerodynamic slots and the differences with modern strategies based on morphological designs of porous structures and membranes. The difference is in the architectural manipulation of wind dynamics, performed for the first cases; something that is missing in the most recent approaches.

- Another of the main points presented in these sections is how the aerodynamics of artificial windbreaks is a matter of developing strategies of design to control wind in the outdoor environment. There are architects exploring designs for microclimatic control with a level of complexity that include porous screens.

- In this sense, the studies of Jacques Gandemer about aerodynamic features of artificial windbreaks provide knowledge about porous screens and how they can interact with the wind. This is something that can be used to develop more sophisticated designs strategies.

4.6 Conclusion

This chapter has presented some ideas about strategies of wind manipulation and mitigation in architectural design. Some examples of architectural projects and the strategies used, to interact with the wind are presented as a theory about architectural strategies for addressing wind dynamics. At the end of the chapter, the use of aerodynamic features, taken from windbreak concepts, is presented as classification of geometrical shapes and aerodynamic effects. This is knowledge that can be used to explore design strategies, aiming for a more sophisticated wind interaction.

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These sections presents some challenges that design currently is exploring with the approach of wind as factor in the design process. Therefore, to address these explorations, the design process must incorporate a more sophisticated method of wind visualisation for architects, in the early design stage.

In the next chapter, a new investigation project is conducted, with wind visualisation techniques, to experiment with a group of windbreak screens with aerodynamic features. The aim is to analyse to what extent current digital technologies can assist architects, with these complex windbreak designs.

(March 2015)

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CHAPTER

Third investigation: wind analysis of a screen with aerodynamic features

5.1 Introduction

This chapter develops the work of the third investigation project. In this investigation I conducted a group of wind visualisation experiments to evaluate CFD-PST (computational fluid dynamics - performance sketch tools) and CFD (computational fluid dynamics) programs for rapid visualisation of wind flow, through windbreak screens with aerodynamic features. The observations were focused on testing methods to generate vertical wind flow deflections with these screens to increase the region of protection at the leeward side of the barrier.

The chapter presents the experiments conducted to explore the wind behaviour around three windbreak screen concepts: a windbreak screen with a single deflector fin, a screen with multiple deflector fins and a curved windbreak screen. The results of visualisation using CFD-PST programs, ANSYS CFX and using a mini airflow tunnel for physical experiments are described; but, at the same time, the performance of the visualisation techniques to show the wind effects around these screens is evaluated.

In the following section I explain the experiments conducted and the aims for each one.

Investigation aim and criterion of evaluation

The intention of this investigation is to test techniques for rapid wind visualisation in the design process of windbreak screen concepts with aerodynamic features. For this new investigation I am going to develop concepts of wind deflector screens that are more complex than a flat porous screen because they integrated aerodynamic features to interact with the wind. The idea is to verify if these features can increase the normal wind deflection and protection region produced by a flat non-porous screen. The wind visualisation techniques were used to evaluate the performance of these screen concepts and the functions of their aerodynamic features.

The aims of the experiments were twofold:

- to visualise the vertical wind flow deflection and the protection region produced by a screen with an aerodynamic slot system (a similar concept to the roof system in the *Escuela Naval* project)

- to visualise and identify the aerodynamic effect that produces this vertical wind deflection.

Criterion of evaluation. The reason for these experiments is to evaluate the performance of the wind visualisation programs with tasks for which they have not been designed. This means, to take programs for analysis of outdoor wind flow around close form buildings and to use them for rapid visualisation of wind through models of thin, small and complex screen shapes, where the airflow has a different behaviour. The criterion to evaluate the performance of these techniques used three tasks. The visualisation of the variation for wind deflection produced by the screen, the visualisation of the variation of protection region and the visualisation of the acceleration airflow through the slots of the screen models. These three observations allow the study of the windbreak screen performance to take decisions about their design and to improve their protection factor. If the tool can visualise the phenomenon, the evaluation is considered as "yes"; if the tool cannot fulfil the task, the evaluation is "no". This exercise shows what can be expected from these techniques, when they are used as a rapid wind visualisation tool (Table 5.1).

Windbreak model	CFD-PST		CFD tool	Physical tool
Windbreak model with single deflector fin	Vasari		ANSYS CFX	Mini wind tunnel
Windbreak model with multiple deflector fins	Vasari	ODS-Studio	ANSYS CFX	
Windbreak model with curved screen		ODS-Studio	ANSYS CFX	

Table 5.1: Table with models studied and the wind visualisation techniques used for each case during this investigation.

This phase of experiments was divided into three stages: preliminary CFD-PST visualisation with Vasari, physical visualisation in the low-tech airflow tunnel, and CFD visualisation with ANSYS CFX software for the first experiment. The second experiment involved the use of Vasari, ODS-Studio and ANSYS CFX. The final experiment considers the use of ODS-Studio and ANSYS CFX. This workflow supported the process of rapid wind visualisation for different models of wind barriers, conducting experiments with a qualitative approach for results (Figure 5.1).
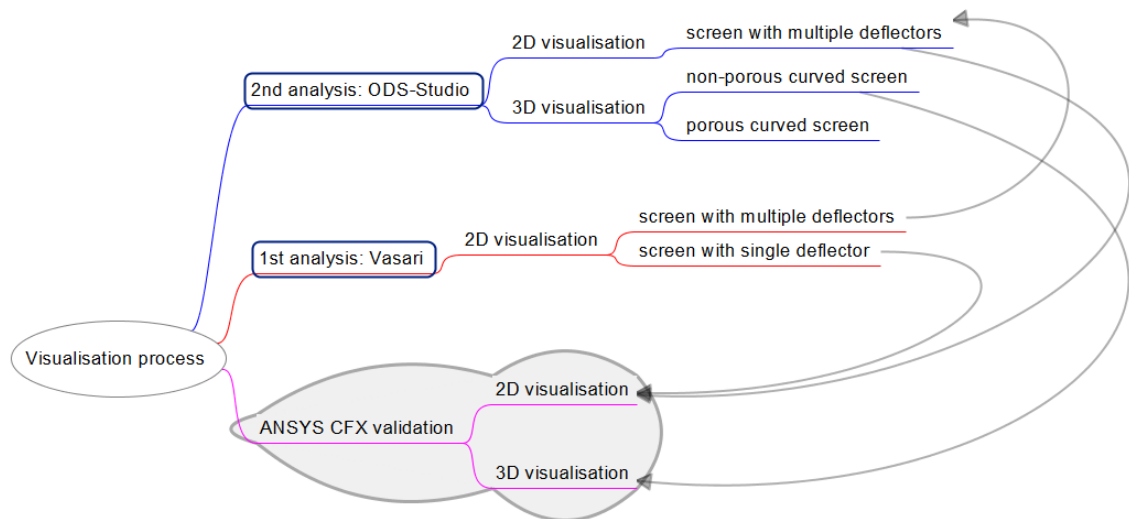
Figure 5.1: Structure of the wind visualisation process for this investigation with three CFD tools: first Vasari, second ODS-Studio and third ANSYS CFX. The idea was to conduct rapid wind analysis with CFD-PST and CFD programs for an architectural exploration of conceptual wind barriers. (Source: author)

In addition to the CFD-PST program already tested, in this investigation I used ODS-Studio, a recent tool aimed at rapid analysis of commercial and residential building

design (Pitman 2013). It is a script that works as a link between several open source programs: the 3D modeller Blender[1] (software to create digital geometries), OpenFOAM[2] (CFD software to run wind simulations), and Paraview[3] (an application for scientific data analysis and visualisation) (Figure 5.2).
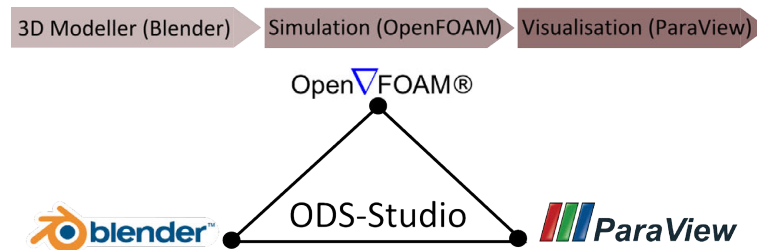
Figure 5.2: ODS-Studio workflow where three programs are incorporated the analysis process: modelling, simulation and visualisation. Each program presents different levels of learning, Paraview being the most difficult. (Source: author)

ODS-Studio was chosen because it is an easy and freely available tool that allows a control of OpenFOAM with a moderate tolerance to import digital meshes from other programs. Using a graphic interface, it is possible to control OpenFOAM's parameters to create digital meshes, set up a virtual wind tunnel and run a simulation generating steady-state solutions, which is the type most commonly used in the building industry[4]. The output data can be visualised using Paraview. Similar to Vasari, with ODS-Studio it is possible to obtain quick feedback on the generation of models, further simulations and visualisation. However, I found that the use of these three tools presents different grades of complexity. The use of Blender and ODS-Studio can be quickly learned with few tutorials. However, Paraview presents a more complex level of operation, which requires more learning time. A final condition of this program is the limitation of this software version to produce only flat velocity profiles of the inlet wind (no ABL). However, it is possible to include screens and roughness condition on the ground of the simulation to produce a friction in the airflow, generating a relative effect of ABL. This possibility will be tested in the investigation of the next chapter.

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[1] http://blender.org/
[2] http://www.openfoam.com/
[3] http://www.paraview.org/
[4] http://www.ods-engineering.com/tools/ods-studio/documentation/cfd-module/

On the other hand, for the validation analysis I used ANSYS CFX as a sophisticated CFD program. This program is a full simulation software for many uses. Its features for CFD simulation and visualisation include a workflow going from geometry-making to visualisation and post-processing. It is a program that allows set up of many parameters for different kinds of simulations. But, the analysis with ANSYS CFX, presents disadvantages for users without previous training or the technical background to use this tool. This means that good expertise is required to operate it. So, it is not an easy tool to be used by architects without a previous learning process.

5.2 Screen with single aerodynamic deflector fin

The first idea for the experiments was to design a wind barrier integrating a horizontal deflector fin to generate an upward wind flow. The original artificial windbreaks are screens up to 5 m high (Gandemer 1981). The case explored here is a screen with a height of no more than 1.6 m, considering this height as the top of a typical person's head. The idea is a wind barrier that can protect like a higher wall (2 m) but without interruption of pedestrian view. Two option groups were developed and visualised: one group with a single fin deflector at the windward side of the barrier and a second group of concepts with more than one deflector fin.

The first design concept of the barrier, with the deflector fin, includes a slot between barrier and fin, to produce an acceleration or airflow that vertically deflects the wind above the barrier. This deflection could increase the height of the protection region behind the barrier (Figure 5.3). This structure can be installed as windbreak in pedestrian zones, near a street or places with strong wind levels.
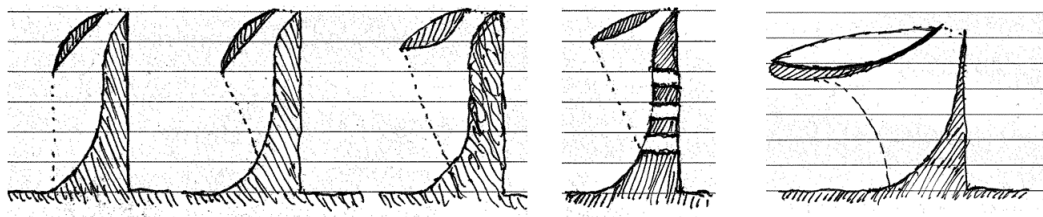
Figure 5.3: First concept of a barrier design with a gap of wind accelerator and the evolution into a deflector fin and slot (Source: author).

The intention of these concepts was to verify that a significant deflection can be produced by the aerodynamic slot at this scale. This idea is based on the design of the aerodynamic slot integrated on the roof of a building, used in the *Escuela Naval* project, to produce a high wind deflection at the top of the building, increasing the size of the protection region behind the building (Ureta Morande 2007). However, the vertical deflection effect, produced by a slot deflector, has been studied with a different scale (building) and in a different context (roof). It is not certain that this effect can be reproduced in a different situation, such as in streets or pedestrian zones. Thus, the intention of a rapid airflow visualisation is to know if the effect can be replicated with smaller screens. The advantage of a screen, with an aerodynamic slot system, is to be installed as a windbreak in a place for an urban shelter where a tall screen can not be installed (e.g. tram stop).

Rapid CFD visualisation test

The processes to set up the rapid visualisation with Vasari and ANSYS CFX can be compared in the following diagram with their main differences (Figure 5.4). The wind velocity criterion of discomfort is considered as a wind velocity of 5 m/s at 2 m high or head level. The barriers were 1.6 m high and they were full scale modelled in the programs (Wisse 1988).

	Model	Wind speed	ABL	Digital mesh	Turb. Model	Validation method
VASARI	Barrier 1.6 m height	5m/s - 10m/s at 2m height	NO	3D domain X=200 cells Y= 90 cells Z= 110 cells	LES	NO
ANSYS	Barrier 1.6 m height	5m/s - 10m/s at 2m height	Ground roughness of 5mm to produce BL	2D domain Nodes=13149 Elements=177164 Inflation=15 layers	RANS - standard K-epsilon	Residual RMS Error values acceptable value Monitoring values of drag and lift with a steady solution Domain imbalance of less than 1%

Figure 5.4: Flow domain set up of the experiments for the CFD-PST and CFD programs. For both cases the parameters to set up the simulation are quite different to get an equivalence. For instance, Vasari decreases the density of the mesh when the grid is large. In contrast, ANSYS CFX requires high density of the digital mesh as parameter for result validation. To generate this digital mesh the process in ANSYS is quite complicated and must be corrected and repeated when the program can not generate a simulation. Left: the domain in Vasari is a 3D grid, but the visualisation reproduces only a 2D airflow simulation. The grid dimensions are x = 200 cells, y = 90 cells, z = 110 cells, voxel size = 0.4 Right: in the case of CFD ANSYS, the domain is 2D. Digital mesh has 15 layers of inflation, 13149 modes and 177164 elements. Ground roughness of 5 mm to produce an airflow with boundary layer effect; 6 m/s wind velocity and 5% of turbulence intensity. The simulations in ANSYS used RANS and standard k-epsilon as turbulence model. (Source: author)

The wind visualisation test with Vasari for a group of preliminary experiments showed that a deflector fin at the front of a wall does produce, in some cases, a significant acceleration of the airflow, passing through the gap in the slot. This effect produces a vertical wind deflection over the height of the barrier - the yellow areas in the middle top and first bottom images (Figure 5.5). However, in other cases of deflector fins, the airflow it is not accelerated and the vertical deflection effect is missing.
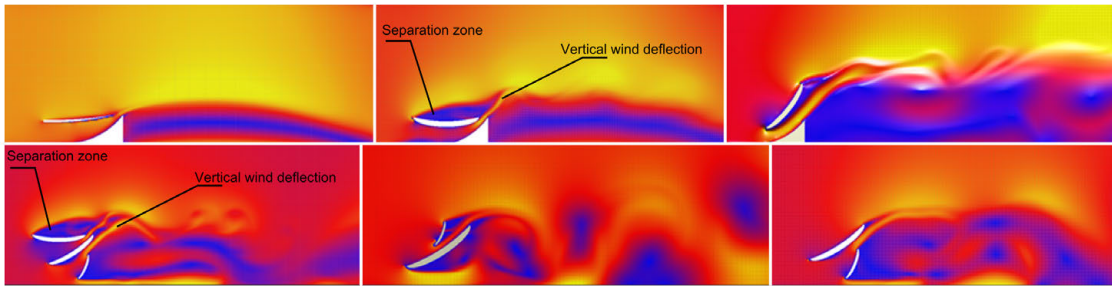
Figure 5.5: 2D vertical visualisations of vertical wind deflection produced by windbreak barrier profiles with deflector fins, generated with CFD Vasari. Several configurations of fins were tested. The yellow regions are areas of airflow acceleration. The second image at the top and the first image at the bottom present the strongest effect of vertical deflection. Wind speed in the inlet region: 4 m/s. (Source: author)

The visualisation with Vasari allows me to understand a possible mechanism that helps to produce the vertical wind deflection. There is a separation zone, with a vortex of air, generated at the top of the deflector fin. Probably, this vortex works as a shield to the incident wind and changes the direction of the airflow that pass through the slot (Figure 5.6). This is a plausible explanation for the cases where the effect is produced, because the effect is missing where the deflector fin has a significant inclination and the vortex is not visible.
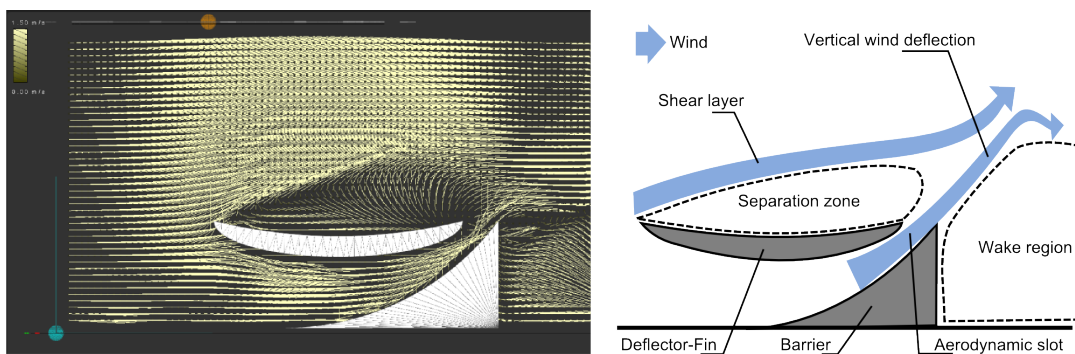
Figure 5.6: 2D visualisations of vertical wind movement with vector fields, of a separation zone at the top of the deflector fin, using CFD Vasari. This effect produced by the fin allows the effect of airflow acceleration of the aerodynamic slot. Left: vector field showing the separation zone at the top of the fin. Right: identification of wind regions in the barrier with more significant vertical wind deflection. Wind speed in the inlet region: 4 m/s. (Source: author)

Moreover, the visualisations with Vasari were useful to evaluate the height of the wake region of the barrier. Two barrier profiles that look very similar with a single fin present a

different height in the curvature of the deflection at the leeward side of the barrier. Based, on those observations, I ran a few experiments using ANSYS CFX to verify the effects on this deflection between different fin sizes and a different curvature. Thus, I tested convex fins of 35 cm, 50 cm, and 75 cm length (Figure 5.7). In those experiments, the fin of 50 cm shows a bigger separation zone and vortex at the top of the fin and a significant effect of wind acceleration and deflection, compared with the others. I interpret this test as evidence of the relevance of a separation zone to increase the acceleration in the slot of the barrier and increase the vertical wind deflection.

1) 75cm deflector-fin   2) 50cm deflector-fin   3) 35cm deflector-fin
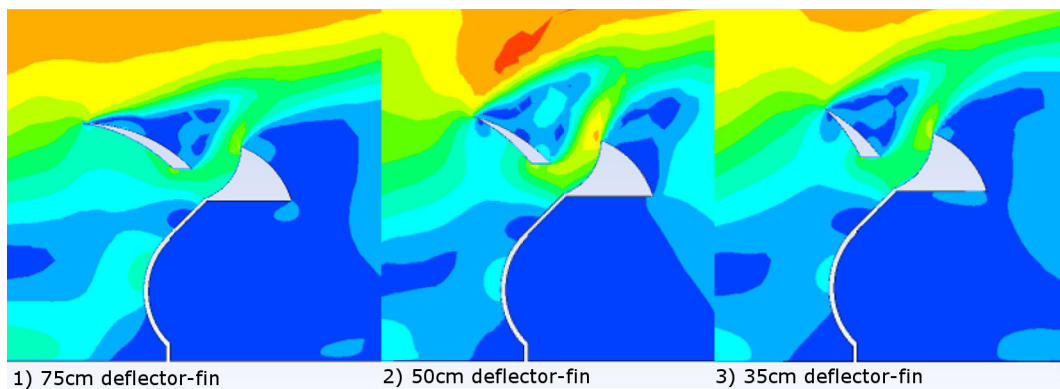
Figure 5.7: 2D vertical visualisations for three different deflectors for the same windbreak screen, using ANSYS CFX. Left: 75 cm deflector. Middle: 50 cm deflector. Right: 35 cm deflector. The visualisation is a 2D wind flow shows the separation zone produced on the top of a deflector fin that has a concave curvature. Wind speed in the inlet region: 6 m/s. (Source: author)

Mini airflow tunnel visualisation

Using the low-tech airflow tunnel, I ran several experiments with the erosion technique to visualise the effects of vertical deflection. These physical experiments showed the barrier working with a (convex) deflector fin which increased the vertical deflection of wind, as was expected. In the following three experiments the deflector was installed in two different positions that produce a vertical upward deflection. In general, the results showed a more vertical effect in the third experiment. These experiments reinforce the idea that the fin generates a low pressure region at the top of the barrier, increasing the suction of the airflow through the slot aperture (Figure 5.8).
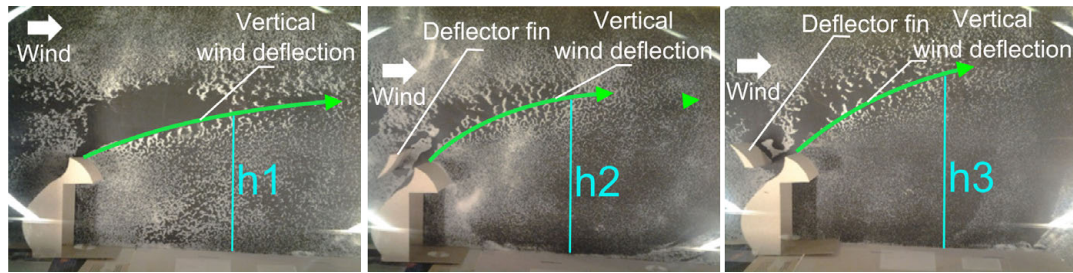
Figure 5.8: 2D visualisations of the vertical wind deflection produced by a barrier with a concave fin, in the mini airflow tunnel, with erosion test. The test shows different deflection heights (h1, h2, h3). Left: barrier without deflector. Middle: barrier with a small deflector fin. Right: barrier with a concave deflector. The erosion patterns show that the effect of vertical wind deflection is more pronounced in the third case. (Source: author)

5.3 Screen with multiple deflector fins

With the idea of testing a windbreak with multiples deflectors, I designed some profiles of screens to generate this effect with several deflector fins integrated at the leeward side of a barrier with gaps that should generate an upward wind flow. This was an exploration for 2D visualisation that was tested with a porosity and non-porosity condition. The original idea was to build a physical model as a final version, for testing in the industrial wind tunnel with an ABL wind flow.

The screen with multiple deflector fins was developed as a simple profile with a duct formed by an accelerator section and a curved deflector. This geometry was repeated vertically, until a barrier of 1.6 m height was created (Figure 5.9).
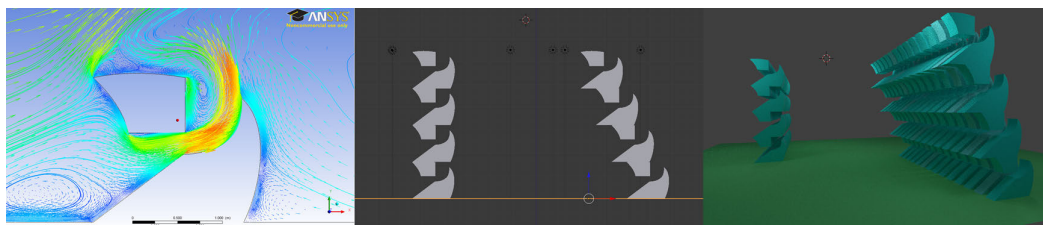
Figure 5.9: Left: 2D visualisation of accelerated airflow in a barrier with a curved deflector at leeward side. 2D wind flow simulated in ANSYS CFX. Middle: configurations of a barrier with several deflectors at the leeward side of the barrier. Right: possible 3D screen with this configuration of wind deflectors. (Source: author)

After designing a preliminary concept, different versions were developed as 3D structures, based on a folded and cut sheet of metal. However, only two of the first versions were tested with rapid wind visualisation (Figure 5.10).
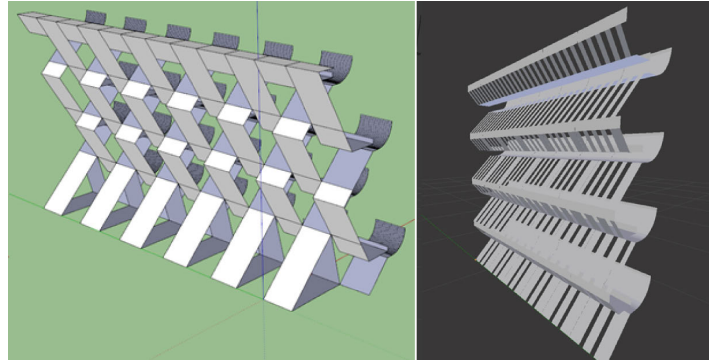
Figure 5.10: Development of two versions for the screen with multiple deflectors at the leeward side. Left: barrier with a slope. Right: vertical barrier with high porosity. (Source: author)

Rapid CFD visualisation tests

To analyse these design concepts of barriers, a group of CFD tests was conducted using Vasari, ODS-Studio and ANSYS CFX with 2D simulation models. The intention was to see the wind movement on each deflector fin and the vertical wind deflection produced by the barrier.

The barriers were 1.6 m high, modelled in full scale in the programs. The parameters for the test in Vasari were similar to previous experiments. A wind speed of 5 m/s without ABL condition in the wind flow was considered. On the other hand, ODS-Studio neearly design stage a few general control parameters set up for mesh generation and simulation. The wind speed was fixed to 5m/s and the ABL was omitted. Finally, the Open-FOAM simulation models were SimpleFOAM with RAS and standard k-epsilon turbulence model (Figure 5.11).

	Model	Wind speed	ABL	Digital mesh	Turb. Model	Validation method
ODS-Studio	Barrier 1.6 m height	5m/s - 10m/s at 2m height	NO	2D domain Cells= 300732 Points=305378	RANS - standard K-epsilon	NO
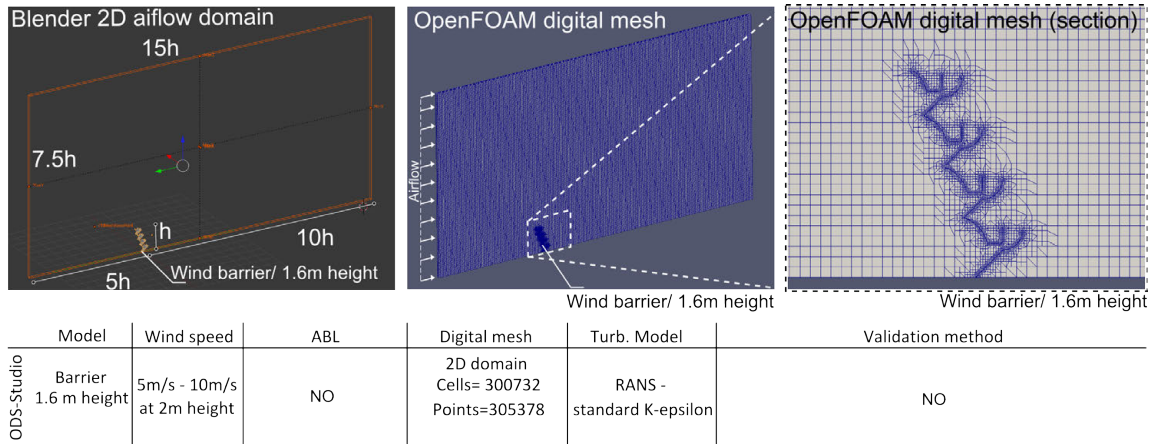
Figure 5.11: Digital domain set up of the experiments for the CFD-PST ODS-Studio. Left: the 2D domain in Blender. Middle: digital mesh generated with OpenFOAM. The Digital mesh has 300732 cells and 305378 points. This part of the process was quickly resolved. Right: section of the digital mesh with the barrier. (Source: author)

The visualisation with Vasari showed the wind pattern of a flow passing through the barrier without any vertical deflection and a strange wake region of high wind speed at the ground, behind the barrier. In general, the visualisation showed such a strange effect from the wind passing through the barrier that it was considered a non-reliable visualisation (Figure 5.12).
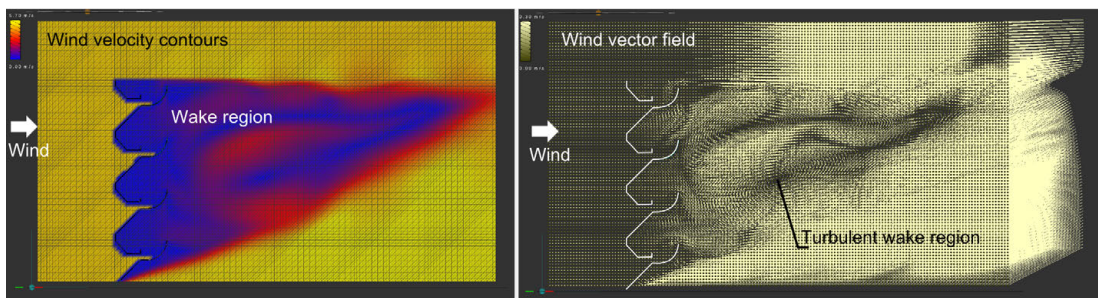
Figure 5.12: Vertical 2D visualisation windbreak screen with multiple deflectors at the leeward side. Display of wind speed patterns and vector field patterns, using CFD Vasari. Left: visualisation of wind speed regions and wake region behind the screen. Right: visualisation of vector field. In both cases, is a simulation of 2D wind flow, and the result is confused (the wake region is very small). In addition, the turbulence level produce by this barrier configuration (porous) might require additional parameters that Vasari does not consider, such as the Reynolds number (Re) of the flow. Simulation with wind speed in the inlet region: 5 m/s. (Source: author)

In contrast, the second group of visualisations was performed using ODS-Studio with a similar geometry of a non-porous and a porous screen. The results were very different from the Vasari output. For the first case, the visualisation shows a vertical deflection from the barrier, and a vortex of airflow on each fin of the screen. Also, the vertical movement of the airflow passing through the barrier gaps was observed. On the other hand, with a screen with a porosity condition, the wind flow passed through the barrier without any vertical deflection of vortex between the fins, and with a wake region more extended behind the barrier (Figure 5.13).
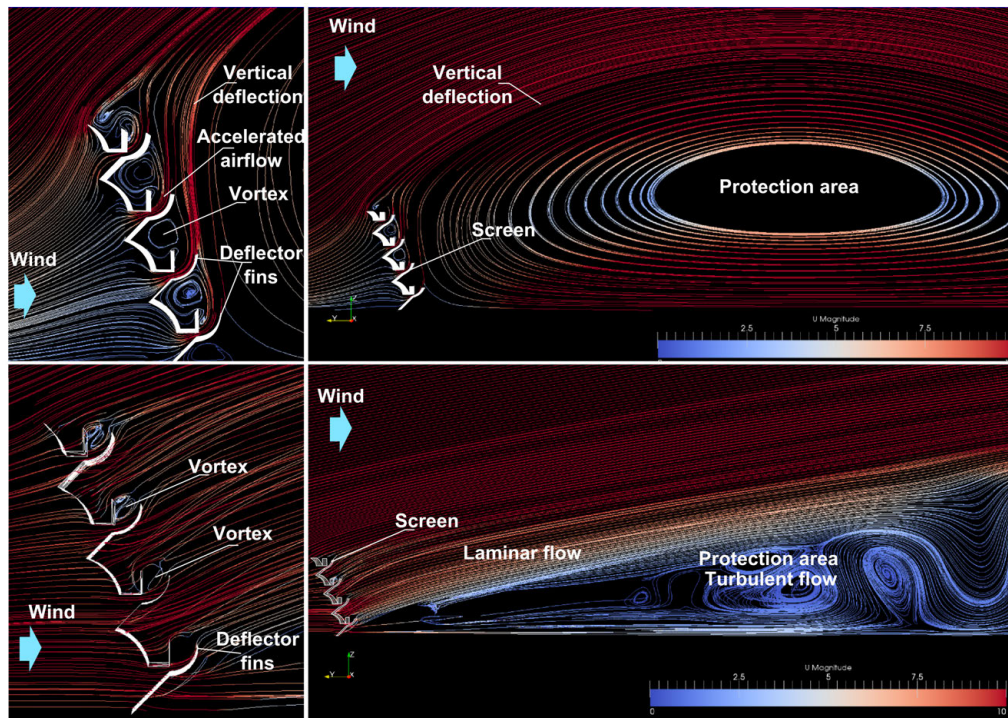
Figure 5.13: Vertical 2D visualisation windbreak with multiple deflectors at the leeward side, using a 2D wind flow simulation in ODS-Studio. Top row: visualisation of vortex in the deflectors and behind produced by the barrier with non-porous surfaces. Bottom row: visualisation of mitigation region produced behind a barrier with porous surfaces. Wind speed in the inlet region: 10 m/s. (Source: author)

Moreover, a CFD test with ANSYS CFX was conducted to see the wind protection produced by this kind of screen, by visualising the regions of wind speed at the leeward side of the barrier. With a 2D digital mesh, similar to the previous experiments, I ran a simulation with a wind speed of 6 m/s at 1.5 m high. ANSYS allows the inclusion of more

parameters in the test. Thus, a boundary condition was recreated increasing the roughness
of the ground in the mesh. The results showed that in the area behind the barrier, the
wind velocity at the head level was between 4.3 and 5.1 m/s. This is a protection factor
of 0.7, which I considered as not very good (discomfort level = 5 m/s) (Figure 5.14).
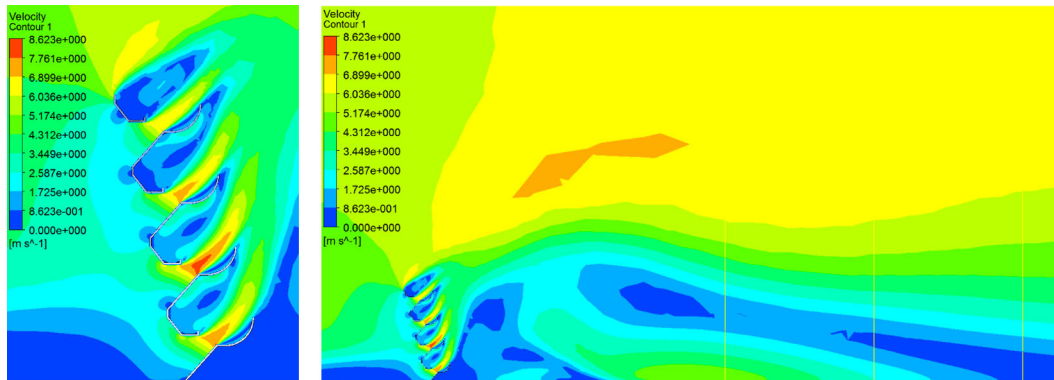
Figure 5.14: 2D visualisation wind speed regions around a barrier with deflectors at the
leeward side, using a 2D wind flow in ANSYS CFX. The observation of the wind speed
patterns and the vertical deflection behind the barrier is similar to the ODS-Studio. Wind
speed in the inlet region: 6 m/s. (Source: author)

The final step of these experiments was to choose a design for this barrier to build a
3D model and test it in the industrial wind tunnel with an ABL condition of wind. The
model was built to 1:10 scale (Figure 5.15). However, this last step in the wind tunnel was
discarded because the strategy of this deflector barrier with multiple fins did not produce
a clear improvement in the mitigation factor of the wind speed (the small fins does not
deflect vertically the wind. For a more complete analysis see section 5.5 on page 145).
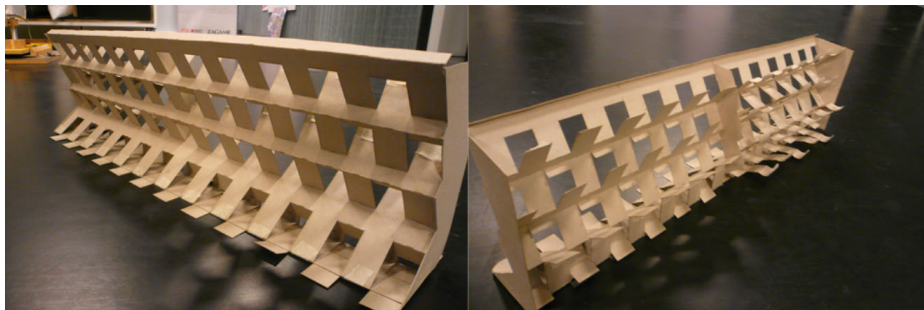
Figure 5.15: Multiple deflector barrier. Model 1:10 scale to be tested in the industrial wind
tunnel. This design with deflectors at the leeward side was elaborated from the previous
observations with CFD visualisations. Finally, the concept was discarded because of
changes in the strategy of design. (Source: author)

5.4   Curved screen with aerodynamic slot

As a final stage of this investigation, the screen concepts were designed with geometries more similar to membrane morphologies. The wind behaviour is different around an irregular curved surface of a screen, with fewer areas of separation of wind flow (see first investigation with a building of irregular form). Thus, using flexible membranes and meshes to produce different forms, curvatures and gaps, I developed 3D designs for these windbreak screens. These screen morphologies can be studied with rapid wind visualisation to understand their performance for further development of windbreaks with flexible fabrics or tensile membranes (to be installed in pedestrian areas). However, this approach has an additional difficulty, because regular geometries of a body produce more uniform flow patterns around, while, irregular forms tend to produce unpredictable flow patterns.

The concept of a membrane is very abstract. These explorations aimed to define an idea of a membrane for a particular context and scale; a footpath of 4 m width and a screen of 1.6 m height. The exploration of geometrical surfaces had two lines: in the first one, physical models were developed in a process of form-finding, being manipulated and embedded into resins and plaster to fix their geometrical properties into a solid surface. They were focused on single features: as aerodynamic slot, deflector surface and porosity. After that process, for the second line some of them were chosen to develop digital models to conduct rapid wind visualisation experiments. These models were only geometrical concepts, without a practical application, materiality or structural design.

Rapid CFD visualisation for screen with multiple folds

The first concept of a screen with membrane morphology was a surface with folds. Using a tight elastic mesh I tried to stretch and bend it with a wire frame to produce a surface with several folds. Once the surface was defined, I applied polyester resin to solidify the mesh (Figure 5.16). The idea was to reduce the vortex effect produced by the wind at the bottom of a solid planar wall surface and the lateral wind deflection. This concept of screen with folds was digitally replicated to visualise the effects of a wind flow on these

surfaces with a rapid CFD visualisation.
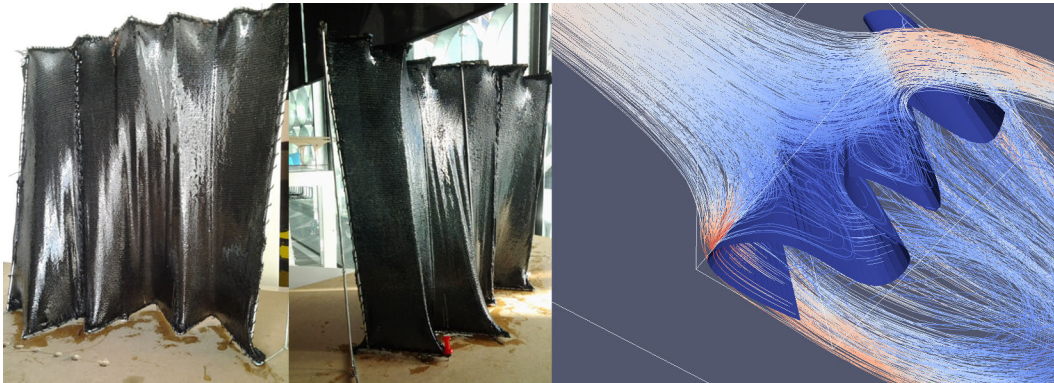
Figure 5.16: Left and middle: Concept of elastic membrane embedded with polyester resin to produce a light and solid screen with multiple curves or vertical folds. Right: 3D wind visualisation of a digital model of the screen with vertical folds tested with ODS-Studio. The aim was to analyse the lateral deflection of the wind with a windbreak screen, using a design of membrane with vertical folds. (Source: author)

For the test with CFD visualisation, the wind conditions considered a velocity of 5 m/s as parameter of discomfort; the ground had a roughness to generate a friction and an ABL effect necessary to reproduce important wind phenomenon, such as the Horseshoe Vortex System (Cook 1990). The turbulence intensity and other obstacles were omitted. To have a point of comparison and validation of the visualisation, I run a previous rapid visualisation with a normal flat wall. The software used for the tests were ODS-Studio for preliminary CFD simulation and Paraview for visualisation of data (Figure 5.17).

In the rapid CFD-PST visualisations of this screen model, I observed that these topologies of folds had a similar area of wind influence to a flat wall. This means that multiple folds aerodynamically work as a massive screen, producing a wide vortex region at the front of the screen. In addition, the leeward side of the barrier showed an irregular area eddy. I thought that the protection region behind a windbreak with this surface would be less extended and unstable (Figure 5.18) than a flat and regular screen.

	Model	Wind speed	ABL	Digital mesh	Turb. Model	Validation method
ODS-Studio	Barrier 1.6 m height	5m/s - 10m/s at 2m height	Ground roughness to produce BL	3D domain Cells= 1593242 Points=1046322	RANS - standard K-epsilon	NO
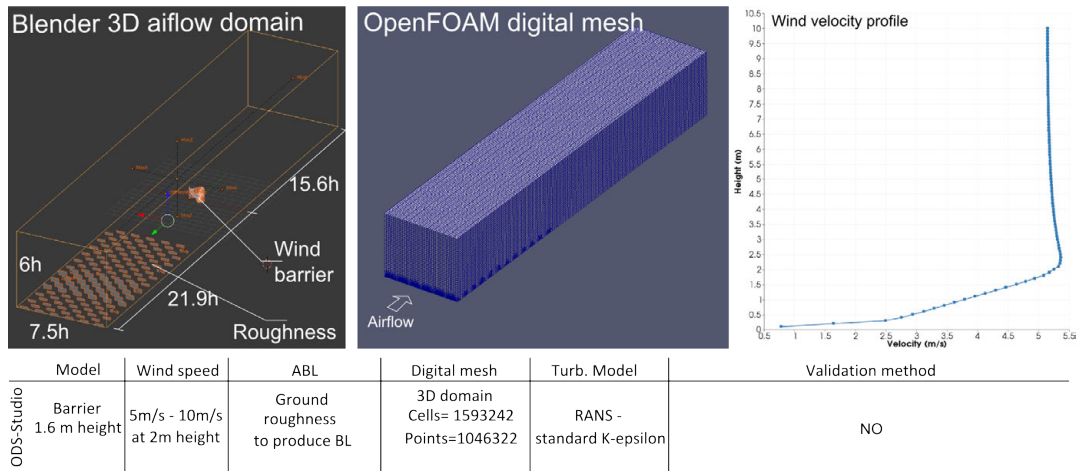
Figure 5.17: Flow domain set up of ODS-Studio for rapid visualisation. For this case, the rapid visualisation considered incorporating an (imprecise) ABL effect as wind condition of the airflow. Left: 3D digital domain to test the screen. To generate a relative boundary layer effect of the wind flow some roughness was included at the front of the model. Middle: digital mesh generated with OpenFOAM: 1593242 cells and 1046322 points. This step was easy to complete in the process to generate a rapid visualisation. Right: wind velocity profile in the flow domain with a decreasing velocity near ground. (Source: author)
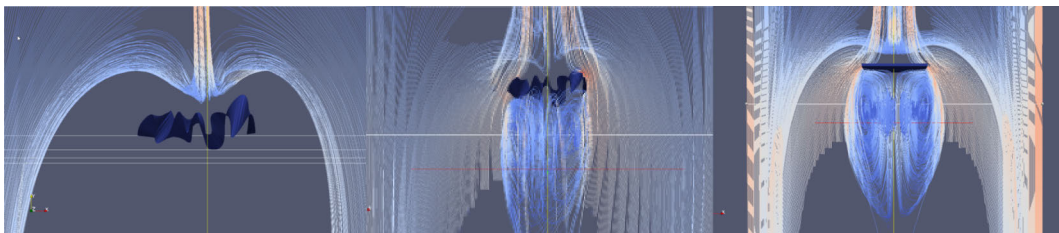
Figure 5.18: CFD visualisations of the horizontal deflection of wind around a screen with form of membrane and multiple folds, using ODS-Studio. Left: a folded surface and influence area of wind around the screen model. Middle: fold surface and influence area of wind at 1.5 m height. Right: flat wall and visualisation of the area of influence. This test allows a comparison point and validation of the parameters set up for the ODS-Studio visualisations. It is possible to observe that the differences are not very significant with the normal flat wall. (Source: author)

Rapid CFD visualisation for screen with double curvature

Another screen model explored is a surface with simple double curvature to produce a high and low horizontal and vertical wind deflection at the same time. The idea was to mitigate the lateral wind deflection on the footpath. A physical model of this surface was built with a straw mesh embedded in plaster to be used in wind tunnel experiments (Figure 5.19).
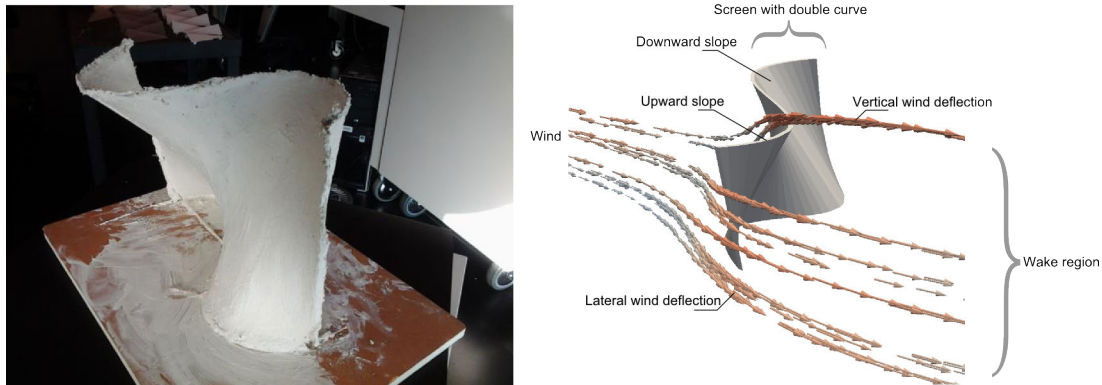
Figure 5.19: Study for a membrane with double curve. The aim is to explore geometries of curved membranes to mitigate lateral deflections of the wind flow. Left: straw mesh embedded with plaster to produce a solid surface with double curve. Right: diagram showing the vertical and lateral deflections of wind around this screen. (Source: author)

The first digital model for this screen was a non-porous surface. The aim is to visualise the two effects of deflection (horizontal and vertical). The screen size was 1.6 m high and 4.0 m long. For the rapid CFD visualisation with ANSYS CFX, the flow domain had a geometry of a channel, similar to a street configuration, and the screen was installed at 3 m near one of the walls, in the area of the footpath (Figure 5.20). The conditions of the wind flow considered ground roughness of 5 mm, and an ABL effect, with 5 m/s wind velocity at 1.5 m height and 5% of turbulence intensity. Other parameters were omitted to facilitate the rapid visualisation.
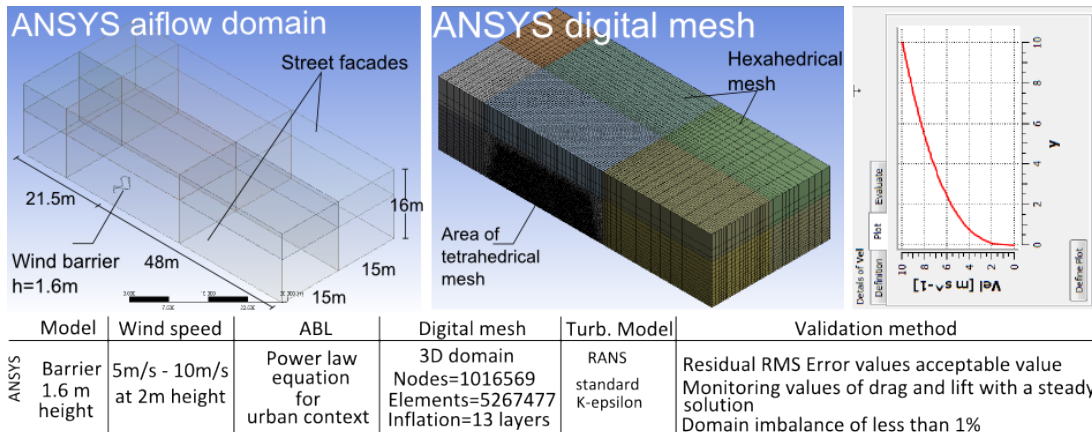
Figure 5.20: Parameters for a rapid visualisation with CFD ANSYS: the flow domain is simplified as a 3D geometry of a channel (street). Digital mesh has 13 layers of inflation, 1016569 nodes and 5267477 elements. In addition, there is ground roughness of 5 mm to produce an ABL airflow, with 5 m/s wind velocity at 1.6 m height and 5% of turbulence intensity. Left: geometry of the flow domain simulating the dimensions of a street. Middle: digital mesh created in ANSYS. This step was the most complicated in the process to generate a rapid visualisation. It required a long time to complete. Right: wind velocity profile for inlet zone. (Source: author)

The tests of rapid visualisation showed that the curvature of the screen with upward slope does not produce a vertical deflection. In contrast, the concave curvature at the bottom of the screen (following the wind direction) produces horizontal accelerations at the head level (1.5 m). Additionally, the wake region behind the screen has irregular boundaries with a region of high wind velocity. This condition means that the protection area probably is smaller than a flat screen of similar size. Moreover, the lateral wind deflection is apparently similar in both sides (Figure 5.21). This means that the double curvature screen will not mitigate the wind intensity at the footpath level, near the screen.

Moreover, a lateral visualisation with ODS-Studio and Paraview, using a filter of streamlines, shows that the protected region, behind the screen, is smaller than a flat screen, and the height of this wake region is more irregular for the curved screen than for a flat screen (Figure 5.22).

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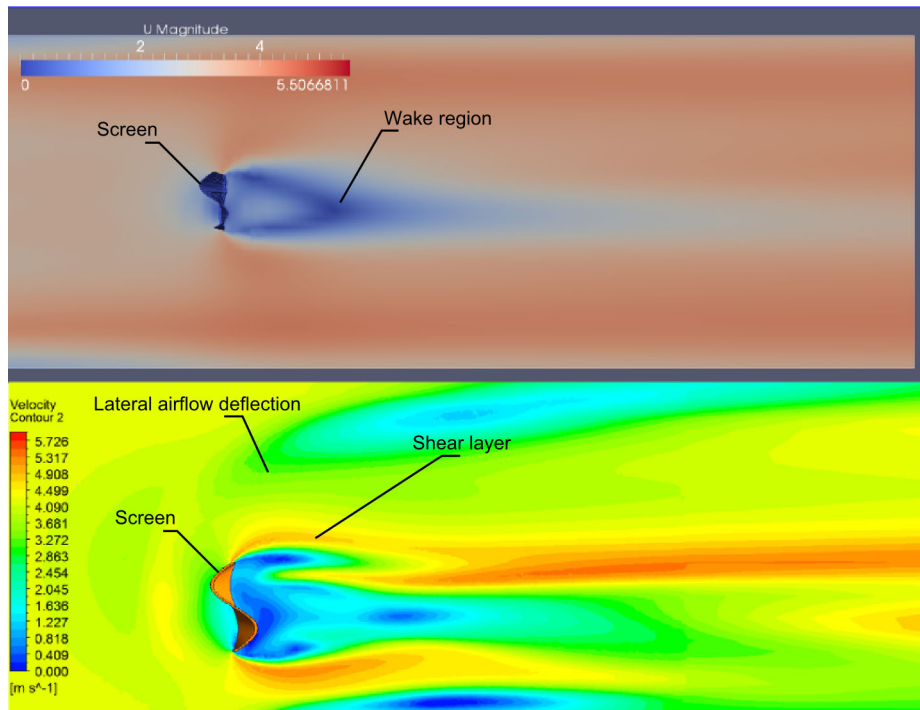
Figure 5.21: Comparison between horizontal rapid visualisations of the wake region and lateral wind deflections. Top: rapid visualisation of wake region behind the screens with double curvature with ODS-Studio and Paraview. Bottom: rapid visualisation of wake region behind the screens with double curvature, generated with ANSYS CFX. Both cases show small protection regions and strong lateral wind deflections. (Source: author)
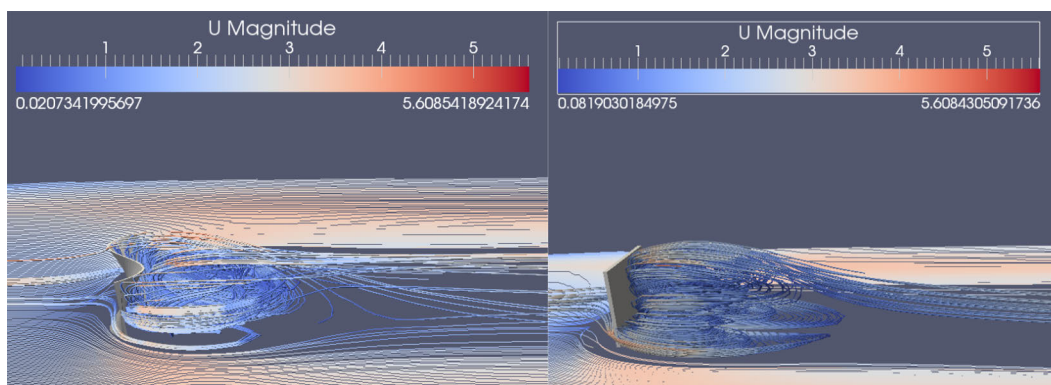
Figure 5.22: Rapid 3D visualisations of elevated vortex pair behind a windbreak screen of $2\,m \times 2\,m$, with ODS-Studio and Paraview. Left: rapid CFD visualisation of a double curved screen. Right: rapid CFD visualisation of a flat screen wake region. Both wake regions are similar on their area. (Source: author)

Another experiment studied was the differences between a porous curved screen with an opaque curved screen (the porosity of the screen, for this case, was 25% density). The

parameters of these experiments were the same than previous experiments. One observation is the absence of elevated vortex pair at the leeward side of the porous screen. Besides, porosity reduces the vortex intensities in the front and back of the barrier and avoids the drag of particles from the ground (Figure 5.23). However, the literature mentions that any pattern of porosity or form of screen will produce a similar effect of mitigation than a thin and flat porous screen (Gandemer 1979). Thus, for a more significant control of the wind flow a different approach is required, with aerodynamic features integrated in the screens.
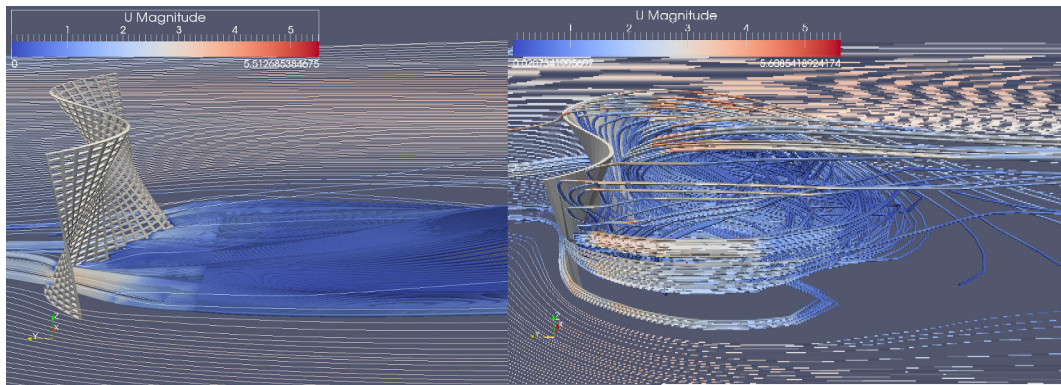
Figure 5.23: 3D visualisations of elevated vortex pair behind a windbreak screen of $2\ m \times 2\ m$ and double curvature, with ODS-Studio and Paraview. Left: preliminary CFD visualisation of a porous screen's wake region (no vortex). Right: preliminary CFD visualisation of a non-porous screen's wake region (with vortex). The first case shows a less turbulence and a larger projection of the wake region than the second case. (Source: author)

Another alternative tested was a curved screen with a partial porous surface at the bottom, to facilitate a ventilation that should extend the eddies in the protection region. This could increase the area of protection. Ventilation of the base has been mentioned in Gandemer's studies as an aerodynamic feature to increase the protection region behind the screen (Figure 5.24).

Finally, the performance of these three models of screens (non-porous screen, semi-porous screen and porous screen) to vertically deflect the wind flow was compared. The rapid visualisations showed that the full porous screen concept has a larger wake region behind the screen at the side of convex curvature. Moreover, the semi-porous screen concept has a strong vertical wind deflection in the area of the convex curvature (Figure 5.25).
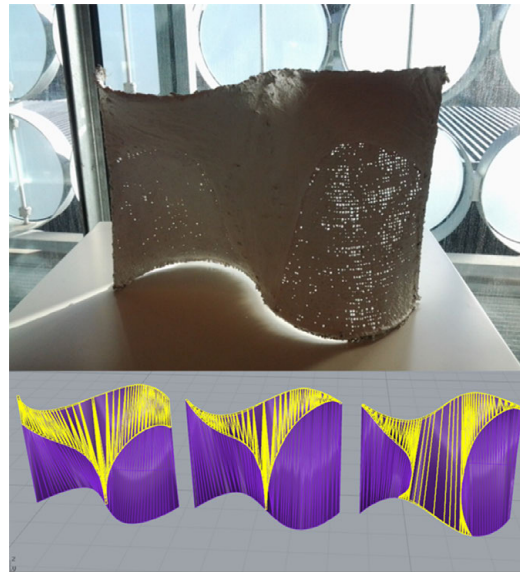
Figure 5.24: Concept of semi-porous screen. One strategy to design a more efficient screen
is to combine the curvature at the top and the porosity as ventilation at the bottom of
the screen. In the image, different configurations for porous regions of ventilation in the
screen with double curvature. (Source: author)
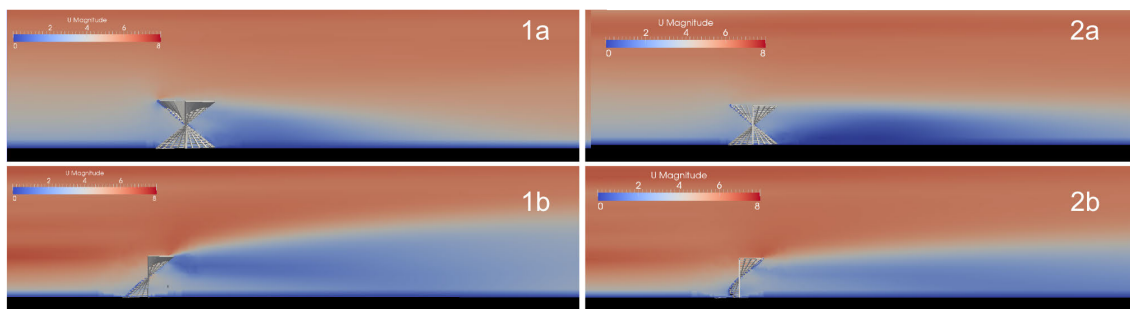
Figure 5.25: Rapid visualisations of vertical wind deflection and wake region behind two
models of porous screen, generated with ODS-Studio and Paraview. Left column: 1a)
wake region produced at the downward slope side of the semi-porous screen. 1b) wake
region produced at the upward slope side of the semi-porous screen. Right column: 2a)
wake region produced at the downward slope side of the porous screen. 2b) wake region
produced at the upward slope side of the porous screen (source: author). The analysis
shows that semi porous is more efficient to vertically deflect the wind only if the screen
has an upward slope (1b, 2b).

Curved screen with aerodynamic slot

An additional aerodynamic feature proposed was a screen with an aerodynamic slot. Using
straw mesh I started to adapt shapes to design lateral and upper slots. These slots should
accelerate the deflected wind and increase the vertical wind deflection produced by the

screen. The surfaces were designed to be integrated with one of the previous meshes, with a combination of slots, deflector surfaces and porous screens in a unique structure (Figure 5.26).
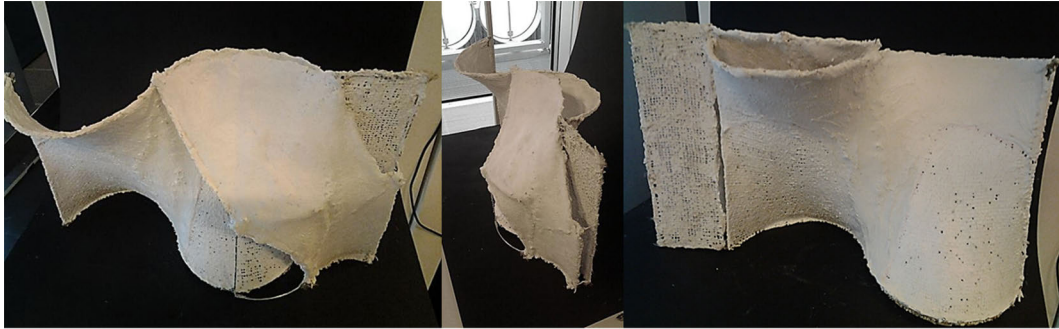
Figure 5.26: Concept of windbreak screen built as a solid surface with slot integrated, deflector surface and a porous screen. These designs were not tested because the investigation focused on analysis of more regular and simple geometries for the screens, in this stage. (Source: author)

However, the general observation about these designs is the strong difficulty to make a comparative evaluation of them. The irregular forms produced irregular and unpredictable wind flow patterns, making it difficult to compare and evaluate. For that reason, the analysis of these concepts of screens was stopped. I chose to conduct tests with more simple geometries that can be easily observed with rapid wind visualisation and physical tests in a wind tunnel.

5.5   Comparison and results between three screens

During the process of exploration I had several doubts about the real efficiency of this windbreak screen concepts, especially the screen with multiple deflector fins. The rapid visualisation exercises showed that apparently, with these designs, the effect of deflection for the upward wind flow was not significantly improved. Moreover, I wanted to know what level of protection was generated by the barrier, and compare this level with other barriers, such as a normal flat windbreak wall. Thus, at the end of this stage, I ran a rapid visualisation for a comparison of these models, using the software CFD ANSYS

CFX to get a more accurate evaluation. To facilitate the visualisation the experiments were prepared with only 2D digital meshes, for a bi-dimensional visualisation, using the parameters from previous experiments.

These simulations were conducted with three models of windbreak screen: a simple non-porous wall, a screen with multiple deflector fins and a screen with a single big deflector fin. The velocity considered for the tests was 5 m/s. Additional parameters, included for this experiment, were a parabolic wind velocity profile (ABL) and friction effect at the ground level. The experiment measured four marks to evaluate the size of the protection region behind the barrier and the wind intensity. The distance from each mark to the next was equal to the height of the screen: 1.6 m (Figure 5.27).
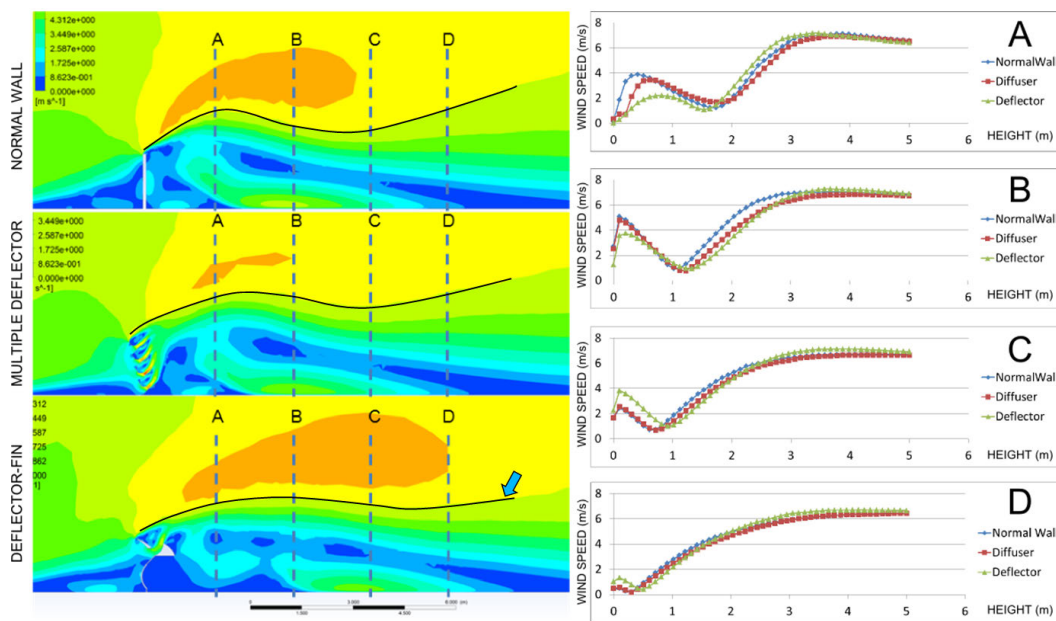
Figure 5.27: Comparison of wind intensity at four points behind three different barrier models, to know their performance to produce a protection region with low speed wind. Left: the diagram shows rapid visualisations of wind speed patterns for a simple wall, a barrier with multiple deflector fins and a barrier with single deflector fin. There is a difference with the height of this protection region between the point A and D, being the barrier with deflector fin the more efficient to produce an extended protection region. Right: the analysis of the wind speed shows that the conditions of wind speed are quite similar for each point. However, the last case shows the lower wind velocity. (Source: author)

The comparison between the simulation of the flat wall (first screen) and the screen with multiple fins (second screen) showed a strong similarity in the leeward region. Even,

the contours of wind speed regions, in both visualisations, had similar patterns. This probably means that the multiple-deflector fins work more similarly to the opaque wall rather than to a porous screen. Another observation was the profile of the wind deflection produced for both barriers. An accurate comparison of velocity profiles with the marks behind both screens shows a very similar curvature of wind velocity and height of the airflow, with a slight deviation in the first mark (A) which is graphically represented in by the curves in the chart. On the other hand, the vortex regions at the front of each screen have some differences. The second screen was more efficient to mitigate the downwash effect of the wind flow (vortex) at the bottom of the screen. For that reason probably, lateral wind deflections were not significant with this concept of screen. However, this particular effect does not have relevance for the original intention of a windbreak screen that increases the vertical deflector of wind.

Finally, the third screen showed a different pattern of protection region, with low speed flow at the ground level and a large curvature of vertical deflection. The results of wind velocity profiles, measured behind the screen, are very similar to the rest of the barriers, as can be seen in the charts, but the third barrier presents the lowest wind velocity at mark A. This means a poor wind mitigation effect but evidence that a deflector fin at the windward side is the best strategy. This means that the acceleration of the deflector and slot, in a screen of 1.6 m height, can increase the protection region behind the screen.

In summary, these screen concepts showed a low capacity to increase the upward wind flow, with the vertical deflection effect, further than a normal wall. But some differences are observed with a rapid visualisation. In the third case, I think that the deflector fin is too small to produce a more significant separation zone to improve the vertical deflection of the airflow. For these reasons I decided to change the perspective based on these models of screens and developed a different approach. This new approach considered a more defined urban context, a strategy with more screens and larger features and more defined wind conditions.

5.6 Summary

Through these experiments I evaluate several tools for rapid wind visualisation, studying several designs of windbreak screens, with slots and deflectors to produce a vertical wind flow deflection. As I explained at the beginning of this chapter, the aim for these rapid visualisation tests was to observe wind flow through the gaps and around windbreak structures more complex than regular building closed forms. The evaluation of CFD-PST and CFD programs to visualise these wind phenomena is gathered in the next table (Table 5.2).

2D visualisation of windbreak models with single deflector fin					
	Vasari	ODS-Studio	ANSYS	Mini AT	Incidence in EDS
Visualisation vertical variation of wind deflection	yes	n/a	yes	yes	• Identification of separation zone at the top of fin as condition to select best alternative of feature
Visualisation of protection region changes	yes	n/a	yes	no	• Selection of deflector associated to more stable protection region
Visualisation of air flow acceleration through slots	yes	n/a	yes	no	• Definition of position and dimension of deflector fin
2D visualisation of windbreak models with multiple deflector fins					
	Vasari	ODS-Studio	ANSYS	Mini AT	Incidence in EDS
Visualisation vertical variation of wind deflection	no	yes	yes	n/a	• Comparison and discard with other alternatives of screens
Visualisation of protection region changes	no	yes	yes	n/a	• Comparison and discard with other alternatives of screens
Visualisation of air flow acceleration through slots	no	yes	yes	n/a	• Multiple fins at leeward side of barrier is discarded because do not increase the total vertical wind deflection.
3D visualisation of windbreak models with curved screen					
	Vasari	ODS-Studio	ANSYS	Mini AT	Incidence in EDS
Visualisation vertical variation of wind deflection	n/a	yes	yes	n/a	• Curvature with slope discarded because produces low vertical airflow deflection
Visualisation of protection region changes	n/a	yes	yes	n/a	• Strategy of semi-porous surfaces incorporated in the screen to increase protection zone
Visualisation of air flow acceleration through slots	n/a	n/a	n/a	n/a	

Table 5.2: Table with results of evaluation test for wind visualisation techniques and impacts in the early design stage of a windbreak barrier. The evaluation shows that the rapid visualisation with CFD-PST Vasari and the mini airflow tunnel were efficient for the observation of wind effects from windbreak model with a single deflector fin as main aerodynamic feature, but it was not enough for the observation of a screen with multiple deflectors and porous surface as main aerodynamic design features. For those windbreak concepts using multiple and complex design features the ODS-Studio and ANSYS CFX were more suitable tools than Vasari. Finally, these rapid visualisation exercises led me to discard the alternatives of multiples fins and the double-curved screen for the idea of a windbreak screen with a single deflector fin.

Therefore, the main points observed in this investigation were:

- The first phenomenon that I visualised was the effect of wind deflection observed in

concepts of windbreak screens with a deflector fin. Using a 2D visualisation with Vasari and ANSYS CFX, the phenomena were clearly observed as an accelerated layer of air passing through a slot at the top of the screen. In addition, the effect was visualised using a mini airflow tunnel with the visualisation technique of erosion of particles.

- The second aspect is that the rapid visualisation of Vasari allows me to observe the separation zone at the top of the deflector fin as one of the mechanisms that increase the vertical wind deflection. When this separation is produced, a region of low pressure is generated in the outlet of the slot and the air passing through the slot is vertically deflected. Thus, the position of the fin and the angle of the attack are very important to produce this effect. The consequence of these observations was to choose this barrier configuration as the best to continue further exploration in the next investigation.

- In the case of the 2D visualisation of a screen with multiple deflector fins and gaps, the CFD-PST did not perform a reliable visualisation. The airflow movements on the group of fins were missing and the patterns of wind behind the screen were unexpected in Vasari, probably because the visualisation included many movement patterns, the structures was too thin and with small details and the grid had a low density (a high density produced a crash in the program). In contrast, with ODS-Studio and ANSYS CFX it was possible to generate a rapid visualisation of the phenomena of vortex on each fin and the patterns of wind movement passing through the barrier with gaps and fins. In addition, with ODS-Studio it was possible to see the differences in the wake region produced for a porous and non-porous barrier.

- For the third experiment of rapid visualisation, using two of the techniques (ODS-Studio and ANSYS CFX), I tested several alternatives of a 3D model of a screen with double curvature. Through several modifications I visualised the different patterns of wind movement in the wake region, behind the screen. I tried to see if the folds of the surface change the normal patterns of deflection and separation zones around the barrier. The main observation was that a curved surface of a non-porous screen

produces an irregular and small wake region behind the barrier. These observations
are useful to understand the possible wind effects using screens with forms based
on flexible membranes. Another observation was the good performance of a semi-
porous screen with a non-porous border at the top, which increased the vertical
deflection of the wind at the protection zone.

- From the point of view of design evaluation, I compared the two models of barriers
  to produce vertical wind deflections: the single deflector fin and the barrier with
  multiple fins. Through a rapid visualisation conducted in ANSYS CFX, I compared
  the differences in the wake regions between these designs and a wake region produced
  by a flat, normal wall. The results indicated that the barrier with single deflector
  fin produced a larger wake region behind the barrier and both barriers with fins
  generate a more extended vertical wind deflection than a normal non-porous wall.

- Finally, for these preliminary experiments, using CFD-PST Vasari it was possible
  to run reliable rapid wind visualisation for screens with simple geometries (single
  deflector fin), but not for thin and porous screens (multiple deflectors fins). This
  issue was related with the low control of the domain digital grid (coarse grid). On
  the other hand, ODS-Studio, worked with a more refined digital grid and several
  meshes with a high level of tolerance, with a facility to exchange digital models with
  other programs and with an adaptation of roughness to produce an approximate
  ABL effect. This capability was useful for a quick visualisation of potential designs
  and variation of the mesh morphology with more wind parameters involved in the
  experiment. From regular geometries to more complex membranes forms, these
  rapid visualisations gave a complete idea about the possible wind effects produced
  by the changes and modifications in the design of the screens.

5.7   Conclusion

This chapter has presented several experiments of rapid wind visualisation, conducted
with digital and physical techniques, to observe aerodynamic phenomena around complex

designs of screens. The intention was to analyse the performance of CFD-PST programs with tasks different to those for which originally they were designed (outdoor wind movement around closed building forms).

One of the conclusions from this investigation is the unreliable performance of Vasari to visualise the phenomena associated with a barrier with multiple gaps, thin shapes and several deflector fins, due to the low quality of the digital grid. However, with more simple geometries, it was useful to visualise a wind effect to increase the protection region behind a barrier (vertical wind deflection) and to analyse the possible aerodynamic mechanism of this phenomenon (separation zone at the top of the deflector fin). These studies will be developed in a new investigation, in the next part of this research.

The structure of the workflow to use rapid wind visualisation with these programs Vasari, ODS-Studio, ANSYS CFX each supporting the areas where the other could not present a reliable visualisation (Vasari with single deflector fin and ODS-Studio with porous screens), was efficient to visualise aerodynamic aspects of an exploration of possible design configurations for a pedestrian windbreak. This method of work supported the definition of a strategy of windbreak design based on single deflector fin, slots and generation of separation zones. Moreover, the process gave arguments to discard other alternatives (multiple fins).

Finally, I concluded that it is necessary to develop the concept of a pedestrian windbreak based on a single deflector fin associated to separation zones to generate larger protection regions. This study of aerodynamic features in a windbreak screen is addressed in the next investigation project, which presents an evolution design of screens as an urban windbreak shelter.

The next chapter will present the last investigation with an evolved strategy of windbreak screen design that increases the protection region in a shelter configuration for a tram stop in the city. Using rapid wind visualisation, I will test adaptations of parallel and more complex screens with different aerodynamic features.

CHAPTER 6 █

Fourth investigation: wind analysis for an urban shelter concept with screens and membranes

6.1 Introduction

This chapter develops the investigation to evaluate CFD-PST (computational fluid dynamics - performance sketch tools) and other techniques for rapid visualisation of wind flow, through experiments with a configuration of parallel windbreak screens and aerodynamic features (for an urban shelter). In this project I conducted a new group of digital wind visualisations and physical experiments to explore arrangements of these screens, with a design developed from the previous investigation results.

The following sections explain the different elements considered for the study of this project:

- The first part presents the investigation aim and the definition of a hypothetical case, considering an urban space and a wind phenomenon that produces discomfort conditions.

- In the second part, the screens configuration and aerodynamic features selection are described, including the adaptation with regular and irregular geometries, using

membrane morphology and porosity.

- In the next section, digital and physical experiments are presented to visualise the wind dynamics around a group of screens with non-porous surfaces.

- In the fourth section I explain the experiments with more irregular and porous screens geometries. This section includes experiments in an ABL wind tunnel and the collaborative work with a colleague from SIAL to conduct rapid visualisation of quantitative data, during physical experiments in the ABL wind tunnel, at RMIT's Bundoora campus.

The details of all these experiments with visualisation techniques and the Bundoora wind tunnel results have been published in papers for the CAADRIA 2014 conference (Moya Castro et al. 2014c) and eCAADe 2014 conference (Moya Castro et al. 2014a). Copies of these papers can be found in the appendix of this exegesis.

Investigation aim and criterion of evaluation

For this investigation, I addressed the study for a group of design concepts for windbreak screens, through rapid wind visualisation. Based on the observations from the last investigation, the approach of a windbreak for pedestrian areas develops a new version of the previous screen concept with a single deflector fin. In these experiments I work with configurations of several screens for wind protection in a pedestrian area. The investigation explores more complex screen geometries, such as regular and irregular shapes, and porous and non-porous membranes.

Thus, the aim of this investigation was to evaluate CFD-PST and other techniques for rapid visualisation of wind flow through a configuration of parallel windbreak screens, integrating aerodynamic features with regular and irregular forms (membrane morphology). The reason to conduct this final group of experiments was to explore the design hypothesis of vertical wind deflection effect and separation zones produced by aerodynamic features, to increase the extension of a protection zone in a significant area at street level. The

rapid wind visualisation will assist in the study of adaptations of design features (fins and deflectors with new scale, position and purpose).

Criterion of evaluation. The criterion to evaluate the performance of these techniques is based on six requirements. Firstly, a group of requirements that involves functions to facilitate the use by the designer, functions to facilitate the workflow process and the parameters of wind conditions to set up. The second group involves the visualisation of three wind phenomena. Each task is evaluated as "yes" or "no" depending the performance of the tool during these experiments. In addition, the evaluation includes a note about the process: easy or complex to fulfil. Finally, an observation is included about the incidence of these visualisations in the design process.

The experiments of wind visualisation were organised in three groups, and the wind visualisation techniques used were Vasari, ODS-Studio, ANSYS CFX and an ABL wind tunnel (Table 6.1).

Windbreak model	CFD-PST	CFD tool	Physical tool
Windbreak shelter with non-porous regular form	Vasari	ANSYS CFX	ABL W T
Windbreak shelter with non-porous membrane form	Vasari ODS-Studio	ANSYS CFX	ABL W T
Windbreak shelter with porous membrane form			ABL W T

Table 6.1: Table with the techniques used and three groups of tests for rapid wind visualisation, conducted in this investigation.

Urban wind phenomenon, context and parameters

After my first explorations with abstract designs and isolated models in 2D wind flow, I decided to work in the development of these windbreak concepts with more defined parameters, conditions and considering a spatial perspective of the phenomena. This approach included a more specific phenomenon and a more defined pedestrian problem.

A wind comfort study generally requires three types of data: statistical meteorological data; aerodynamic analysis of the site (provided by CFD or wind tunnel data); and a comfort criterion (Blocken 2013). However, much of the information has been simplified

for the purpose of this study and to facilitate the aerodynamic experiments and analysis
with the perspective of a rapid visualisation exercise.

I selected a specific place with an urban wind phenomenon present in the Melbourne
context: a phenomenon caused by some prevalent wind in the Melbourne CBD. The
high wind speed along Swanston St, known as a channel effect, which causes discomfort to
pedestrians (Gandemer et al. 1978, Savory et al. 2004). This is a case of an omnidirectional
wind flow that I take as prevalent wind condition. The spatial configuration of the street
facilitates this kind of wind effect because other airflow directions are not possible or
significant due to the obstruction of buildings along the street. Therefore, it is perfect to
simplify the issue for the further experiments[1] (Figure 6.1).
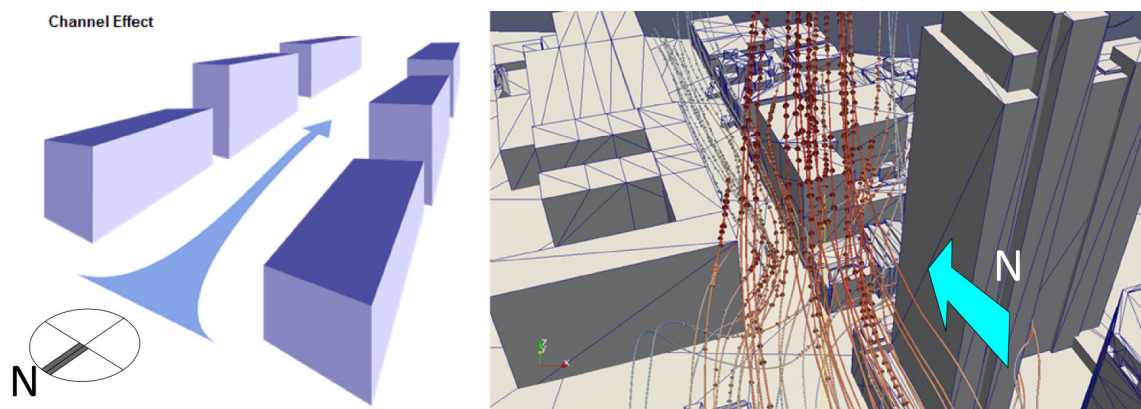
Figure 6.1: Wind discomfort phenomenon in the local context of Melbourne. Left: wind
phenomenon called channel effect produced by the geometrical configuration of a street.
The wind flows and is accelerated along the street producing high levels of discomfort
in the footpaths. Right: preliminary CFD visualisation of the wind in the local area of
Swanston St, using ODS-Studio and Paraview. The south wind flows along the street but
is deflected by the buildings and the corners, producing a channelisation of the airflow
and high levels of wind velocity in the areas of pedestrians (e.g. at a tram stop). (Source:
author)

The weather statistics show a trend of prevalent winds from north to south during
the morning in Melbourne (Bureau of Meteorology 2013), which could be a cause of this
phenomenon (Figure 6.2). On a windy day, with wind blowing from the north, the channel
effect is produced along Swanston St, with more intensity around a tram stop area near
the street's crossroad and corners. There are seasonal variations and changes during the

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[1]For more information about wind analysis in Melbourne, I recommend the paper "wind environments
studies in Australia" by W.H. Melbourne (1978)

day in the wind speed intensity and direction, but to simplify the study, considering that the discomfort issue is caused by the wind coming from the corners of the street to the south, I will consider a wind flow only in one direction (north to south) with a 5 m/s speed as the predominant wind condition.
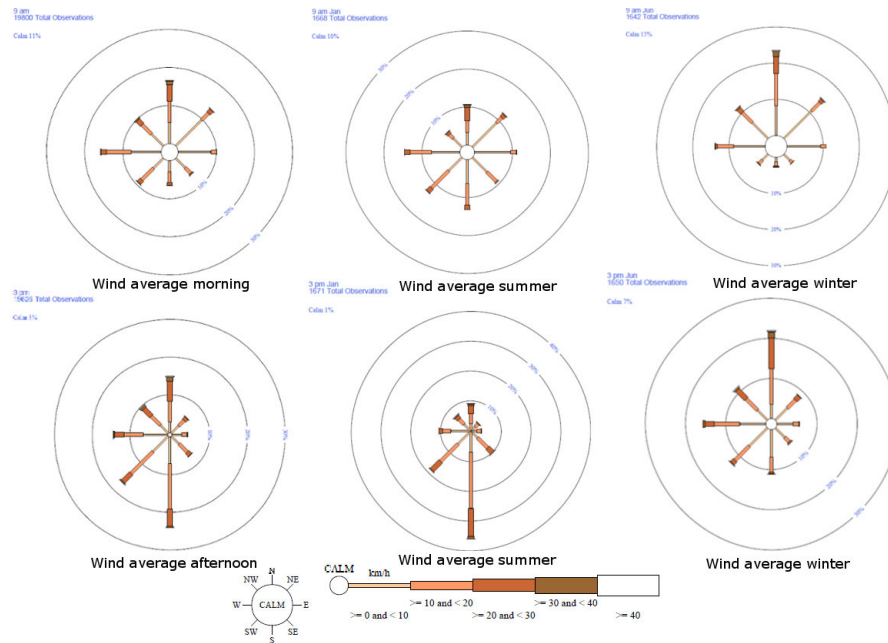
Figure 6.2: Wind roses with wind intensity and direction data of Melbourne. Top row: year wind average at morning, morning wind average in summer and morning wind average in winter. Bottom row: year wind average at afternoon, afternoon wind average in summer and afternoon wind average in winter. (Source: (Bureau of Meteorology 2013))

The local spatial context involves two areas: the street space and a tram stop site. The street runs from south to north, is 30 m wide and includes a tram track of the public transport system. The tram stop is an area of 4.5 m width and 69 m length on the west footpath. It contains urban furniture and two roofs to protect pedestrians while they are waiting for trams (Figure 6.3). This area receives in some moments high wind speearly design stage that can produce levels of discomfort.

In addition, the tram stop in Swanston St is in the vicinity of a group of tall buildings. Rodrigues and Gomes have developed a study to visualise how a group of tall buildings, arranged in a row, increased the channel effect of wind along parallel streets for a regular urban net. This phenomenon increases the discomfort risk (Moret Rodrigues et al. 2003). That effect could be similar to what has happened along this street.

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Figure 6.3: Pedestrian area near crossroad of Swanston St and Franklin St In this site
there is a tram stop with seats and a roof as shelter. In addition, in this area there are
other public spaces such as circulations to the entrance of the university building and a
restaurant. All these people are affected by the wind discomfort when they walk in the
areas of the tram stop. (Source: author)

Here, there is no protection from the wind by the natural foliage of trees, and the

wind flows at ground level with high velocity along the footpath near the corners and the

tram stop (probably intensified by corners of façades), causing discomfort for pedestrians

who are waiting for public transport (Figure 6.4).
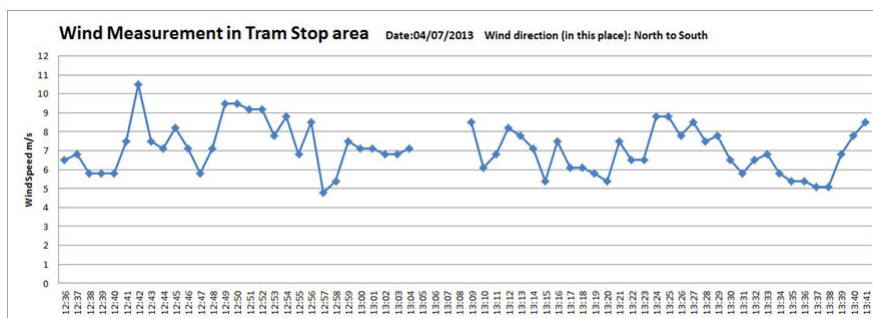
Figure 6.4: The wind speed intensity in this place can reach high level of discomfort. The
chart shows the fluctuation of wind speed in the tram stop area. The information was
collected each minute, with a weather station at 2 m height from the ground. In general,
the velocity of wind is higher than 5 m/s, which is considered a threshold of discomfort.
(Source: author)

This case is a good example of the phenomena of wind that can produce discomfort. The street configuration is a typical space in the city, and this phenomenon is frequently associated with street configurations (Erell et al. 2011). Because of the limitation of instruments, data and time, it is not possible to replicate the real wind conditions of the place for the purpose of these experiments. Therefore, to simplify the parameters of the rapid visualisation, the complexity of this urban context was represented as a simple and regular geometry of a channel with two walls and a floor. The wind flows along the street, without variation or obstacles and the acceleration from corners is omitted.

There are studies that modernise the original wind comfort criterion based on the Beaufort scale, suggesting several standards (Lee and Song 2010). However, it is important to understand that the criteria for conditions of discomfort depend on a wide range of parameters including pedestrian activities (Stathopoulos 2006). In this case, a person standing in the tram stop, waiting for public transport, can be affected by a level of discomfort with a wind intensity that is less strong than the standard scales. In the tram stop people cannot move far in that space because they need to wait for the tram. Besides, they must have a clear vision of the traffic to see the transport that they are waiting for. That makes it difficult to install a tall screen as windbreak, to mitigate wind discomfort. Therefore, wind can affect pedestrians with changes in their stability, the thermal condition of their bodies and projection of particles to their eyes. A windbreak screen may deflect the wind. However, a screen can interrupt the vision of the traffic, produce lateral accelerations of wind on the opened footpath, and the turbulences behind the screen can drag particles from the ground to eye level.

Like previous parameters, the standard of wind discomfort was simplified to an airflow speed of 5 m/s at 1.5 m height (head level) (Wisse 1988). Another wind parameter considered in these experiments is the ABL (gradual decrease of wind velocity to the ground), which is a velocity profile based on the power law equation (Aynsley et al. 1977).

6.2 Adaptation of windbreak screens with aerodynamic features

Based on the observation of pedestrian circulations, a large protection region in the area of a tram stop in the crossroad of Swanston St and Franklin St is required. This large protection region must consider three basic programs in the site. The first one is a shelter area with roofs, seats and a platform for pedestrians who are waiting for the tram (width of 4 m). The second program is an area in front of a main entrance of a building of the university, where many students constantly enter or gather around. Finally, there is the space of the footpath where people walk along the street (width of 3 m). These three spaces overlap each other with their activities and functions, and all them are affected with moments of strong wind. A group of windbreaks is thus required, for a large protection region that involves these three spaces, without interruptions of their activities. Therefore, artificial big screens are not a good strategy because the space is narrow and pedestrians need to circulate. Instead, windbreak screens are necessary that can extend their protection without increase in their own size. To achieve this, the design of screen concepts as mitigation elements is based on a literal interpretation of the windbreak shapes and aerodynamic features studied by Gandemer (Figure 6.5). They are adapted as part of physical installations to produce larger wind thresholds and protection regions.
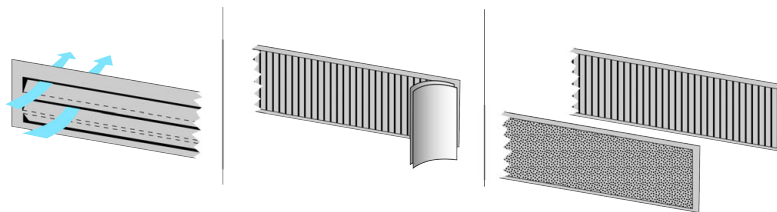
Figure 6.5: Gandemer's study about models of porous screens with aerodynamic features, to modify the wind flow patterns changing the deflection levels and increasing the boundaries of the protection regions. Left: screen fins and slots. Middle: porous screen with lateral deflector fins. Right: parallel porous screens. (Author's sketches based on (Gandemer 1979))

Taking the results of the previous investigation (generation of separation zones and vertical wind deflection with fins and a slot integrated in a wind barrier), I develop an adaptation of windbreak screens for this tram stop area. These screens will generate vertical wind deflections for a large protection area, but with an improved performance

using aerodynamic features, without increasing the size of the screen. To achieve this, the mitigation elements must create an upward wind deflection to be projected as a layer of low pressure above the tram stop area. This effect is similar to the building concept with fin on the roof from *Escuela Naval* project (Figure 6.6).
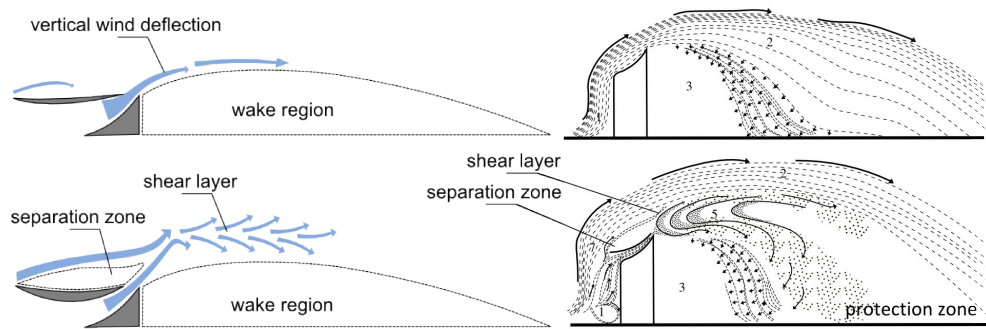
Figure 6.6: Two examples of conceptual wind deflector fin as aerodynamic feature, to produce a vertical wind deflection, which will enlarge the protection region. Top left: concept of aerodynamic slot system and vertical wind deflection in a barrier. Bottom left: slot with a separation zone effect at the top of deflector fin, to produce a strong shear layer to increase the wind deflection (source: author). Top right: concept of a building roof design and wind deflection effect at the top of the building. Bottom right: concept of aerodynamic slot system at the top of the building roof with separation zone and protection zone (study developed for the *Escuela Naval* project, 1953; author's sketch based on (Ureta Morande 2007)).

These elements will be organised in parallel groups along the footpath, including a structure of canopies for the shelter of the public transport stop. The strategy is the association of three basic features: a porous screen with 20% porosity, a horizontal curved surface as a small deflector fin with a double slot system and a convex deflector canopy above the screen. The main requirement is to keep a low vertical barrier (1.6 m height). The protection area must be extended by the wind deflection effect.

Aerodynamic features in screens with regular geometries

The adaptation of these windbreak features started with a regular geometrical shape for each one. This adaptation is necessary to isolate the effect, associating it with a basic geometry. The group of aerodynamic features developed includes the porous screen and curved surfaces as deflector fins, slots at the top of the screens, parallel screens and a

deflector canopy. The use of regular geometries helps to build the digital models in the
CFD-PST and CFD software. Moreover, the tests in the ABL wind tunnel were simplified
with regular geometries to observe more stable phenomena. The evolution of more complex
morphologies of membranes is a further stage of this research.

The screen concepts with aerodynamic features integrated were gathered as groups
associating two and three elements (Figure 6.7).
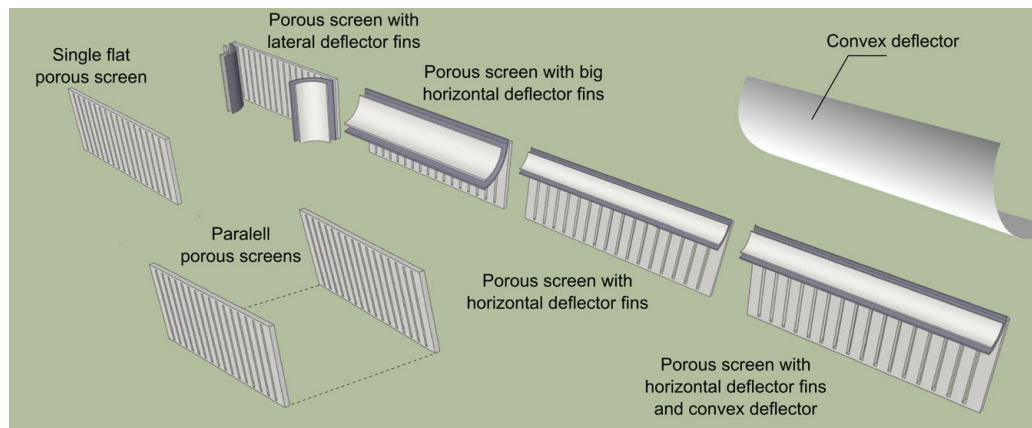
Figure 6.7: Adaptation for several versions of porous screen models (25% of porosity)
and curved fins as deflectors (aerodynamic features) using regular geometries. (Source:
author)

The configurations of these screen concepts tested in these experiments are:

- component 1: single porous screen with 25% of density

- component 2: porous screen with 25% of density and lateral deflectors with double
  slot.

- component 3: porous screen with 25% of density and horizontal deflectors with
  double slot as accelerator.

- component 4: porous screen with 25% of density, horizontal deflectors with double
  slot as accelerator and convex deflector above the barrier

- component 5: parallel porous screen with 25% of density.

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Vertical screen. The main change or variation with the features already known is the horizontal deflector with double slot and the convex deflector canopy. The horizontal deflector is a combination of porous screens and a lateral deflector. The reinterpretation is the horizontal position of the deflector at the windward side of the screen. It is similar to the previous chapter with the deflector concept with a single fin, but in this case the deflector and slot are double. The horizontal deflector has a curvature of one quarter of a circle, with a radius of 50 cm. And it is one third of the height of the barrier, which is 1.6 m. The distance between fins is 10 cm. Specific dimensions are not mentioned in Gandemer's studies; therefore, these experiments considered that the position of the deflector should be under the stagnation point of the screen and the curvature should avoid a downwash effect. The effect of this feature is a combination of deflection and acceleration. The deflection is produced by the curved surface, while the acceleration is produced by the gap between the deflectors and the screen. One of the original options of windbreak features to increase the protection area behind a porous screen is to install curved fins at the ends of the screen, in the windward side. And the experiments in the previous investigation mentioned the positive effect of a fin for this purpose. The intention here is to install these double fins horizontally at the top of the screen and see if a similar vertical deflection is produced (Figure 6.8).
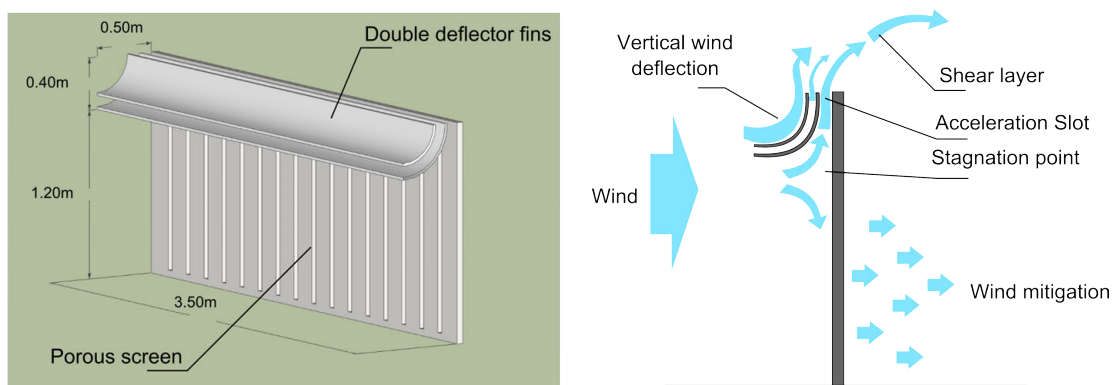
Figure 6.8: Left: details of the porous screen model and horizontal deflector fins to configure an aerodynamic slot. Right: the screen is a combination of deflector fins and the slot to produce and deflection-acceleration of the airflow at the top of the barrier. (Source: author)

Convex canopy. Similarly, the convex deflector or canopy was thought to work in association with the horizontal deflector. The first model was a curved surface above the screen. The idea is to replicate an effect mentioned in the literature about natural windbreaks, where to make more efficient the arrangement of rows of trees around farms, it is recommended to put lines of shorter shrubs behind the foliage of the rows tall trees (Melaragno 1982). For this case, the convex deflector replaces the foliage of a tree. The idea is to install the convex deflector to produce a wake of low pressure as a layer above the screens. The effect of upward wind should be increased for this low pressure region. Moreover, the curvature of the membrane is to avoid the separation of the wind flow, in the lower side of this deflector. As the concept is based on an appreciation of a natural windbreak, the dimensions of the set are not tied to specific rules. For this case, the criterion was to build a screen and convex deflector no higher than 5 m, which is the standard height of windbreak screens used to produce levels of protection in the studies by Gandemer 1979 and Pescaru 2011. This height is the standard of the porous screens analysed by the literature. In the windbreak screen concept there is a gap between the small screen and the convex deflector. This gap must be 1.4 m to keep a clear view at the head level (Figure 6.9).
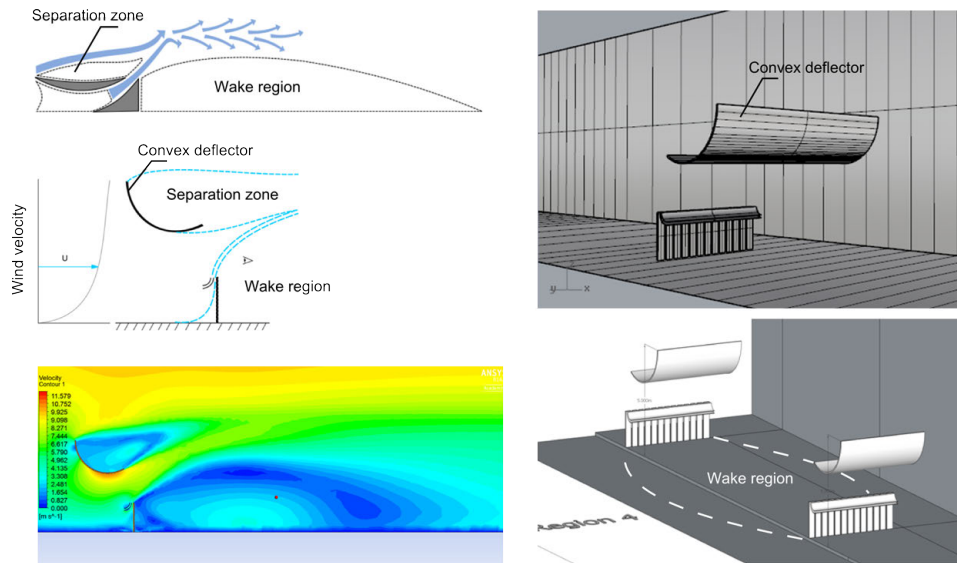
Figure 6.9: Evolution of a windbreak design to produce vertical wind deflection. Left column: replacement of the separation zone at the top of the deflector fin. The low pressure area is moved up with a new curved element (canopy) above the screen to increase the vertical deflection of air. At the bottom of the column a rapid CFD visualisation with ANSYS CFX shows the effect of vertical wind deflection and an "aerodynamic bubble of protection" (wake region). Right column: 3D design of the windbreak screens with double deflector fins and curved canopy designed with regular geometries to facilitate the rapid CFD visualisations. The idea is to install them in a parallel arrangement to extend the effect of protection in the footpath. (Source: author)

Shelter roofs. For the area of the shelter, in the tram stop, the roof was originally designed as a continuous curved surface. However, after several wind tests I changed the design to three curved surfaces with gaps. The two big roofs are 8 m long and 4 m wide. The small roof is 3 m long and 4 m wide. The whole area is 20 m long. These roofs must deflect the airflow from the "vault of wind" and evacuate the high airstream from the shelter zone (Figure 6.10). The optimisation process and validations made with rapid wind visualisation are presented in the further section about aerodynamic tests and visualisations.

As already explained, these windbreak screens will provide a larger protection effect in the area of the tram stop, footpath and building entrance. The main requirement is to keep low vertical porous barriers (1.6 m height). Thus, the protection is produced by the combination of these windbreak screens, which hypothetically will generate vertical wind deflections and a "vault of airflow". This will induce an aerodynamic effect of a long
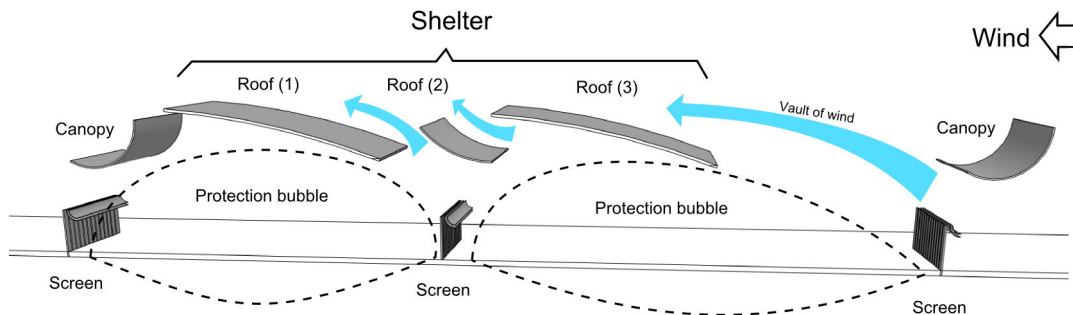
Figure 6.10: Designs of surfaces for roofs of the shelter zone. The roof for the shelter zone is made of three surfaces; the gaps between the surfaces and the curvatures are designed to evacuate the airflow to the upper side. This development was conducted through rapid wind visualisation. This exercise is explained in a further section. (Source: author)

chain of "protection bubbles". I call this aerodynamic effect the *extended wind threshold*. To work along the tram stop area (65 m), these windbreak screens must have a parallel arrangement to extend the protection area and create more regular boundaries for the protection bubbles. Therefore, the disposition of these barriers will be validated through rapid wind visualisation with wind analysis software (Figure 6.11).
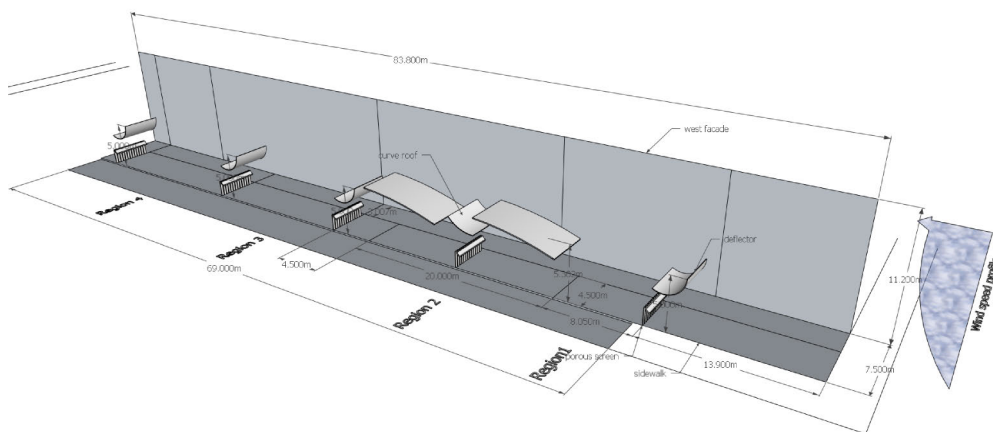
Figure 6.11: Design of the parallel windbreak screens and canopy configuration in the whole tram stop area. The site has four areas of protection: one area behind each screen and one area below the roof as shelter. These areas are a row of "aerodynamic protection bubbles" produced by wind deflections from each windbreak. (Source: author)

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Because these screens are developed as preliminary concepts for and design exploration, construction details and materials have not been considered. The experiments are focused only in a morphological exploration of aerodynamic phenomena using geometrical surfaces. One approach for further explorations is to consider these geometries as flexible fabrics or meshes to be temporarily installed around the tram stop area.

Aerodynamic features in screens with membrane morphology

After rapid wind visualisation tests were conducted with the previous concept designs (see next section), membrane adaptations were developed based on these aerodynamic features, in a progressive evolution from regular forms to more complex morphological explorations (Menges 2011). The idea was to elaborate geometries of tensile meshes. The difficulty is the more unpredictable wind flow patterns produced by these geometries. For that reason, the designs are based on the tension of the membrane surface, but keeping some regular forms and symmetry in the screens like the previous regular geometrical concepts.

The method used was a digital form-finding process using Rhino 3D software with Grasshopper and the Kangaroo plug-in. Kangaroo is a live physics engine for interactive simulation and optimisation of geometries to be used with Grasshopper. One of the qualities of Kangaroo is to produce an effect of relaxation of arbitrary morphology nets, simulating lightweight and tensile structures. This software generated minimal membrane surfaces for each group of screens. The curvatures of these tensile meshes can be used to interact with the wind flow. For the current experiments, the surfaces are considered as non-porous.

Convex canopy. The study of membranes for the convex deflector started with a curved surface of three faces. In this exploration, the tension of the mesh generates a minimal surface with a double curvature for each side: a concave curvature at the upper side of the mesh and a convex curvature at the lower side. The first curvature is to produce an upward deflection. The second curvature is to minimise the separation of the downward deflection, from the convex surface to the ground (Figure 6.12).
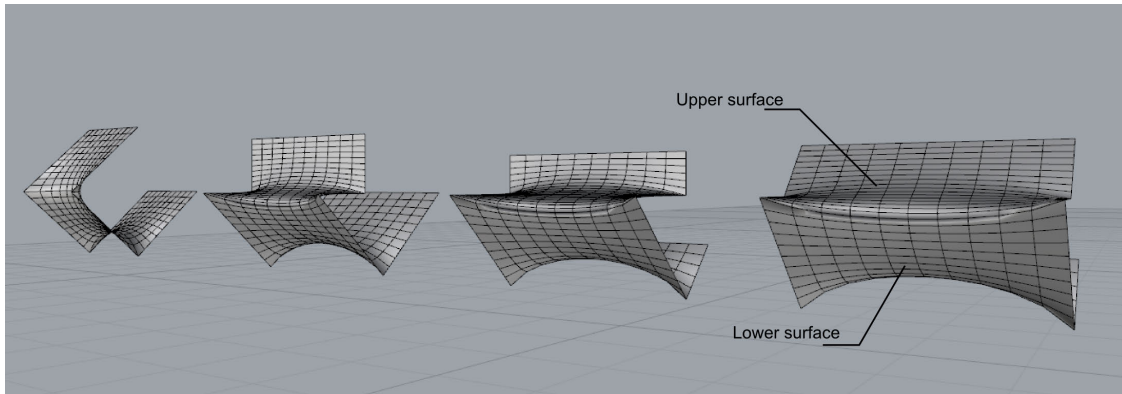
Figure 6.12: Group of alternatives membranes of curved deflector canopies. The canopies above each screen are adapted to geometrical form of membrane morphology, using a form-finding process with Grasshopper 3D. (Source: author)

This group of deflector canopies with membrane surfaces should generate a wake of low pressure with a larger distance from the ground. Also, the curvature of the membrane was designed to keep the form in case of a high dynamic pressure of the wind: the leeward side of the membrane is a low pressure area and the windward side is a relative high pressure area. If an elastic membrane is affected by the wind, deformations should occur. The main parts of these curvatures should not change orientation with a deformation produced by the wind drag (Figure 6.13).
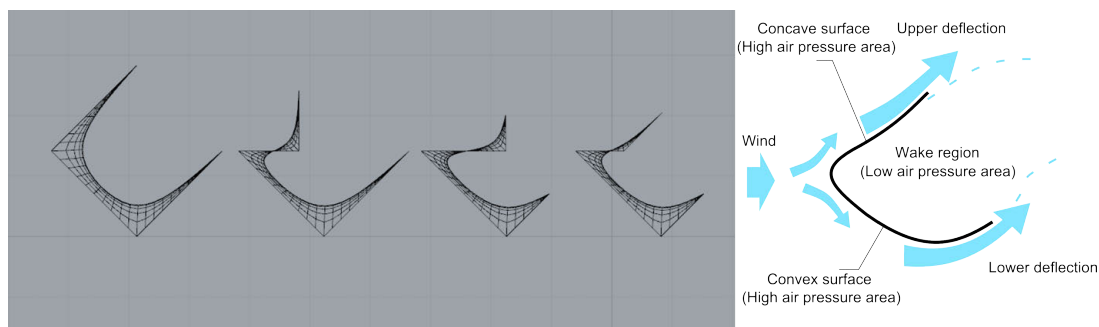
Figure 6.13: Profile evolution for a convex membrane canopy using Grasshopper 3D. The membrane must keep a convex surface at the lower side and a concave surface at the upper side to facilitate a wind deflection without separation zones. The form of the membrane should remain unaltered by the balance between high and low air pressures. (Source: author)

Vertical screen.   Moreover, the vertical screen was designed with several panels and gaps between them. Each panel is a vertical membrane with a framed edge forming a surface of double curvature. This membrane has a curved surface and a ventilation gap at the base. The dimension of each panel is 160 cm height and 50 cm wide. The curvature of its vertical surfaces facilitates the flow of wind to the gap. For this first model, the surfaces were defined as opaque. No porosity was considered, except the gaps between membranes. The total dimension of the screen is $325\ cm \times 160\ cm \times 50\ cm$. The vertical screen included double horizontal deflector fins to create an aerodynamic slot. With similar digital processing of relaxed mesh, each surface with two faces is transformed as a continuous surface with a double curvature (Figure 6.14).
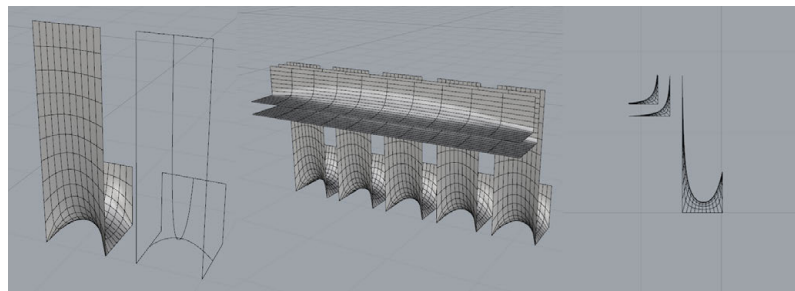
Figure 6.14: Design of membranes as vertical screens in Grasshopper 3D with the same dimensions of previous screen design (the gap between each panel provides the 20% of porosity). The membrane includes a gap at the bottom for a ventilation airflow. The group includes two horizontal membranes for double aerodynamic deflector fins and slot. (Source: author)

Shelter roofs.   For the area of the shelter, in the tram stop, three membranes were designed as roofs. The two big membranes were developed from a digital mesh with the form of a channel. This mesh, after a process of relaxation, was transformed into a curved membrane with a convex surface, with two fixed edges and four points of springs. The points allow the necessary tension to produce the curvature. The general shape of this membrane is a rectangle, $300\ cm \times 700\ cm$. The small membrane between both big membranes, has one fixed edge and 10 points of suspension. These points of springs have different heights to produce two different curvatures: a first convex curvature and a second concave curvature. The size of this membrane is $300\ cm \times 324\ cm$ (Figure 6.15). The

first and third membranes are similar in their geometry, but the membrane in the middle

has a shape profile like an "S". The gaps between the membrane roofs are supposed to

facilitate the ventilation of accelerated airflow from the shelter to outside.
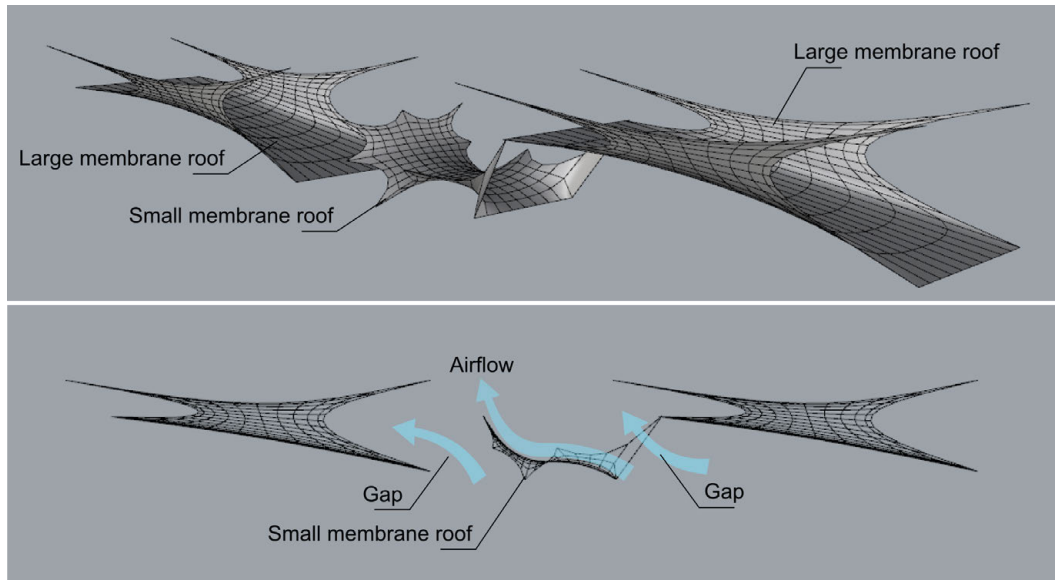
Figure 6.15: Designs of membranes for roofs of the shelter zone using Grasshopper 3D.
Top: the roof for the shelter zone are three membranes; largest roofs are membranes with
eight points as tensors; and the smallest roof is a membrane with 12 points as tensors.
Bottom: the gaps between the membranes and the curves of the small roof are designed
to evacuate the airflow above the membranes. (Source: author)

These parallel windbreak screens and canopy deflectors were installed in the tram

stop area, following the similar disposition of the previous designs with regular geometries

(Figure 6.16).
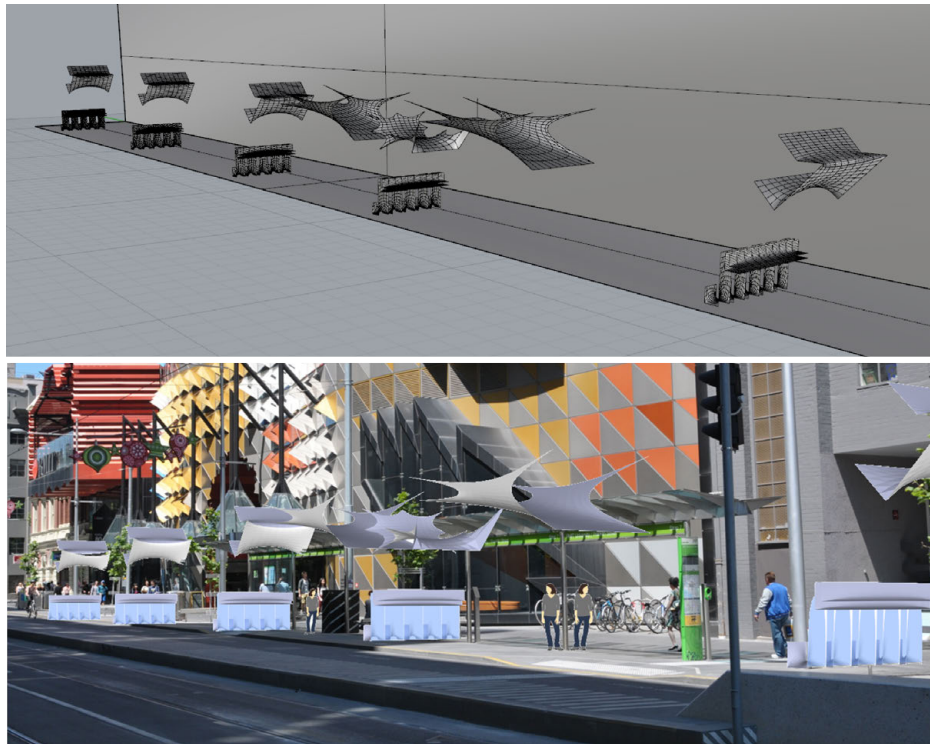
Figure 6.16: Group of parallel windbreak screens with membranes morphology to provide regions of wind protection in the tram stop. Top: 3D digital model of the windbreak shelter. Bottom: representation of the windbreak shelter in the context of the street. (Source: author).

The idea with these membranes is to replicate the effect of vertical wind deflection, as a chain of "protection bubbles" produced by a "vault" of wind. Each windbreak screen will deflect and accelerate the airflow through slots and deflector fins (Figure 6.17).
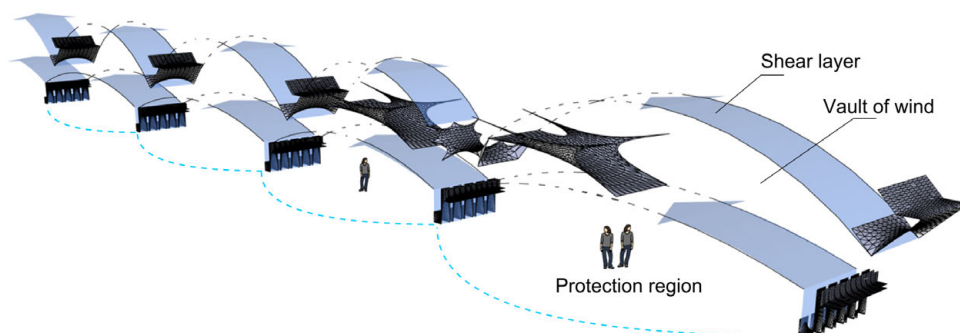
Figure 6.17: Hypothesis of aerodynamic "protection bubble chain". The effect produced by the screens and canopies is a vertical wind deflection that configures "vaults of wind", as protection regions, in the tram stop. (Source: author)

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6.3 Rapid wind visualisation of windbreak screens with CFD-PST and CFD software

As explained before, the experiments involved the use of different techniques for these tests: the use of rapid wind visualisation with ODS-Studio and Vasari was focused on the windbreaks with regular and membrane morphology. In contrast, the windbreak screens with regular geometries were visualised with ANSYS CFX software. Finally, the use of an ABL wind tunnel was to visualise the configuration of windbreak screens with porous meshes.

Calibration of experiments for rapid wind visualisation

For the experiments for rapid wind visualisation a calibration process was necessary to set up the main parameters in the wind analysis programs. The parameters were focused to facilitate the exploration of a big and complex windbreak shelter with several screen concepts, in a large configuration and with small details of design. The rapid visualisation must address the screens and associated aerodynamic phenomena to get rapid feedback during the design process.

The program CFD-PST Vasari has the most simple process to set up a visualisation. However, the simplification of parameters make it difficult to establish a base to compare with other programs. The model of the test is the group of screens and a surface wall as the west façade. Therefore, it was configured the grid as a 3D flow domain to include the whole tram stop area, footpath and west façade for a 3D airflow simulation. This flow domain has three times the width of the footpath and two times the height of the façade. In addition, it is necessary to consider that Vasari does not simulate the ABL and it is not possible to make an adaptation to produce a similar effect. Then, the experiments were set up with a flat wind velocity profile. The parameters of velocity were 5 m/s. Another thing is that Vasari did not allow a more refined grid, to improve the quality of the visualisation, because of the length of the windbreak shelter (Figure 6.18).
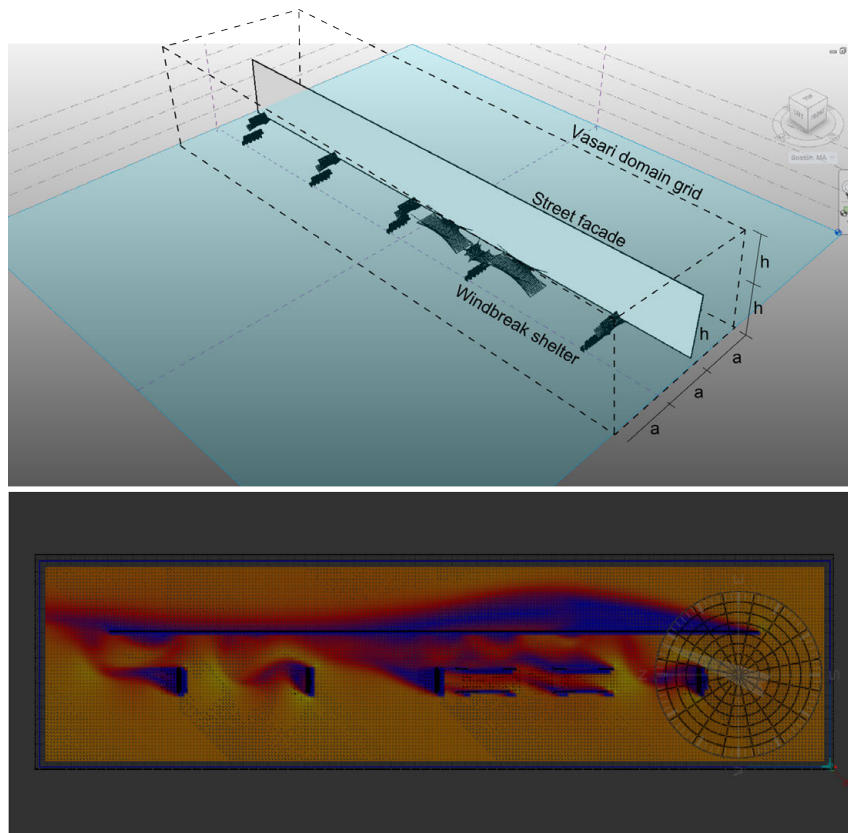
Figure 6.18: Digital domain of for rapid CFD visualisation using Vasari. Left: digital grind domain in Vasari. Right: grid dimension visualised with Vasari. X cells = 82, Y cells = 318, Z cells = 57. Voxel size = 1.0. (Source: author)

As a second tool, the parameters for ODS-Studio considered for the tests an airflow domain size similar to the street with the footpaths and tram stop space dimensions. The wind speed is 5 m/s at the level of 2 m, which is considered as the threshold of discomfort. In the ODS-Studio module, the wind is simulated as a simple and constant laminar flow without the ABL effect. For this reason, as a part of the calibration for these experiments, it was necessary to set up the virtual wind tunnel to produce a minimal ABL condition. This condition is a basic requirement to get a common base of comparison with the tests developed with other wind analysis techniques. As a way to overcome the limitations of the virtual wind tunnel parameters, some roughness elements and vertical panels were included in the inlet zone and on the ground of the domain for each simulation. The idea is to increase the ground friction and turbulence, following similar methods used by real boundary layer wind tunnels (Cermak 2003). The aim is to generate this approximate

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ABL to test windbreak screen models up to 5 m tall (Figure 6.19).
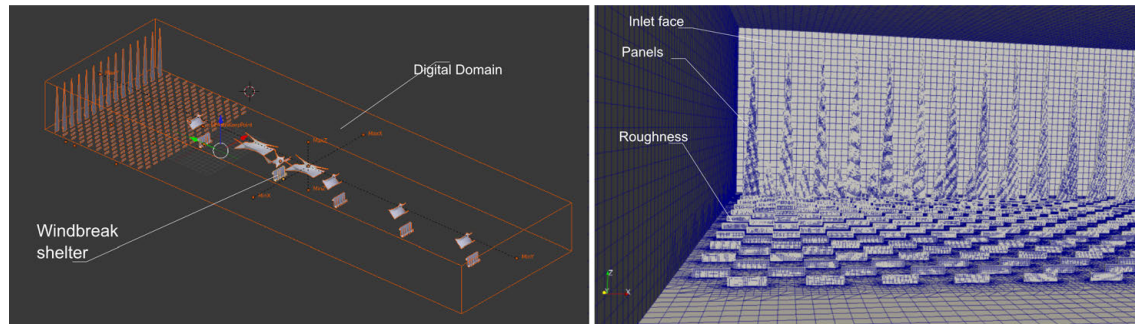
	Model	Wind speed	ABL	Digital mesh	Turb. Model	Validation method
ODS-Studio	Windbreak Shelter 5 m height	5m/s - 10m/s at 2m height	Ground roughness and panels in inlet zone to produce BL	3D domain Cells= 4896421 Points=2949167	RANS - standard K-epsilon	Test of stagnation point

Figure 6.19: Digital domain and mesh with de dimensions of the street for rapid CFD visualisation using ODS-Studio. The mesh has roughness elements on the ground and panels in the inlet zone to generate a relative ABL effect. Left: digital domain modelled with Blender at $30\,m \times 16\,m \times 101.5\,m$. Right: digital mesh generated with OpenFOAM and visualised with Paraview. (Source: author)

An experiment of control was prepared to analyse the ABL condition of the simulation (Groat and Wang 2002). The idea is to reproduce a wind flow on a roughness surface of the ground. The criterion is to visualise and measure the wind speed flowing around the area of the model up to 1.6 m height. This height is the head level where pedestrians feel a discomfort (the turbulence intensity was not considered for protection). As a result of this calibration test, the Paraview visualisation showed a vertical layer represented by streamlines with a speed gradient (colours). This effect is the proximately ABL condition produced by the roughness elements. In the image, the wind speed is shown on the chart on the left side (Figure 6.20). The chart shows the gradient of wind velocity profile and a wind intensity of 7-8 m/s at 2 m (input wind = 10 m/s). The control experiment included a visualisation with a non-porous wall of $2\,m \times 2\,m \times 0.1\,m$ as a model. The idea was to reproduce the classical downwash wind deflection flowing on the base of this model. As a result of this calibration test, the Paraview visualisation showed a vertical deflection represented by streamlines with the stagnation point relatively well located on the windward face of the wall (80% height). This method is not precise, but it is enough to produce an observable ABL for these rapid visualisation experiments.
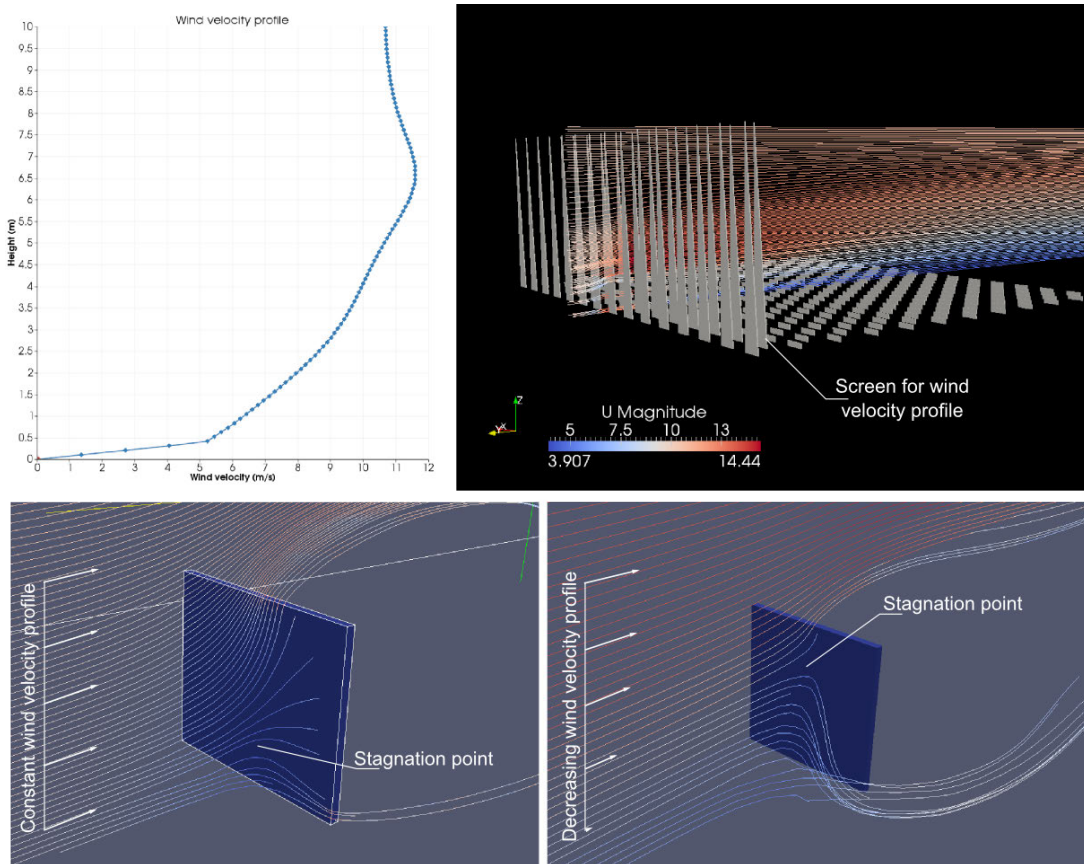
Figure 6.20: Visualisation of decreasing wind velocity profile generated by ODS-Studio. The simulation considered an approximate calibration of an ABL effect in the wind velocity profile to simulate the wind at ground level. Top left: visualisation of chart with data of the wind flow speed decreasing to the ground of the domain. Top right: visualisation of screens, roughness (to produce a decreasing wind speed profile) and streamlines with variation of wind speed (colour). Bottom left: test of vertical deflection of wind on a windward surface of the wall, with constant wind velocity profile. The stagnation point is on the middle and the lateral deflection is low. Bottom right: test of vertical deflection of wind on the windward surface of a wall, with decreasing wind velocity profile. The stagnation point is high and the lateral wind deflection is significant. (Source: author)

For the second stage, using ANSYS CFX software, two domains were set up for the experiments: the street space and the tram stop site. The first one defines the aerodynamic phenomenon (channel effect); the second one is the wind comfort issue (strong and discomfort wind). Only these two dimensions were considered for the visualisation, avoiding designing large urban structures impossible for a quick visualisation process. Using the Design Modeller module of ANSYS, the fluid domain is the first setting where the channel effect is recreated. This domain has 30 m width (similar to the distance between

opposite façades in Swanston St), 16 m height and a 101.5 m long. The bottom face
represents the ground, the front and back sides are the street façade (Figure 6.21).
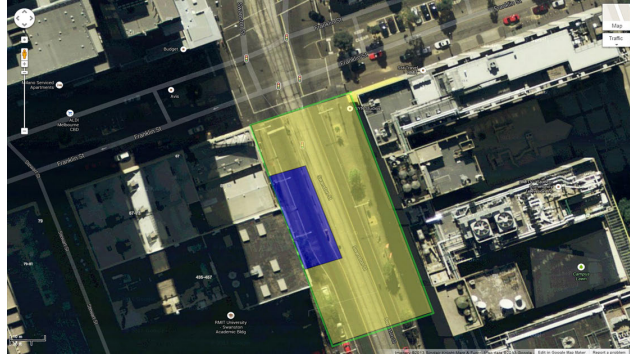
Figure 6.21: Definition of areas for the CFD visualisation. Each area is a domain with an
independent digital mesh to facilitate the simulations: tram stop area (blue), Swanston
St area (yellow). (Source: author)

The second setting is the tram stop domain with 10 m height, 15 m width and 80 m
length, which represents a small tram stop area, covering the width of the footpath (3 m),
the tram stop (4.5 m) and the platform (4.2 m). This small domain allows a major density
of the digital mesh for a more detailed visualisation of the wind around the windbreak
models, and the effects at the windward side, leeward side and in the protection region
(Figure 6.22).

Model	Wind speed	ABL	Digital mesh	Turb. Model	Validation method
Windbreak screen 5 m height	5m/s - 10m/s at 2m height North to south	Power law equation for urban context	3D domain Nodes=6453381 Elements=20307062	RANS standard K-epsilon	Residual RMS Error values acceptable value Monitoring values of drag and lift with a steady solution Domain imbalance of less than 1%

Figure 6.22: Pre-process of the model for CFD analysis with ANSYS CFX. Left: fluid
domain of the street split into several regions including the tram-stop domain. Right:
domains transformed into digital meshes with different patterns to facilitate the simulation
(ANSYS 2012). Nodes = 6453381, elements = 20307062. (Source: author)

To clearly visualise the aerodynamic phenomena produced by the features of screens, the conditions of ground and wall friction with the wind flow required dense digital meshes to visualise the grade of wind deflection and protection around the windbreak screen models. The domain that represents the street airflow has a digital mesh with two cell sizes: the fluid domain with big cell mesh representing the street and the tram stop domain with a more dense mesh. Additionally, the cell sizes near model faces (walls) were manually reduced, and five layers of inflation were applied on the ground and on the geometry of the windbreak model. The ABL condition in the simulation was the same as in previous experiments, following the power law equation, and using as a reference wind speed of 5 m/s at 2 m height. RANS with standard k-epsilon was the turbulence model used. All these conditions were necessary to set up the experiments in the ANSYS CFX software; something that required some grade of training and time as previous processes to the visualisation stage. For these reasons it was necessary to get expert assistance to complete this step. The step of the digital mesh (domain) resulted in the most complex part of the visualisation process and required several corrections to avoid interruptions in the calculation process (ANSYS 2012).

The porous condition in the screens could require special consideration for the Reynolds number (Re), and I was not sure how different CFD visualisations compare with the experiments of windbreak screens made by Gandemer in a wind tunnel. To simplify these technical considerations of flow mechanics I run a rapid visualisation with a similar screen model of 5 m height to compare with results of Gandemer's studies. The outcome had a similar patter to Gandemer's diagram, and both present a 50% of wind mitigation. In the case of validation, for rapid visualisation I only observed that output data was stable and in acceptable levels of convergence, as recommended by ANSYS support (LEAP-CFD-team 2012) (Figure 6.23).

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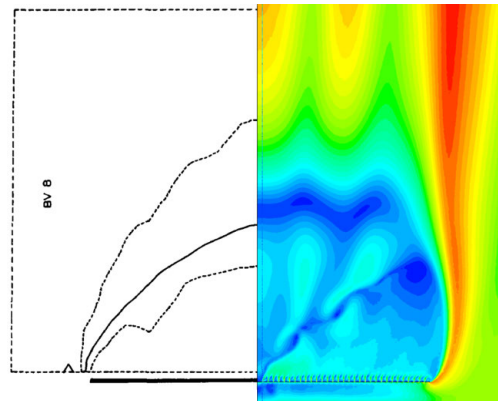
Figure 6.23: Comparison of rapid wind visualisation with ANSYS and Gandemer's study of wind patterns through a screen of 5 m height and 120 m length with 20% porosity. The results of protection areas are considered as similar (Source: author)

Rapid wind visualisation with ANSYS CFX

With the assistance of a specialist, it was possible to complete some steps to set up ANSYS CFX for rapid visualisation in this investigation. However, only a first group of windbreak screens with regular geometries could be visualised. The exploration and development of more complex membrane shapes and membranes with porous conditions requires an accurate pre-process elaboration that is not possible at this time. The geometries generated with Grasshopper are not easily exportable to ANSYS CFX. Therefore, and because of limited time, windbreak screens with membrane morphology were not visualised with this tool.

The rapid wind visualisation with ANSYS CFX verified that the combination of a porous screen with a horizontal deflector and a convex canopy can generate a significant upward wind flow and a larger "bubble of protection". This accelerated wind layer increases the height of the protection region at the leeward side of the barrier. The visualisation showed, on the first windbreak screen, a strong vertical deflection and protection region. This vertical deflection is defined as a free shear layer that separates the free stream flow from the recirculating area, increasing the protection area behind the barrier. For this case, the protection region had a height of 3.5 m. This is twice the height of the barrier itself (Figure 6.24). The effect depends on the deflector position, angle and size (deflector fins and the canopy). The effect was visualised with an isolated screen test,

a configuration of screen plus canopy and a configuration of screen plus canopy without deflector fins. The second option was the best arrangement. Thus, with this effect of upward wind, it is possible to reduce the height of the vertical porous screen in order not to interrupt the pedestrians' view. Finally, based on this first visualisation, I redefined the distances between the other screens.
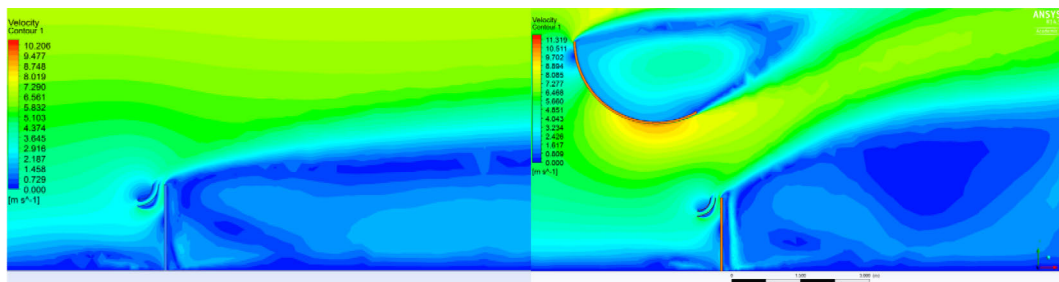
Figure 6.24: Rapid wind speed visualisations of regular screens with deflector fins as aerodynamic features, using ANSYS CFX. Left: normal protection region with low airflow speed behind a flat porous screen. Right: higher protection region produced by a porous screen with an upper canopy deflector. This is the "protection bubble". (Source: author)

Moreover, through several visualisations I tested the effects produced by a roof on the tram stop shelter area. This roof had a curvature to deflect the incident wind flow. This wind is projected from the slot on the first screen to the upper surface of the roof. Through several CFD tests it was possible to define changes to the roof design, with the intention of reducing possible acceleration of the wind flow below this roof. As a result, a ventilation gap at the top of the roof curvature was suggested. However, in a second visualisation, an acceleration of the wind at the outlet area of the shelter is observed. To avoid this effect, a second porous screen was installed under the roof. A new CFD test verified the generation of an area of protection behind the second screen, but at the same time, an additional phenomenon is produced between both regions. The second screen produces a change in the direction of the wind, directing it back to the inlet area of the shelter and producing a neutralisation of the incoming wind (Figure 6.25).

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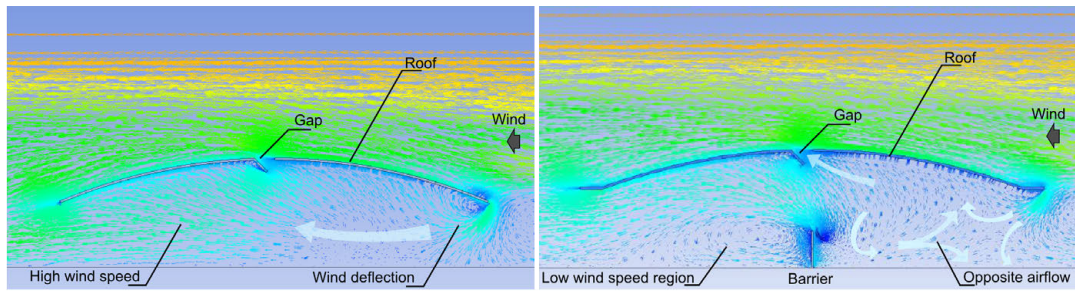
Figure 6.25: CFD visualisation of vector field with ANSYS CFX. Left: curved roof in the shelter area with strong wind deflection in the front and a high wind speed region below. Right: a screen increases the protection region below the roof and mitigates the wind velocity in the shelter with an opposite airflow. (Source: author)

Also, the second porous screen extended the protection area of the first porous screen, increasing this region. This effect of protection regions between parallel screens was an expected effect, already mentioned in Gandemer's work. Thus, parallel screens can extend the protection region at both sides: leeward and windward (Figure 6.26).
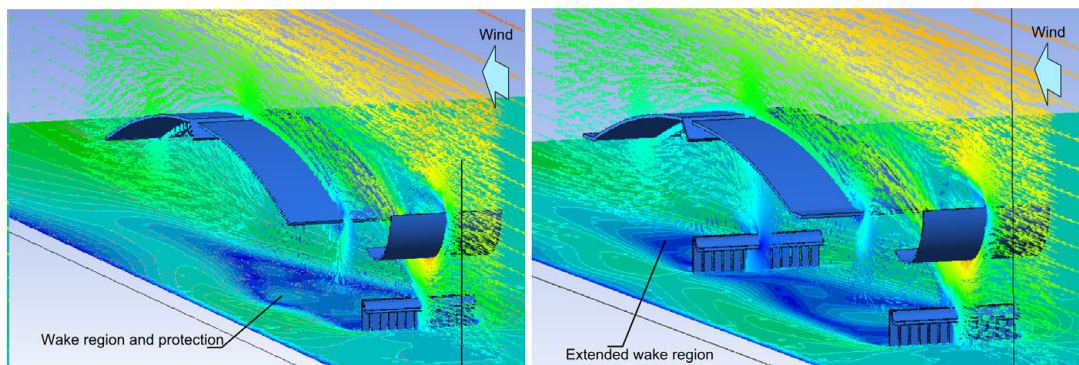
Figure 6.26: CFD visualisation of wind velocity vector plot with ANSYS CFX. Left: extension of the protection region from first porous barrier (blue region). Right: a second screen increases the protection region below the roof and makes more regular the region boundaries. (Source: author)

The wind visualisations showed an acceleration of wind at the outlet area of the roof. This acceleration could affect the comfort of the pedestrians in the tram stop. For that reason, I split the roof into three independent parts to create output gaps. In this design, the second section in the middle of the roof was crucial. The upper surface of this roof section should deflect the wind to the outside of the roof, and the lower surface should generate a drag force to direct the airflow to the third roof (Figure 6.27).

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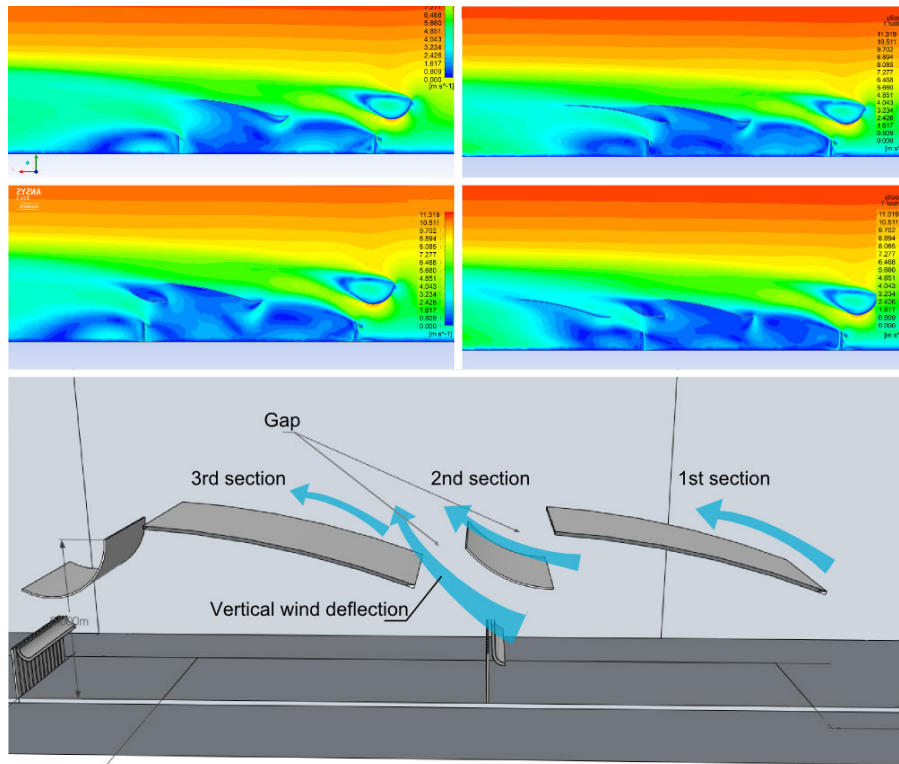
Figure 6.27: Top: CFD visualisation of wind velocity with ANSYS CFX for four different roof configurations. Bottom: final alternative of roof with three sections with a better protection region below the roof. The gaps between the roof sections work as ventilation to reduce the wind velocity in the shelter. (Source: author)

These changes in the roof configuration were tested with progressive simulations. The results showed a significant area of low wind velocity with a configuration of three roofs and screen. Additionally, the second gap between roofs evacuated the upward wind of the screen increasing the protection region in the shelter zone (Figure 6.28). A general observation about this group of screens and canopies is the fact that between the 160 cm to 300 cm height, there is no physical structure or screen blocking the wind flow. This effect is because the accelerated air deflection from the windbreak screen works as curtain and the wind intensity in the shelter zone is kept with an acceptable low velocity.

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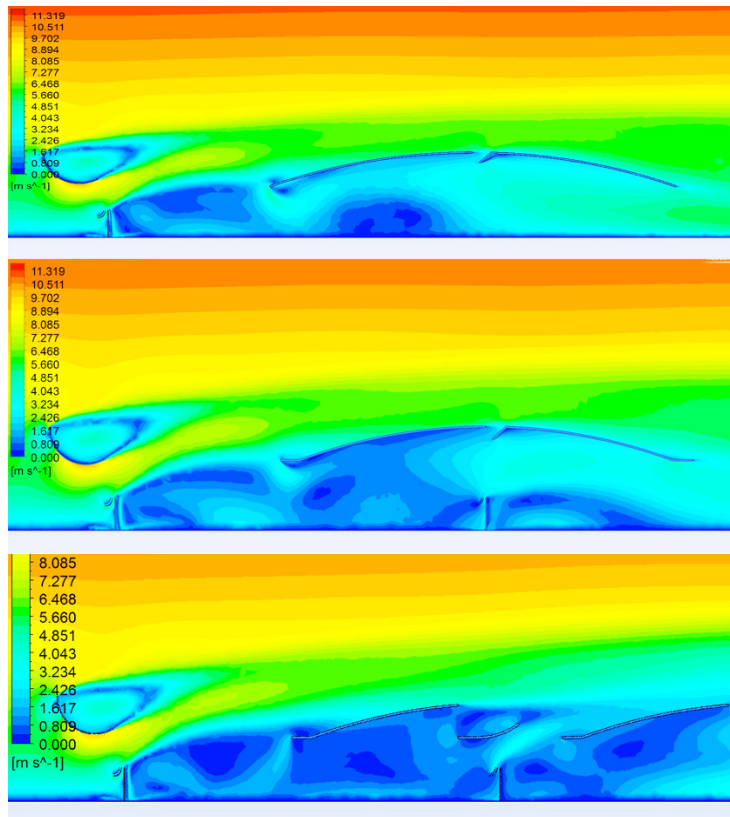
Figure 6.28: Wind visualisations of three shelter and roof configurations, with ANSYS
CFX. Top: continuous curved roof with a high wind speed region below. Middle: a
second screen increases the low wind speed region below the roof. Bottom: the roof is
split into three parts with gaps to facilitate the evacuation of airflow. The low speed
region generated below is the largest protection zone. (Source: author)

For the total area of the tram stop, the CFD visualisation showed the screens, with
deflectors, in a parallel order to produce a continuous region of wind low velocity, extending
their boundary to the next screen. This area is protected by a succession of "vaults of
wind" where the high speed of the wind remains above the screens and the pedestrians'
level (top image of Figure 6.29). One question is how relevant the aerodynamic double
slots of each screen are for the effect of "vault" and the height of the "protection bubble".
I ran two visualisations, one with the porous screens and fins slots, and another with
only the screens. This comparison showed that the horizontal deflector fins and slot only
work deflecting the wind in the first region of the tram stop with the incident wind. This
phenomenon happens with the first screen set installed as vanguard and with the second
screen under the roofs. Both screens with slots are more efficient to keep a larger region

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of low velocity for pedestrians. However, at the second half of the tram stop area, the performance of the screen sets is similar in both simulations (bottom image of Figure 6.29). In that sense, a possible strategy could be to orientate the deflectors and slots of the last two parallel screens in the opposite direction. Thus, the north part of the tram stop will be prepared to use aerodynamic features to deflect the wind flowing from the north; while, the south part has aerodynamic slots orientated to deflect the south wind.
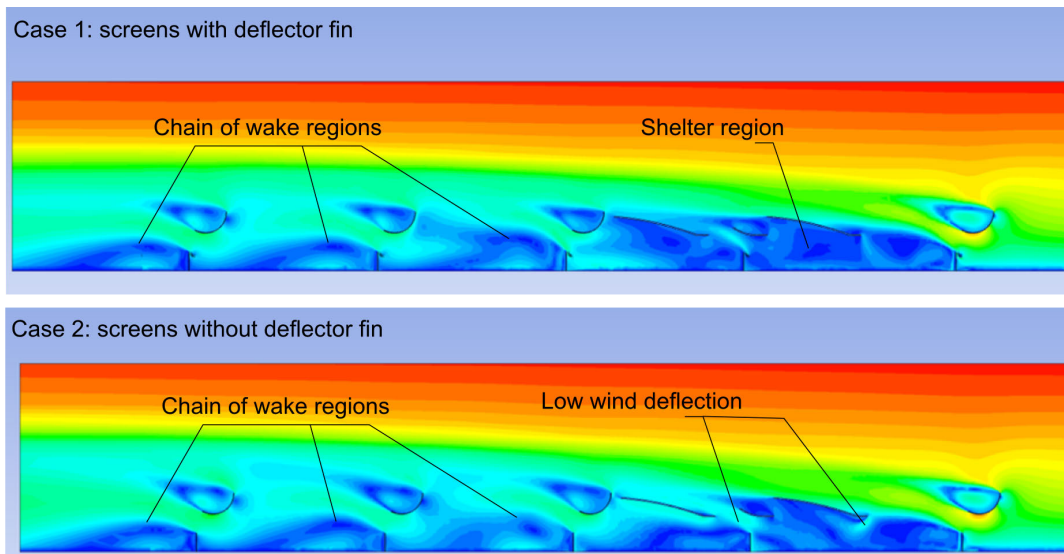
Figure 6.29: Comparison between CFD wind speed visualisations of the full model, with ANSYS CFX. Top: configuration of screens with horizontal deflectors fins. Bottom: configuration of screens without deflector fins. The wind conditions in the roof zone are different in the second case. The wind speed is higher in the roof zone than the first visualisation. These fins are necessary to produce an effective vertical deflection of wind. (Source: author)

From a top point of view, the simulation showed that, around 90 cm height, the second porous screen has a small wake region. Probably, the low pressure region, in the shelter area with the roofs, produces a sucking effect from the lateral areas of the free air stream with a relatively high pressure (Figure 6.30). It is suggested for this second screen to install a lateral deflector at the east side. This deflector could extend the horizontal protection region behind the second screen.
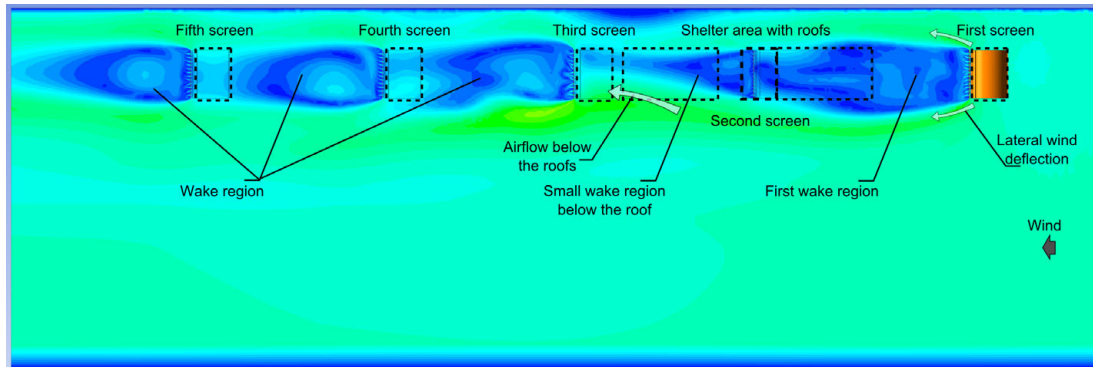
Figure 6.30: Horizontal wind visualisation at 1 m height generated with ANSYS CFX. A large and continuous wake of "protection bubbles" is produced by the group of screens and canopies in the tram stop. However, the second screen under the roofs generates the smallest protection zone. (Source: author)

Rapid wind visualisation with Vasari

The group of screens with regular forms was imported to Autodesk Vasari to analyse how Vasari can visualise the wind effects in this windbreak shelter concept. The visualisation in Vasari showed acceleration in the vertical wind deflection with some clarity, through a visualisation with a vertical 2D slice. However, the screens did not produce the strong change of wind direction and the "protection bubble" that were previously observed with the ANSYS CFX program. In fact, wind flow is deflected to under the group of horizontal canopies of the shelter and not above them, as expected. Moreover, below these roofs the second screen did not show a vertical deflection passing through the gap between the canopies. In fact, the wind flowed horizontally with zones of acceleration through the shelter, making the protection ineffective (Figure 6.31).

With a structure of screens with small features, and the length of the whole installation being too large, the resolution of the grid could not be refined and the visualisation has a poor quality for details. Because of this, it is not possible to visualise other adaptations of the small deflector fin positions on the screens, to analyse the changes in the wind flow pattern.
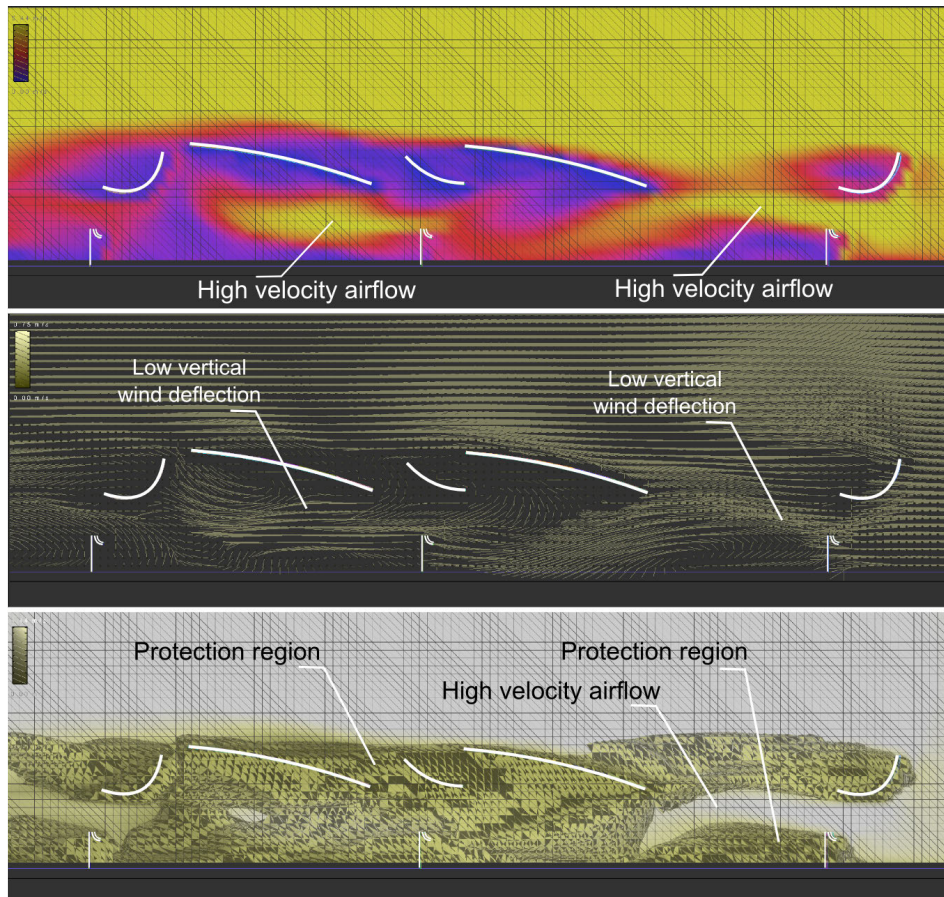
Figure 6.31: Wind visualisations of the regular geometries of screens and canopies, using CFD Vasari, that present different results from ANSYS CFX. Top: 2D wind speed visualisation of the screen wake. There are high wind speed regions behind the first and second screen. Middle: 2D vector field visualisation showing a low vertical deflection from each screen and lack of airflow ventilation through the gaps of the roofs. Bottom: 3D isosurface visualisation showing a region of low wind speed (1.5 m/s). The gaps are zones with high wind flow velocity. (Source: author)

On the other hand, the visualisation of the whole protection region is represented in a comprehensible way. Using isosurface as a digital visualisation it was possible to define the space of the "protection bubble" with a low wind velocity condition (around 1.5 m/s). However, this representation is difficult to control, and the parameters are ambiguous to define the right threshold of wind intensity for an accurate representation.

In general, the visualisation with Vasari performed relatively well to visualise the general region of protection and the vertical deflection of the wind through the group of screens. But it was not possible to visualise the aerodynamic effect produced by the

screens features. Moreover, the vertical wind deflections were less effective and the protection zone presents regions with strong airstreams. Something different from the previous experiments visualised with ANSYS, that showed calmer protection zones.

Rapid wind visualisation with ODS-Studio

The windbreak shelter with membrane morphology was observed with rapid CFD visualisation with ODS-Studio, using OpenFOAM for numerical simulation and visualised with Paraview to see how these membranes generate wind protection. The visualisation clearly showed the upward flow pattern of wind through the screens. In fact, the effect visualised by these structures was as expected (Figure 6.32). Behind each canopy or convex deflector, between the 3 m to 5 m height, a region of low pressure is formed. This low pressure region increased the upward effect of the wind flow deflected from the slots of the screens. In addition, an acceleration of wind velocity is observed, produced in the gap between screen and canopy, improving the vertical deflection of the wind.
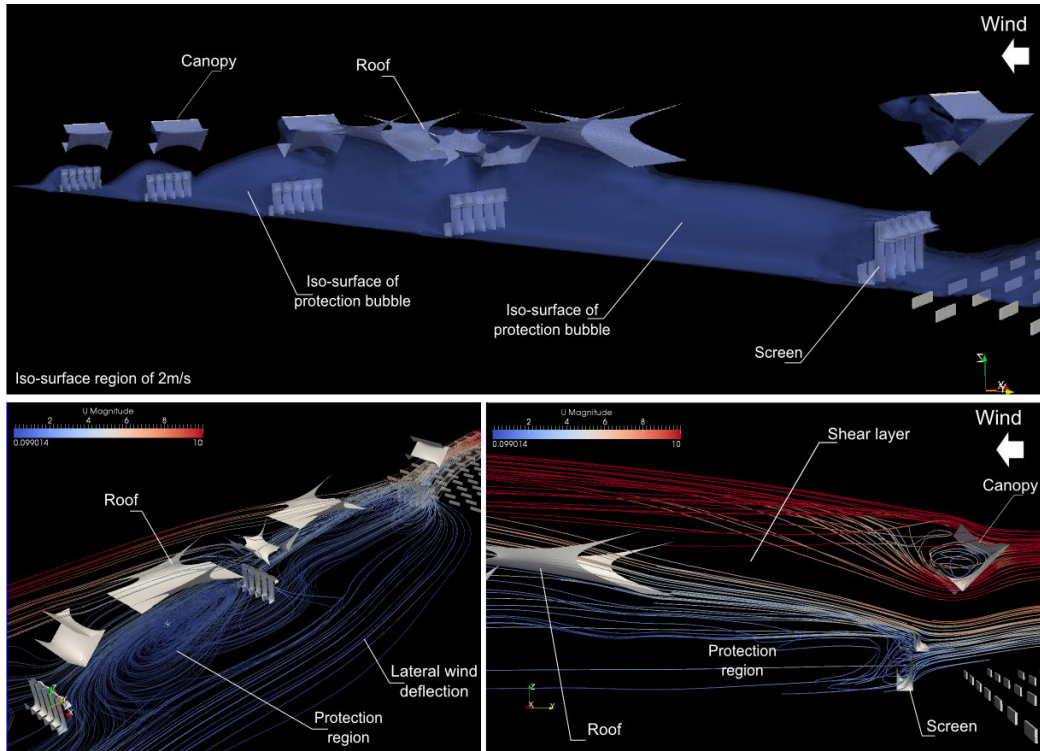
Figure 6.32: 3D wind visualisation to show vortex of the protection regions around screens with membrane morphology, using ODS-Studio, OpenFOAM and Paraview. The use of ODS-Studio program was because in ANSYS CFX the geometries of membranes require a more complex process to set up for a simulation. Thus, to get a rapid visualisation, these geometries were studied with ODS-Studio. Top: isosurface of 2m/s wind speed region, to show protection bubble produced by membrane screens. Bottom left: streamline visualisation of the vortex in the protection region, behind the first screen. Bottom right: vertical deflection of airflow produced by the first screen and canopy. The wind is flowing up above the roof and this effect is similar to visualisation with ANSYS CFX. (Source: author)

A more close observation shows, behind each curved canopy, the wake regions with upward airflows around the membrane surfaces. The wind visualisation allows a comparison between two positions for the fin at the top of the canopy, to work as wind deflector. In the same way, the visualisation shows how the ventilations gaps designed at the bottom of the screens mitigate the lateral wind deflection in the area of the footpath (Figure 6.33).

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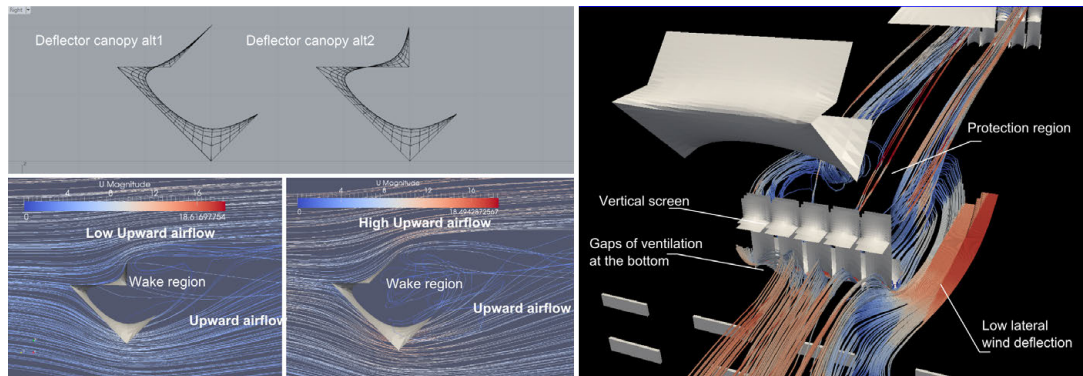
Figure 6.33: ODS-Studio wind visualisation of design adaptations effects. Top left: two
alternatives of canopies with membrane morphology. Bottom left: the visualisations show
upward airflow around the surfaces of the canopy. The upper surface with slope produces
a more smooth wind deflection than the second alternative. Right: visualisation of air
flowing through the gaps at the bottom of the screen, designed to mitigate the lateral
airflow deflection from the screen to the footpath. (Source: author)

This method of concept design exploration allows understanding the effect of wind
interacting with the geometry of the objects. Even though these screens have membrane
forms, they are symmetrical and the surfaces follow a similar pattern to the previous
version with regular geometries. Thus, the effect of vertical wind deflection was achieved
and positively evaluated (Figure 6.34).
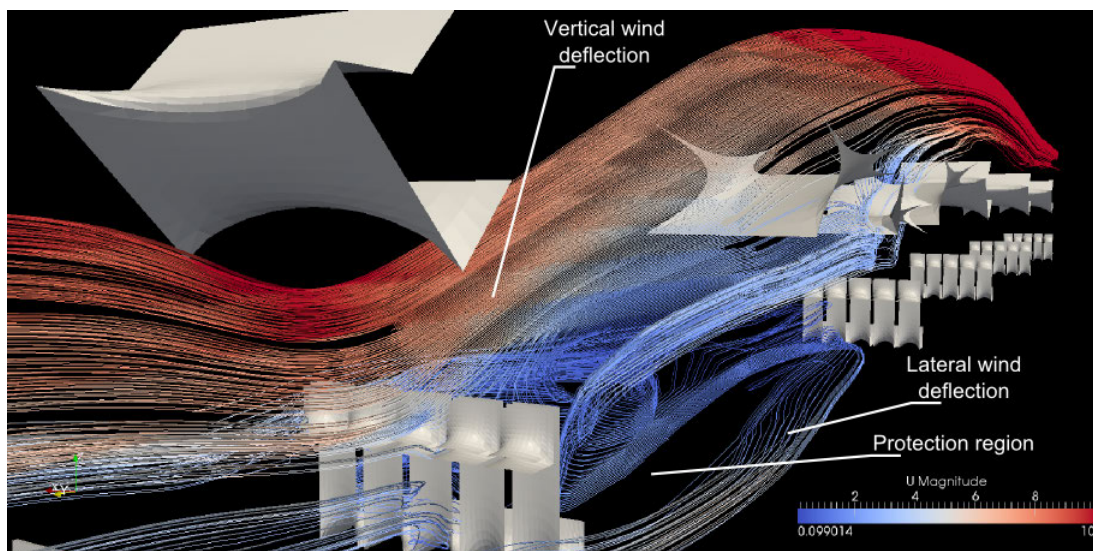
Figure 6.34: 3D wind visualisation of streamlines to show upward wind flow, using ODS-
Studio, OpenFOAM and Paraview. The visualisation shows a vertical wind deflection
projected from the first screen with membrane morphology to the upper side of the roofs.
(Source: author)

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Rapid wind visualisation with Vasari for membrane morphologies

For a new group of visualisations, I moved the membrane screens to Vasari to compare with the previous observations. In general, these rapid visualisations present a very similar protection effect than the previous Vasari tests with regular geometries. Again, the main observation is that the vertical wind deflection, from these membrane screens, is not observed in this case. The visualisation showed a wind deflection that is not as effective at lowering wind speed in the roof areas. On the other hand, the visualisation with a color slice and isosurface patterns showed that the area of roofs present the smallest protection region in the second part, something that was observed in ANSYS CFX (Figure 6.35).
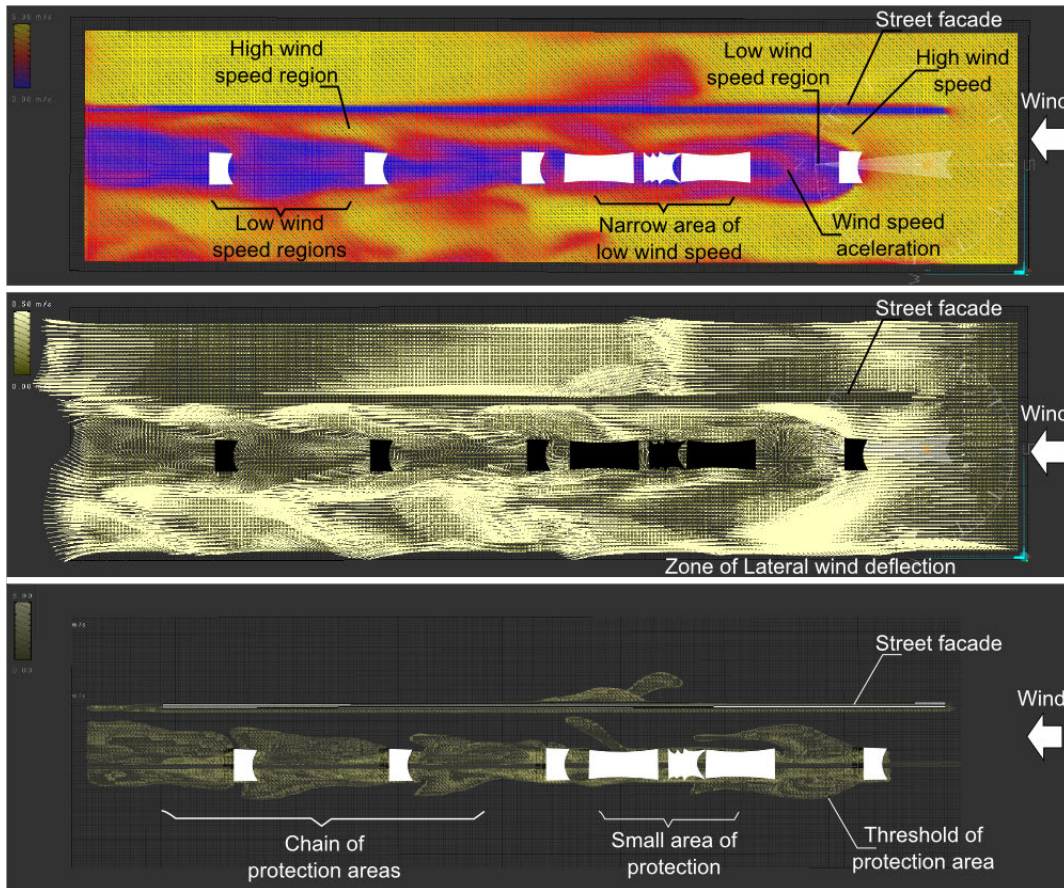
Figure 6.35: Wind visualisations of the protection wake produced for the membrane screens, with CFD Vasari. Top: 2D horizontal wind speed visualisation at 1 m height. The roof area presents levels of high wind speed. Middle: 2D horizontal vector field visualisation showing lateral airflow deflections around the screens. The first screen produces a strong and significant deflection. Bottom: 3D isosurface of wind speed region (1.5 m/s). The roof area has a thin region of protection. (Source: author)

What it is observed clearly is the chain of "protection bubble" behind each screen
and along the tram stop area. But the condition of these protection regions with low
wind speed is different in the ANSYS visualisation, because the area with more screens
(shelter) appears with a small protection area and the area with few screens has a wider
region of protection (Figure 6.36).
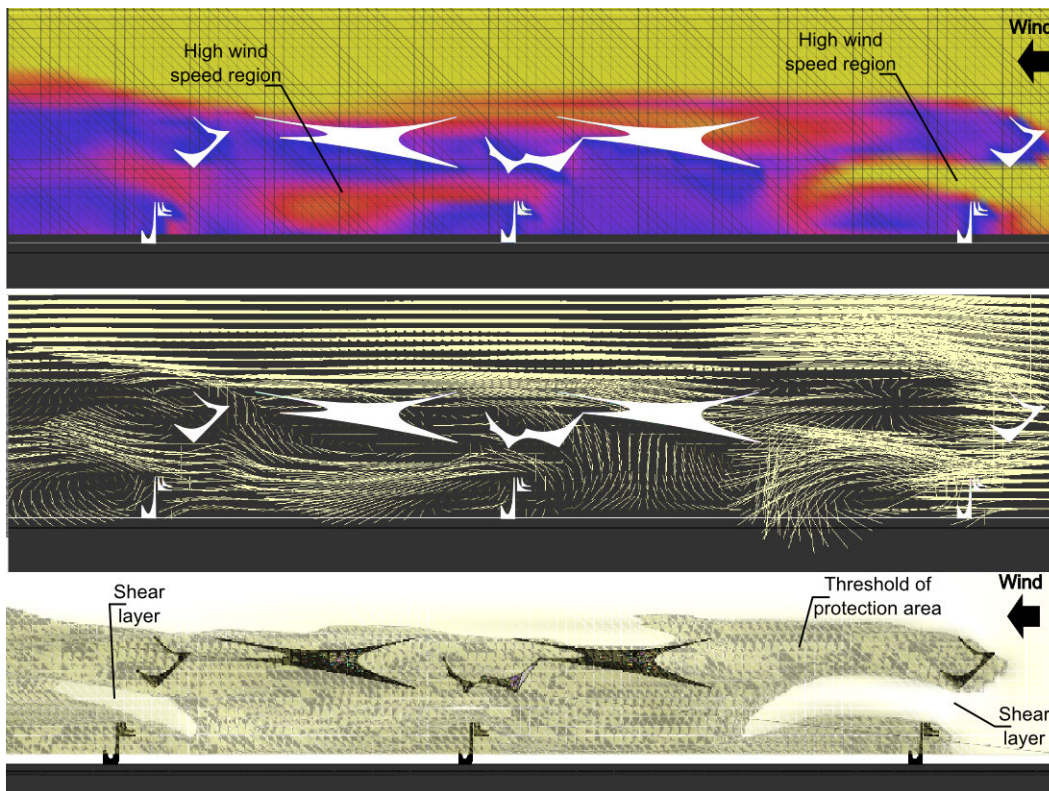
Figure 6.36: Wind visualisations of the wake produced for the membrane screens, with
CFD Vasari. The wind flow patterns are the same from visualisation of screen with regular
geometries but are different from Visualisation with ANSYS CFX. Top: 2D vertical wind
speed visualisation of the screen wake. There are high wind speed regions behind the first
and second screen. Middle: 2D vector field visualisation showing a low vertical deflection
from each screen and lack of airflow ventilation through the gaps of the roofs. Bottom:
3D isosurface visualisation showing a region of low wind speed (1.5 m/s). The gaps are
zones with high wind flow velocity. (Source: author)

As mentioned, the Vasari software reaches its limit with a low level of grid refine-
ment, that makes it difficult to visualise more clearly the differences between aerodynamic
features such as deflector fins, with regular geometry and irregular geometry (at this scale).

6.4 Rapid wind visualisation in an ABL wind tunnel

The ABL wind tunnel was a complementary tool in this investigation. The results from Vasari and ODS-Studio were quite different about the effect of vertical wind deflection and the protection bubble. For this reason, I decided to conduct experiments in the ABL wind tunnel to validate in some grade any of the results. In addition, it was an opportunity to evaluate the performance of a real wind tunnel for the purposes of wind analysis in the early design stage. That is, for rapid wind visualisation.

For these experiments, a visualisation method of data display was considered (from the experiment to a graphical interface), to show the intensity and the fluctuation of the wind flow velocity. The aim was to see if this way of visualisation works as a method for rapid feedback. It is necessary to mention that these experiments were a collaborative work with PhD candidate Daniel Prohasky and the assistance of Professor Simon Watkins who provided the access to the ABL wind tunnel.

Experiment set up

The group of physical tests was conducted in a boundary layer wind tunnel, in the School of Aerospace, Mechanical and Manufacturing Engineering, at RMIT's Bundoora campus. Scale models of screens (1:30) and porous membranes were built and installed in the wind tunnel, to analyse their performance as deflectors and mitigation screens. The reasons to perform these physical tests were:

- to visualise the vertical wind deflection on a windbreak designs with a non-porous condition.

- to visualise the vertical wind deflection on a windbreak designs with a porous condition.

- to visualise the effects of wind ventilation, through the gaps, between the roofs.

- to evaluate the digital visualisation of data from a physical experiment in a wind tunnel.

The experiments in the boundary layer wind tunnel had two stages. The first stage was to test a scale replica of the regular non-porous geometrical models of windbreaks and measure the wind speed in strategic points. These measurement points were predefined using the visualisation of the past CFD visualisations: the areas of high wind speed and wake regions behind the screens. Also, the numerical simulations were the main reference to calibrate the wind velocity profile in the wind tunnel from an original 1:100 scale to 1:30 scale (the size of the windbreak model).

The second stage was to test screens with canopies using porous membranes (Figure 6.37). These membranes replace the first convex deflector and the canopies in the shelter model. The idea was to measure the same strategic points to see the differences. However, this rapid visualisation has a qualitative approach based on the rapid feedback during this exercise. The quantitative data gathered in these experiments has not been fully validated. However, more information can be found in the papers for the eCAADe 2014 conference (see the appendix).

The boundary layer wind tunnel was prepared with a screen of timbers and a roughness on the ground to produce a wind velocity profile replicating an urban boundary layer profile (Figure 6.38). To simplify the conditions and keep the fragile models safe, the velocity intensity of the wind tunnel was regulated to 7-10 m/s, while the ABL speed variation was based on the power law equation. Using as reference wind speed of 5 m/s at 2 m height, the velocity profile was scaled from 1:100 and 1:30 for the experiments. Turbulence intensity was omitted for these experiments (Table 6.2).

Wind tunnel velocity	ABL	Scale model
4 m/s at 50mm height	Power law equation for urban context	1:30

Table 6.2: Table with main ABL wind tunnel parameters for rapid visualisation used in these experiments.
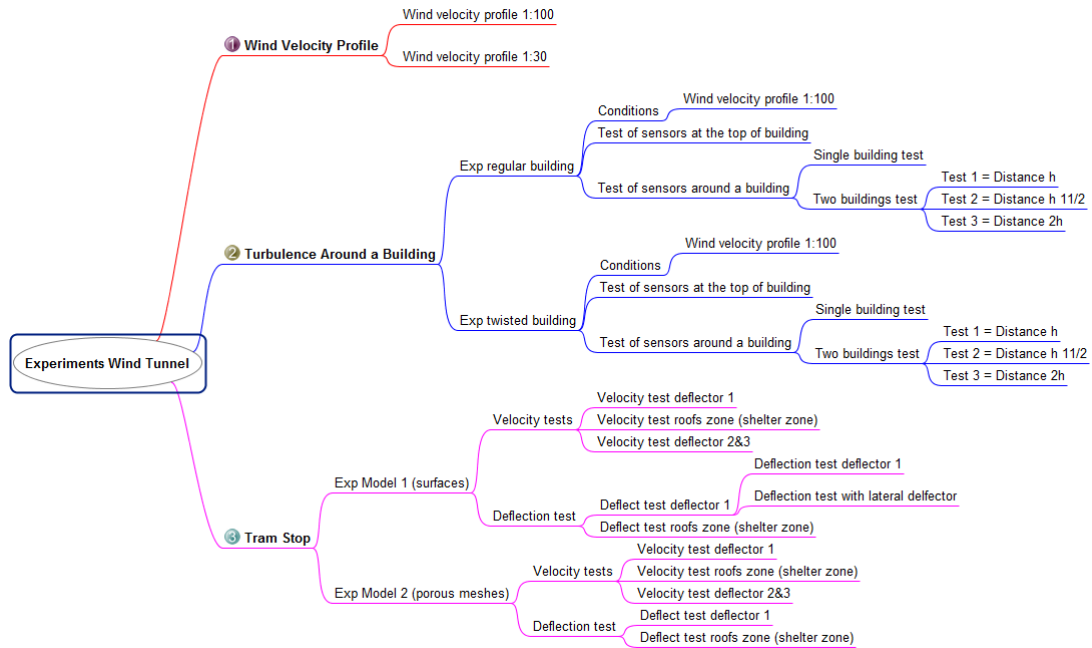
Figure 6.37: Program of physical experiments in the boundary layer wind tunnel of Bundoora campus. First task: calibration of wind flow velocity profile of the wind tunnel to 1:100 and 1:30 scale. Second task: measurement of wind flow velocity around a regular building form, 1:100 scale (see the appendix). Third task: measurement of wind speed around the mitigation screens, 1:30 scale. (Source: author)
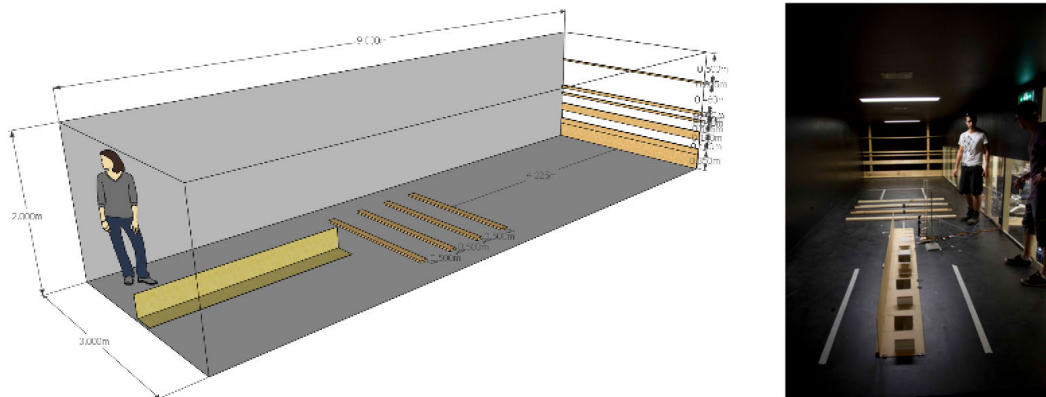
Figure 6.38: Left: diagram of the physical experiments in the boundary layer wind tunnel. Right: image taken from the inside of the boundary layer wind tunnel. (Source: Daniel Prohasky and Rafael Moya's work)

An ABL wind tunnel is a facility that is not always suitable to conduct wind analysis in the early design stage, because of its high cost and complex operation. For instance, for these experiments it was necessary to book the access of the facilities with plenty of time

in advance. In addition, for an exercise of rapid wind visualisation some adaptations in the process were necessary to allow a comprehensible visualisation and rapid feedback in a short time. Therefore, I considered that the process required adaptations in two stages: the method of data collection and the method of visualisation of this data.

To set up a technological platform for rapid wind visualisation in the ABL wind tunnel, these experiments were planned as a collaborative project with my colleague from SIAL, Daniel Prohasky. His contribution to this investigation was to develop a micro wind sensing platform and a graphical interface to visualise wind data in real time (Prohasky et al. 2014). Five micro anemometers were installed, after a process of calibration, to collect and visualise ambient temperature, analogue signal and wind speed data in real time. The sensors were used for two main tasks in the wind tunnel: the first task was to use the sensors to measure the vertical variation of the wind speed profile. With this information, it was possible to change the position of the timbers in the inlet zone of the wind tunnel to adapt the boundary layer effect to different scales. The second task was to put the sensors around the models to measure the speed at specific points. Using Grasshopper 3D with the Firefly plug-in and Rhino5.0 it was possible to develop a digital and graphical interface to directly receive the analogue signals from the data in real time, during the experiment for rapid feedback (Figure 6.39). The information about the sensing platform and interface of visualisation was published in the paper "Wind sensing with real-time visualisations for designers: An approach to understanding wind phenomena for pedestrian comfort using low cost wind sensors" (Prohasky et al. 2014).

(March 2015)
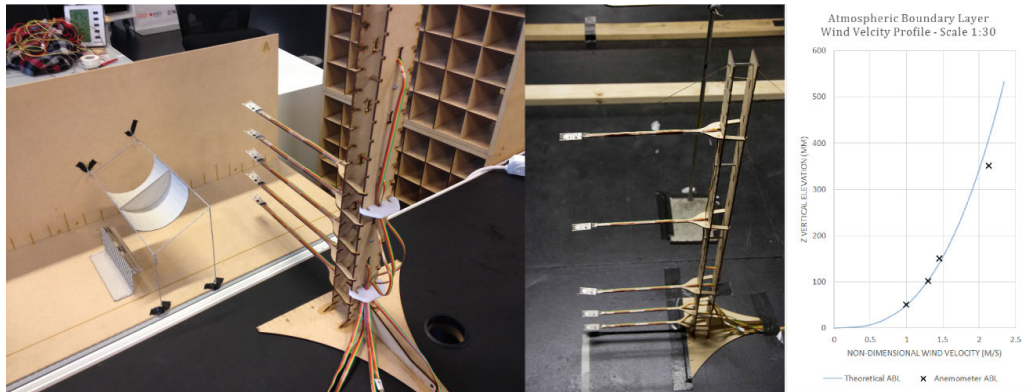
Figure 6.39: Left: electronic wind sensors to measure vertical profile of wind velocity near the windbreak screen. Middle: calibration tests with micro wind sensors to measure the ABL effect in the wind tunnel for a 1:30 scale model. Right: diagram with the boundary layer wind profile measured in the ABL wind tunnel. (Source: Daniel Prohasky and Rafael Moya)

Models of the screens and canopies were built to 1:30 scale with a vertical panel simulating a continuous wall of the street channel. The idea was to try to simplify the context in the same way as the numerical simulations. Thus, the MDF panel was installed to represent the west façade of Swanston St but the rest of the urban complexity was not considered, simplifying the wind phenomena observed. A first model with regular geometries was built with cardboard and a second model of porous membranes was created using a straw mesh embedded in plaster (Figure 6.40).
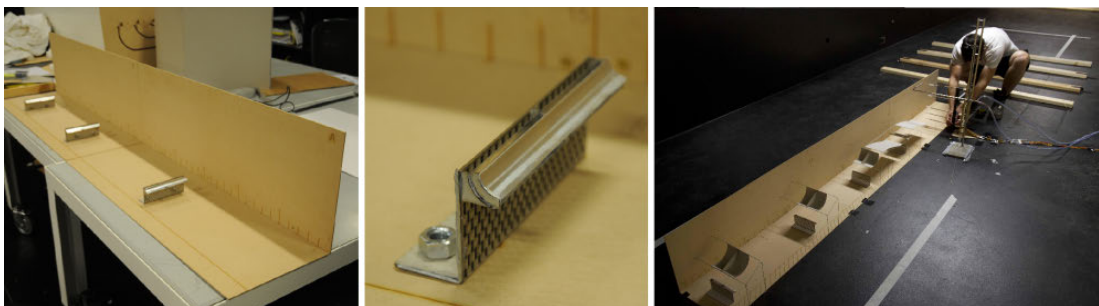
Figure 6.40: Left and middle: models of parallel porous screens with double deflector fins and vertical wall to simulate street façade (west footpath). Right: 1:30 scale screen models installed in the wind tunnel. In front of the model there is a group of timbers as roughness surface to increase the boundary layer effect at the ground level. (Source: Daniel Prohasky and Rafael Moya)

Rapid wind visualisation of windbreak screens with regular geometries

I have already explained that the experiments in the wind tunnel with the models had two parts: the study of screens with aerodynamic features as regular geometries, and porous membranes with similar configuration (Figure 6.41). Even though the intention was not to compare these experiments with the previous CFD experiments, the wind conditions of the wind tunnel tried to replicate the main parameters used in the previous CFD simulations with ANSYS.
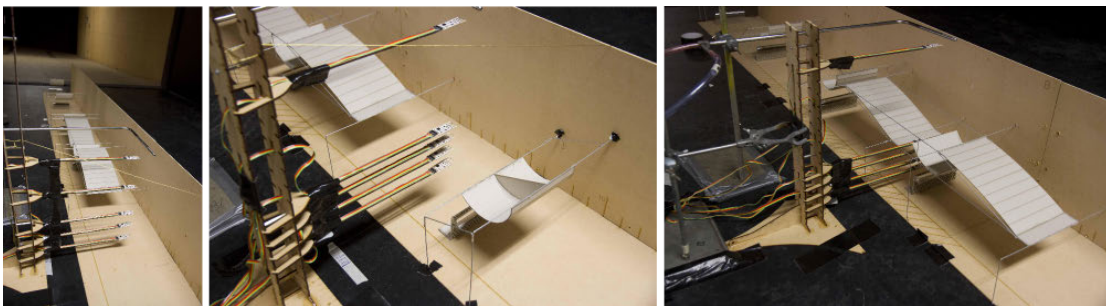
Figure 6.41: Measurement points in the models of screen with regular geometries in the ABL wind tunnel. Left: measurement of vertical wind velocity profile without screen. Middle: measurement with screen and canopy. Right: measurement in the shelter zone below roofs. (Source: Daniel Prohasky and Rafael Moya)

The previous CFD visualisation of these screens showed several upward vertical deflections behind each porous barrier, and an extended low wind velocity along the area of the tram stop shelter. This analysis identified the main flow patterns for the experiments in the wind tunnel. The first region tested with the group of micro wind sensors, in the ABL wind tunnel, was behind on the first windbreak screen and deflector canopy. In this place, the sensors measured the velocity intensity at 5 0mm, 75 mm, 100 mm, 125 mm, 150 mm and 175 mm height (scale model 1:30 / 50 mm = 1.5 m). The data displayed showed that both elements mitigated the velocity intensity above the height of the porous screen (1.5 m). In general, the average velocity of 3.9 m/s in the wind tunnel was measured by the sensor at 100 mm (3 m), behind the convex deflector. This means that the aerodynamic slot and the convex canopy produced the "vault of wind" at that height and with that wind velocity (Figure 6.42).
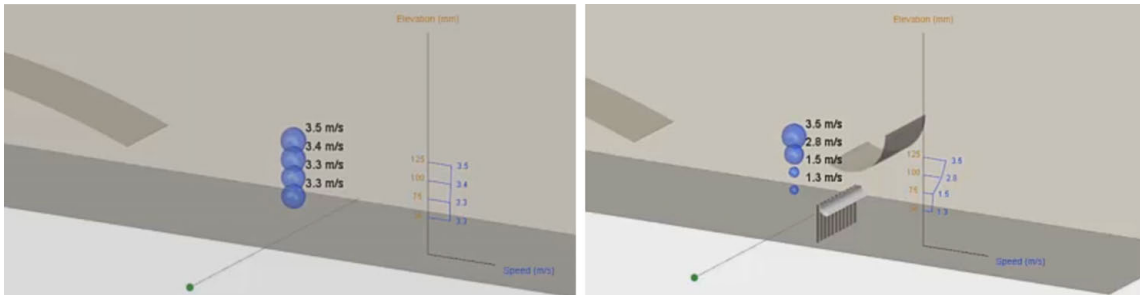
Figure 6.42: Left: real-time visualisation of vertical wind speed profile at the ground level without screen. Right: real-time visualisation of vertical wind speed profile behind the windbreak screen of 1.5 m height and canopy. The measurement points at 1.5 m and 2.25 m show a lower wind speed intensity as evidence of a high protection region, because of the vertical wind deflection. (Source: Daniel Prohasky and Rafael Moya)

In a new experiment, the sensors were placed in the roof area to measure the intensity of the wind deflection below the canopies. Under the first roof section, the wind speed kept constant. Then, the sensors were moved to a point behind the second screen to verify the ventilation gap in the roof; this test showed the acceleration of airflow through that gap, demonstrating that the design features performed as expected (Figure 6.43). The experiment showed how the canopies' configuration with three sections as roofs worked in a similar way as the ANSYS experiments, deflecting and mitigating the wind in the shelter area.
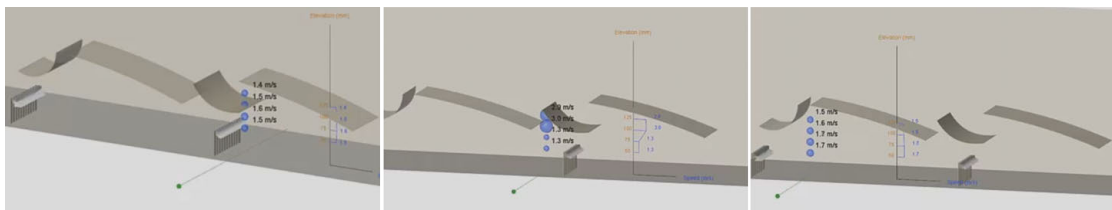
Figure 6.43: Left: real-time visualisation of vertical wind speed profile at the first outlet gap. The wind velocity is constant in the four measurement points and there is not acceleration of airflow through the gap. Middle: visualisation of vertical wind speed profile at the second outlet gap. A strong airflow acceleration is observed in this gap. Right: visualisation of airflow speed at the third gap, showing constant velocity for the group of points, without acceleration of airflow. In general, these results are more similar to the ANSYS CFX visualisations. (Source: Daniel Prohasky and Rafael Moya)

After these tests, a new experiment considered the manipulation of the model, changing the aerodynamic design features. For this test (not previously tested with CFD) the porous screen was changed to a smaller screen with an additional lateral fin, to generate a lateral deflection. The micro-sensors were placed behind the barrier to see the changes between these two different barrier models. Four sensors were installed behind the screen to measure the lateral deflection of this barrier. One of these sensors was in the protected region of the barrier. In a second moment, the screen was changed to a small screen leaving the sensors uncovered. The wind sensors were able to verify the effects of the adaptation. The experiment showed that a small screen with lateral deflector extended the region of protection for the sensor uncovered. This means that a small screen with aerodynamic deflector is a valid replacement for the first screen model. We could notice this in the same moment of the test by the graphical display of data in our rapid visualisation process (Figure 6.44).
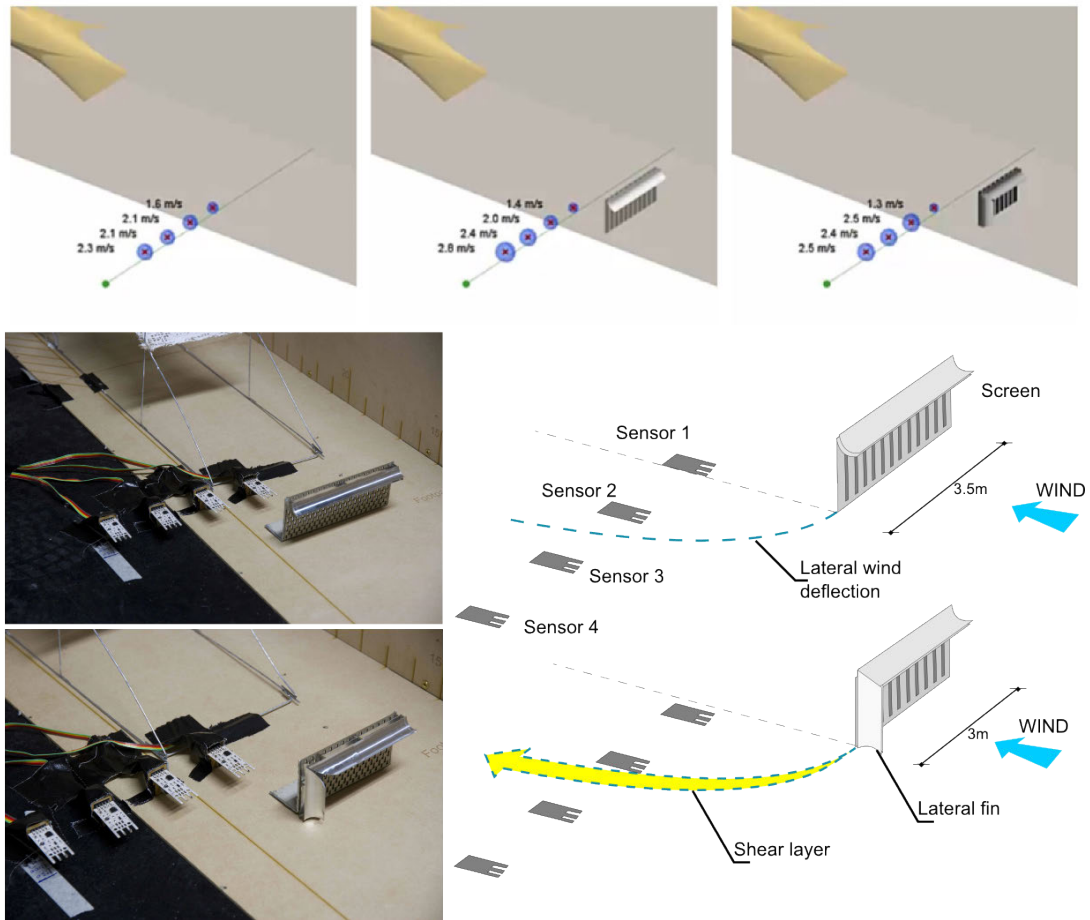
Figure 6.44: Physical tests and real-time visualisation of wind speed at the ground level with two screens with different sizes. Top left: visualisation of wind speed intensity from each sensor. Top right: small porous screen with lateral deflector fin. The last sensor is uncovered. Bottom right: visualisation of wind speed intensity from each sensors shows that last sensor still detects a low wind speed. Bottom left: models of large porous screen with sensors and small porous screen with lateral deflector fins. The last sensor is covered by the screen. Bottom right: diagrams showing the effect of shear layer projected from lateral deflector to keep the area of protection region on sensors. (Source: Daniel Prohasky and Rafael Moya)

Rapid wind visualisation with porous membrane morphologies

In the second stage, the roofs and the first canopy were changed for a porous membrane. The idea was to verify is the porosity condition changes in the vertical wind deflection produced by the windbreak screen. However, for the limitations in the time and the nature of these experiments as exercises of rapid visualisation, I avoided to consider complex wind parameters that are related with turbulent airflow (Figure 6.45).
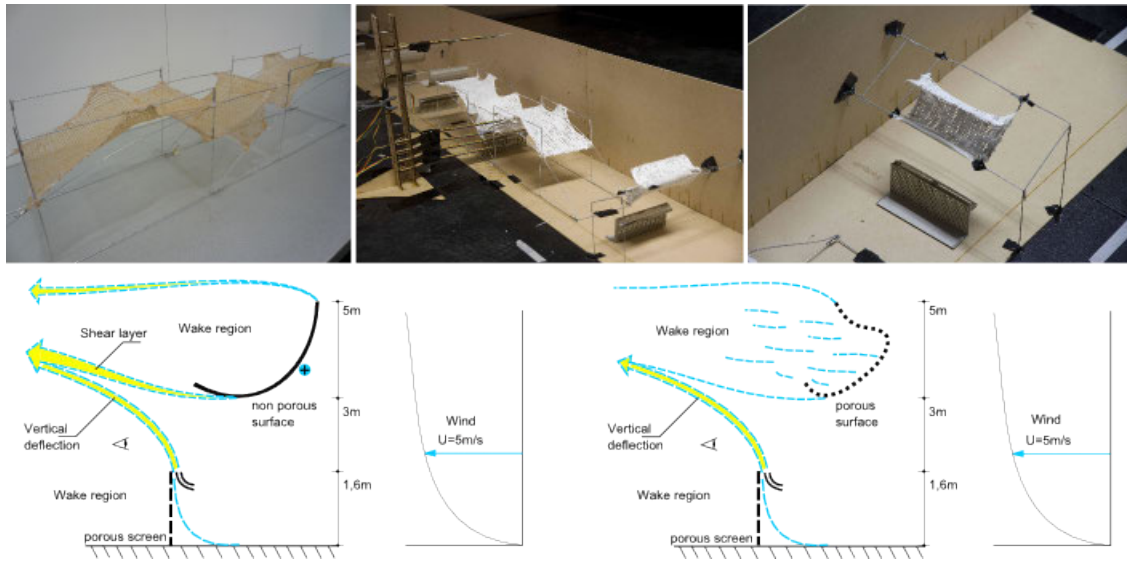
Figure 6.45: Experiment with porous membrane morphologies for the canopies and roofs.
Top left: models of porous membrane for roofs using a stretched mesh. Top middle: roofs
of porous membrane built with straw mesh embedded with plaster, 1:30 scale model. Top
right: first screen with upper porous membrane as canopy. Bottom left: upper non-porous
deflector produces a wake region with strong shear layers. This shear layer could be a
barrier for the upward deflection from the screen. Bottom right: a porous surface for the
upper canopy will mitigate the shear layers, facilitating the vertical airflow deflection from
the screen. (Source: Daniel Prohasky and Rafael Moya)

For these experiments with porous membranes, the general observations were similar
to the previous experiment with regular geometries. Similar vertical wind deflections and
upward flow behind the screens were observed. The main difference was with the porosity
condition of these membranes that decreased the wind speed intensity in the region behind
them (Figure 6.46).

In general, the observation of the data, graphically visualised in real time, gave a good
comprehension of the intensity levels of wind flow, because a new parameter is involved:
the time in the fluctuation of the wind velocity intensity. This parameter is not explained
in this research, but to see the variation of the wind speed by time, in some points around
the model, was useful to understand the dynamic nature of wind. For the cases where
elements were modified in the experiment, the comparison of wind velocity was clearly
observed (high differences with the low and high velocity), facilitating the association of
wind velocity intensity and the boundaries of the protection region. In fact, the idea
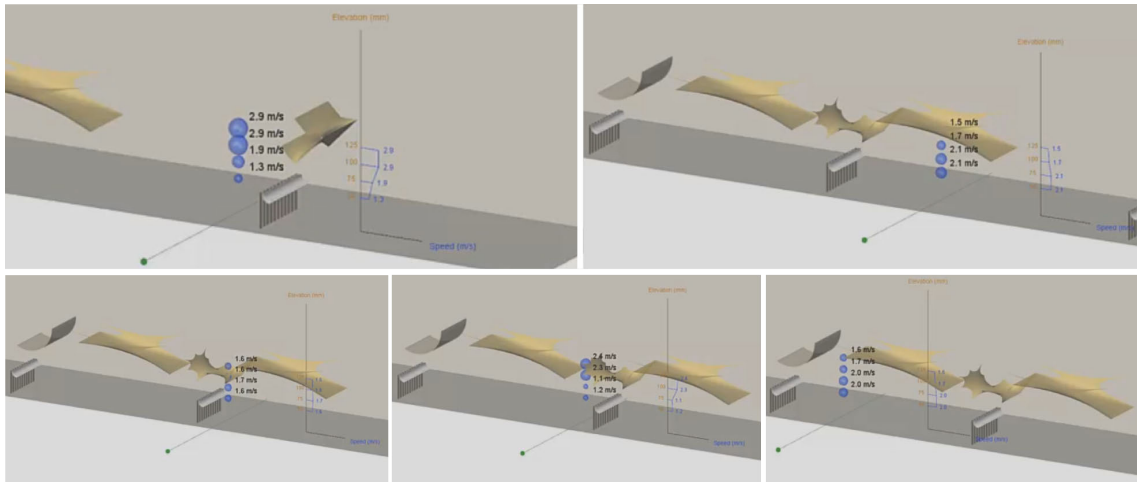
Figure 6.46: Real-time visualisation of vertical wind speed around screen with porous membranes. Top left: visualisation of high wind speed produced by the vertical wind deflection behind the porous canopy. Top right: visualisation of low wind speed in the roof area. Below the membrane roof the wind speed is lower than near to the ground. Bottom left: visualisation of wind speed at the first ventilation gap. The velocity is similar above and below the membrane roof. Bottom right: visualisation of wind speed at the third ventilation gap. The wind speed decreases with the height because the porous membranes produce an upper region of airflow mitigation. In general the membrane morphologies have similar performance a deflectors and increase the mitigation of wind velocity in the shelter zone of the tram stop. (Source: Daniel Prohasky and Rafael Moya)

of thresholds as gradual and fluctuating boundaries of these zones is clearly understood with this method of data display, integrating time in the visualisation. However, for cases where the wind velocity intensity shows a different pattern, with random fluctuations, this method was not sufficient to have a rapid idea about the changes. For example, when the frequency of the velocity fluctuation is lower, it is difficult to see the differences through the graphical display of data. It is necessary to post-process the information with charts to have a more clear idea of the phenomenon.

In this case, a post-process analysis (see papers in the appendix) has shown that the wind velocities are reduced behind the porous deflectors with respect to the non-porous deflectors. Turbulence intensities are also decreased in the same fashion due to the graduated distribution of pressure differences by filtration through the porous elements. Therefore, the results validate the hypothetical concept of windbreak screens and their effects observed in the ANSYS and ODS-Studio visualisations.

6.5   Summary

For a quick wind visualisation of these screens with aerodynamic design features and wind phenomena it was necessary to set up different parameters and conditions for each wind analysis tool. In addition, it was necessary to used more sophisticated techniques that are not frequently used by architects for rapid visualisation in the early design stage, such as the ABL wind tunnel.

The general evaluation of these tools shows that for rapid visualisation, tools such as an ABL wind tunnel required adapting with a platform of sensors and graphical data display, specifically for this case. In the same way, it was necessary to simplify the process of modelling and digital meshes (3D grid) in the sophisticated program ANSYS CFX to facilitate a rapid visualisation of several models. When complex geometries were included (porous surfaces or membrane morphology) the complexity of the process increased significantly. On the other hand, the CFD-PST program Vasari presented a low performance for visualising some details of airflow phenomena and different results (due to low control of the 3D grid). These results invalidated the hypothesis of the vertical wind deflection, while ODS-Studio and ANSYS presented more positive results validating it (Table 6.3).

Visualisation of wind screens of regular form for a shelter

Requirement	Vasari	ANSYS	ABL WT	Incidence in EDS decisions
It requires training and asistances of experts	no	yes	yes	
Import- modeling - mesh generation	yes-yes-n/a	yes-yes-yes /complex	built model /complex	The digital mesh generation with ANSYS was the more complex part.
Atmospheric boundary layer wind profile	no	yes /easy	yes /complex	Wind sensor platform with real-time visualisation was used in WT to calibrate two different scales of models in short time.
Visualisation of vertical wind deflection	yes	yes	yes /complex	ANSYS was defined position and configuration of canopies for screens and shelter zone. Vasari: showed low vertical deflection.
Visualisation of variation protection regions	yes	yes	yes /complex	ANSYS and Vasari: similar effects of protection regions when parallel screens are installed. ANSYS: design of shelter roof with ventilation gap.
Visualisation of airflow acceleration through slots	no	yes	yes /complex	ANSYS: visualisation validated the use of double fins in the vertical screens.

Visualisation of wind screens with NON-POROUS membrane morphology for a shelter

Requirement	Vasari	ODS-Studio	ANSYS	Incidence in EDS decisions
It requires training and asistances of experts	no	yes	yes	
Import- modeling - mesh generation	yes-yes-n/a	yes-yes-yes /easy	yes-yes-no /complex	ANSYS: The complexity to generate digital meshes with this geometries made not feasible a quick work with this program for quick visualisation.
Atmospheric boundary layer wind profile	no	yes /imprecise		It was possible to set up a imprecise ABL in ODS-Studio to visualise wind patterns with this condition.
Visualisation of vertical wind deflection	yes	yes		ODS-Studio: adaptation of deflector canopy design with membrane morphology and fin with slope.
Visualisation of variation protection regions	yes	yes		ODS-Studio: verification of similar wind effects with membrane morphology.
Visualisation of airflow acceleration through slots	no	yes		Vasari: it is not visualised this level of details for low resolution of grid.ODS-Studio: ventilation at bottom of screen for low lateral wind deflection.

Visualisation of wind screens with POROUS membrane morphology for a shelter

Requirement	ABL wind tunnel	Incidence in EDS decisions
It requires training and asistances of experts	yes	
Import- modeling - mesh generation	built model /complex	
Atmospheric boundary layer wind profile	yes/ complex	Wind sensor platform with real time visualisation was used in Wind tunnel to calibrate two different scales of models in short time.
Visualisation of vertical wind deflection	yes/complex	Wind tunnel required a system of graphic display of data for a rapid visualisation. Verification of porous canopies as best strategy for a more efficient mitigation of wind speed in vertical screens
Visualisation of variation protection regions	yes/complex	Verification of porous canopies as best strategy for a more efficient mitigation of wind speed in shelter zone.
Visualisation of airflow acceleration through slots	yes/complex	Verification of airflow ventilation through gaps between porous canopies in shelter zone, to keep low wind speed conditions under roofs.

Table 6.3: Table with evaluation of wind visualisation techniques and results of performance test for the analysis of a windbreak shelter. The evaluation established a group of requirements for easy and quick operation of the tool in the early design stage. The table shows the visualisation of specific phenomena that have an incidence in the design decisions. The tools can fulfil easily the conditions (yes/easy), with complex and slow process (yes/complex) or not be able to solve the task at all (no).

As a summary, the main outcomes of this investigation project were:

- The wind visualisation and analysis of more complex designs, such as screens with gaps and fins, required in ANSYS CFX an accurate pre-process of the 3D grid elaboration for the digital domain (with assistance). However, the wind visualisation of these windbreak screens with regular geometries showed the vertical effect of wind deflection produced by the screens and their improved effect of protection. These experiments demonstrated that the configuration of deflector fins in the screen and the whole group of wind screens were efficient in keeping a low wind speed at ground level, in the tram stop area. The wind visualisation of different positions and configuration of roofs was an interesting exercise of design exploration assisted by the CFD tool. In this sense, ANSYS CFX can be a tool to analyse simple design configurations, being suitable for a final step of validation of design concepts in the early design stage. However, complex design could be a challenge, because the level of work to prepare the conditions for each analysis is high.

- On the other hand, the preliminary experiments using ODS-Studio had a limited level of calibration, because of the lack of functionalities in the available version used for this experiment. For instance, the control of the boundary layer wind flow is not numerically set up. It was produced with an imprecise method, and local distortions in the wind flow could be produced, with the impact on the final effects. However, the requirement of an ABL was possible to generate. That said, the tolerance of the program to work with complex geometry forms and better 3D grid control were useful to analyse the screens with more complex shapes, such as membrane geometries. The visualisation level of the experiments was enough to confirm the vertical deflection of wind produced in the screens with deflector fins, and the protection regions generated on the area of the tram stop with the new configuration of windbreak screens. This means that the morphology of membranes presented a similar performance to the regular geometries tested in ANSYS CFX, producing a larger region of protection.

- In contrast, Vasari does not incorporate ABL as a parameter in the visualisation and it was not possible to set up a method to provide this effect. In addition, the scale of the model makes it difficult to increase the density of the grid to refine the visualisation. For the experiments of rapid visualisation, Vasari showed opposite results in the area of the roofs in the tram stop: the protection region was smaller than the other regions and the aerodynamic features do not improve the vertical wind deflection produced by the screens. In addition, Vasari presented several limitations for the study cases and development of design strategies based on thin surfaces, and porous structures, where the wind flow goes through the structures.

- The ABL wind tunnel required adaptations in two steps of the process for rapid wind visualisation: sensor platform and graphical data display. The main difficulty for the use of the platform of data visualisation, in the ABL wind tunnel, was the visualisation in real time of small changes and random variation of the data fluctuation. However, for this case, the visualisation of wind velocity intensity in a graphical interface, considering the time, was a useful technique to see the gradual variation in the wind produced by the height and the acceleration of the wind in several points around the group of screens. These methods showed the turbulent and fluctuating conditions of wind flow, which allows the understanding of other parameters of wind variation, in the boundaries of the protection regions. The interpretation of the information was easy for users without extensive training, such as architects. Thus, for this case, the results observed work as validation of the ANSYS and ODS-Studio results. However, it is not clear how this tool (even with these adaptations) could be more accessible in the early design stage.

In summary, the main challenge for the wind analysis with CFD software in the early design stage, was the high grade of sophistication in the interaction with wind that it is possible to achieve for designs of thin, large and porous structures. This means that the complexity of the designs involving porous conditions and surfaces with multiple curvatures could be rapidly vitalised by architects using tools such as Vasari or ANSYS CFX, but in some case the results can be contradictory, or adaptations in the visualisation

process could be required. In addition, a high level of skill could be necessary to operate
sophisticated software. Moreover, physical tests in an ABL wind tunnel showed a possible
friendly dimension as a tool for architects when integrated to a digital interface for real-
time visualisation of data, but without clear application at the beginning of the design
process.

6.6   Conclusion

This chapter has presented the process and results of several digital and physical exper-
iments of rapid wind visualisation. Through these tests involving a design process of a
sophisticated strategy of wind mitigation with screens and aerodynamic features, it was
possible to evaluate how these techniques perform under requirements of wind visualisation
for rapid feedback.

The preliminary results of these experiments of wind visualisation, for design concepts
of windbreak screens in a hypothetical tram stop area, suggest that the aerodynamic
features integrated in the screens extend the normal protection regions of a flat windbreak
screen, without modifying the height or length of the screen. These results validate the
idea of a row of protection bubbles produced by the windbreak shelter. Additionally, these
experiments have tested these features of membrane morphology, which are more complex
forms than the original regular geometries of a flat screen, and the preliminary results
showed a similar performance to produce larger protection regions. Therefore, there is a
potential in the application of these features, as a design strategy, for artificial windbreak
solutions, with designs based on tensile fabrics or more complex membrane shapes.

On the other hand, the wind visualisation techniques evaluated were suitable for rapid
visualisation of general wind flow around the screen models incorporating aerodynamic
design features, but in some cases (membrane morphology) presented high complexity in
the process, making more difficult their use for rapid wind visualisation. In another case
(Vasari) the results were quite different between techniques and a validation was necessary.
Moreover, sophisticated technologies, such as ABL wind tunnels, could become more user-
friendly for architects if a data visualisation approach is incorporated (graphical interface

and low-cost devices).

The next chapter will present a general discussion of the outcomes of the previous four investigation projects and draw conclusions from the whole study. This discussion will consider the main findings of each group of experiments, the gaps that this research leaves, and possible future lines of exploration.

Outcomes: discussion and future implications

7.1 Introduction

As research by project, this study has explored concepts of wind screens and a windbreak shelter design, applying wind visualisation techniques in the design process, to evaluate the aerodynamic performance of these concepts (Figure 7.1). At the same time, the project allowed me to evaluate these tools under requirements of rapid feedback in the early design stage. The findings of the four investigations are specified at the end of each corresponding chapter. In the following sections I present those empirical findings to respond to the research question and to elaborate some suggestions about improvement for the experience of wind visualisation, for architects with these wind analysis tools.
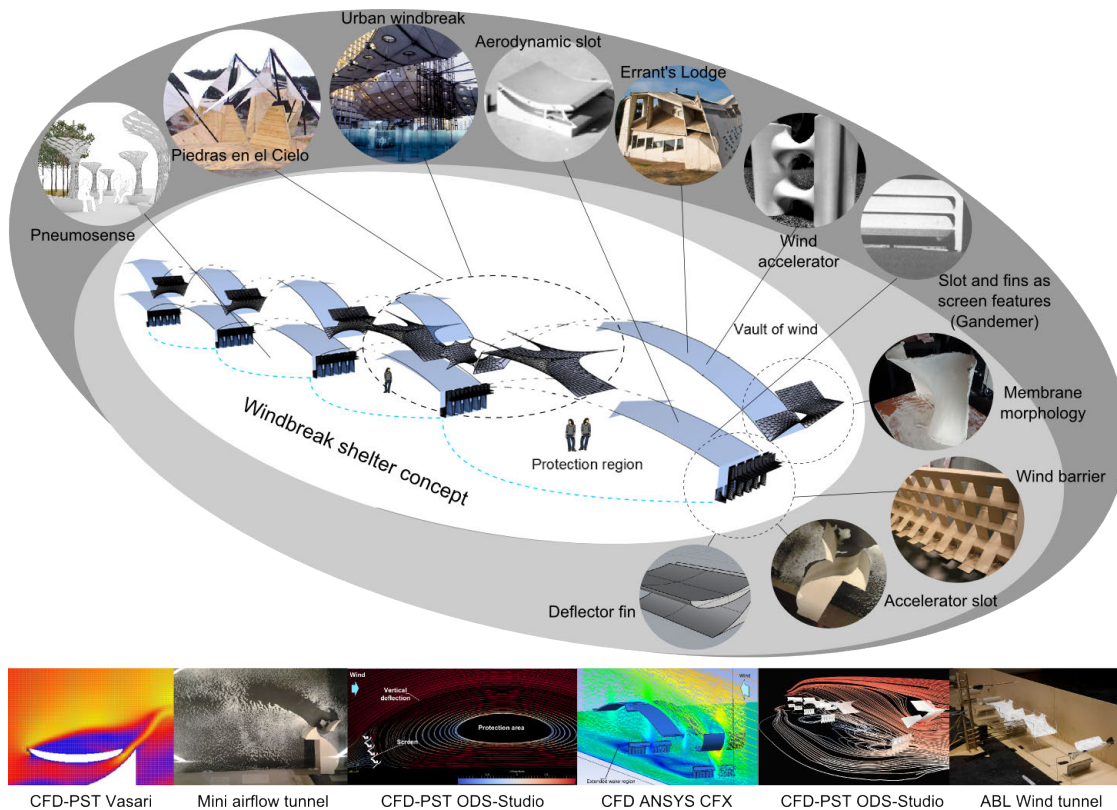
Figure 7.1: Diagram of different topics incorporated in the exploration of a conceptual design for a windbreak shelter. This project allowed me to evaluate several techniques of wind visualisation for their use in the early design stage. The external boundary involved the ideas extracted from literature review and previous works. The second perimeter considers the concepts of aerodynamic design features explored in the second investigation. The centre shows the project of a windbreak shelter for a tram stop. At the bottom, the different wind visualisation techniques used to link all these ideas and concepts through the study of their aerodynamic properties are shown. (Source: author)

7.2 Empirical research findings

In this section are presented the main findings for each investigation developed through my research. From these empirical research findings to answer the research question about the performance of CFD-PST (computational fluid dynamics - performance sketch tools) during the early design stage, it is possible to make two statements. The first explains the performance level of these techniques in relation to the requirements of the rapid visualisation process, timing and complexity of analysis in the early design stage. The second statement refers to a definition of basic elements of a criterion, that can be used to

improve visualisation functions and for a better interaction and feedback using CFD-PST in scenarios of wind phenomena around more complex design topologies.

- **Evaluation of CFD-PST and other techniques for rapid visualisation of main wind movement patterns around an isolated closed building form.** The first investigation considered a group of basic aerodynamic phenomena around a building, as parameters of evaluation for each tool. The results showed that a CFD-PST program (Vasari) is suitable for observing and identifying windward airflow phenomena, while the turbulent leeward wind phenomena is more difficult to identify. However, as a result of lack of a good practice to conduct 2D flow visualisation, the correct identification of wind phenomena could be difficult; especially the windward phenomena at the base of a building. Any CFD-PST program that uses 2D wind flow simulation, as the main method of visualisation, could improve the experience and feedback by elaborating functions and instructions to facilitate the 2D visualisation, based on a first 3D wind flow simulation. Another observation related with 2D visualisations is the disassociation effect between CFD-PST visualisation of partial areas or 2D sections and the 3D nature of wind phenomena. This dissociation can make more difficult, for designers, the identification and comprehension of wind flow around a building. In this sense, a physical airflow tunnel showed that a method of 3D visualisation, as the first observation stage, could facilitate the preliminary comprehension of the general wind movement, for users without a strong theoretical background.

- **Evaluation of CFD-PST for rapid visualisation of the main wind movement patterns through a large built environment and around an artificial windbreak in a local context.** The results of the second investigation demonstrated that CFD-PST allows an easy visualisation of high and low wind speed areas along streets, and areas of wake regions behind buildings in local contexts. However, due to the limited control of the grid domain in CFD-PST Vasari, it is more difficult to identify local wind movement patterns in a large scale visualisation (deflection of airflow around corners, and vertical wind patterns such as vortices in streets

produced by canyon effects). In general, Vasari allows a rapid and comprehensible visualisation of horizontal wind movements through an urban grid configuration of streets (channel effects). However, the vertical and transversal movements of wind in the streets are more difficult to visualise (canyon effects). A low density level of the digital grid in CFD-PST Vasari is enough for observation of continues long areas, but inadequate for observing the vertical movements in a street section (for large scale visualisation).

On the other hand, in a local scale context and for analysis of windbreak structures, CFD-PST Vasari produces confuse visualisations of wake regions of porous structures. It is not possible to estimate the level of wind protection in artificial windbreaks (even with a qualitative approach). Therefore, it is not possible to compare or evaluate the protection produced by windbreak design alternatives, using this kind of tools.

A simultaneous visualisation process of large and small scale visualisation is not well addressed by a normal CFD-PST workflow. The programs can not extrapolate the results from one visualisation scale to the next visualisation, in order to maintain a continuous workflow. On the other hand, the elaboration of wind maps with digital data can be a useful function, if it is incorporated into a CFD-PST workflow to work as a link between different visualisation. Thus, workflows with CFD-PST programs should consider functions and protocols for rapid visualisation through multiple visualisation scales.

- **Evaluation of CFD-PST and CFD for rapid visualisation of wind flow through isolated windbreak screens with aerodynamic features.**

CFD-PST Vasari was able to visualise wind phenomena (separation zones and vertical wind deflection) associated with a simple design of a wind barrier (barrier with single fin deflector and slot). However, for barriers with multiple and more detailed features, CFD-PST Vasari generated misleading visualisations. This issue does not allow the exploration of small and more sophisticated aerodynamic design features (multiple deflector fins or multiple slots, porosity, and so on) with this kind

of program. However, if a CFD-PST program has a better control of the digital grid generation, such as ODS-Studio, it is possible to conduct more active design exploration and visualise airflow through small design features. More sophisticated CFD programs can be efficiently used in rapid wind visualisation, but with simplifications of parameters. For instance, the complexity of the control to generate digital mesh, for domains in ANSYS (as traditional CFD), can be a challenge for rapid visualisation process in the early design stage.

- **Evaluation of CFD-PST and other techniques for rapid visualisation of wind flow through a configuration of parallel windbreak screens with aerodynamic features (for an urban shelter).** CFD-PST programs facilitate a quick set up of parameters for visualisations in the pre-process stage. Thus, it is easier to visualise simultaneously several structures, such as large groups of screens and canopies. Vasari allows the visualisation of the protection bubble region associated to the large configuration of a windbreak shelter. However, it cannot visualise the airflow interacting with the screen design features, such as slots and multiple deflector fins. This is because a low sensitivity to work with detailed designs and the limited control of the coarse grids of the digital domain. When the idea is to explore more complex forms, such as the aerodynamic design features incorporated on screens (studied by Gandemer), the pre-process in sophisticated CFD programs can be complex. This means a slower rapid visualisation process (this was the case of the sophisticated program ANSYS with some of these tests). The positive performance of CFD-PST was the tolerance and flexibility to work with complex geometric forms for rapid wind visualisation. ODS-Studio allowed the exploration of Gandemer's screens concepts and evaluation of complex membranes morphologies for the screens and canopies, due to better control of the digital grid generated for the flow domain. Other techniques, such as CFD ANSYS and ABL WT, were efficient in the design exploration process and as validation methods. However, they required the simplification of parameters and geometries to simplify visualisation; or a graphical interface was needed to have a visual representation and quick feedback.

7.2.1 First group of deductions: CFD-PST programs allow rapid visualisation with a qualitative approach that is useful for quick observation, basic comprehension and dynamic design exploration

A first conclusion of this investigation is that the associated functionalities of two CFD-PST programs (Vasari and ODS-Studio) contribute to simplify the visualisation process (timing, stages and complexity of operation) for preliminary and qualitative analyses in the early design stage of a project, regardless of the influence of complex wind conditions, such as ABL effect or the interaction of airflow with complex structures (porous surfaces).

This study has identified some aspects that define or are required in the process of generating rapid visualisation of aerodynamic phenomena in built environments, using CFD-PST and other wind analysis techniques. These aspects determine the main differences between tool performances, complexity of visualisation process, possible causes of slow visualisation process and what kind of features and functions must be adapted to facilitate rapid visualisation (when additional wind parameters or complex and porous structures are involved in the analysis).

In a comparative evaluation of these techniques, based on the observations and results of the investigations conducted in my research, it is possible to establish a diagram to represent the requirements of early design stage as a ratio of time of analysis process and complexity level of simulation, to classify the tools tested by their performance. However, this evaluation only applies for visualisation of outdoor airflow (Figure 7.2).
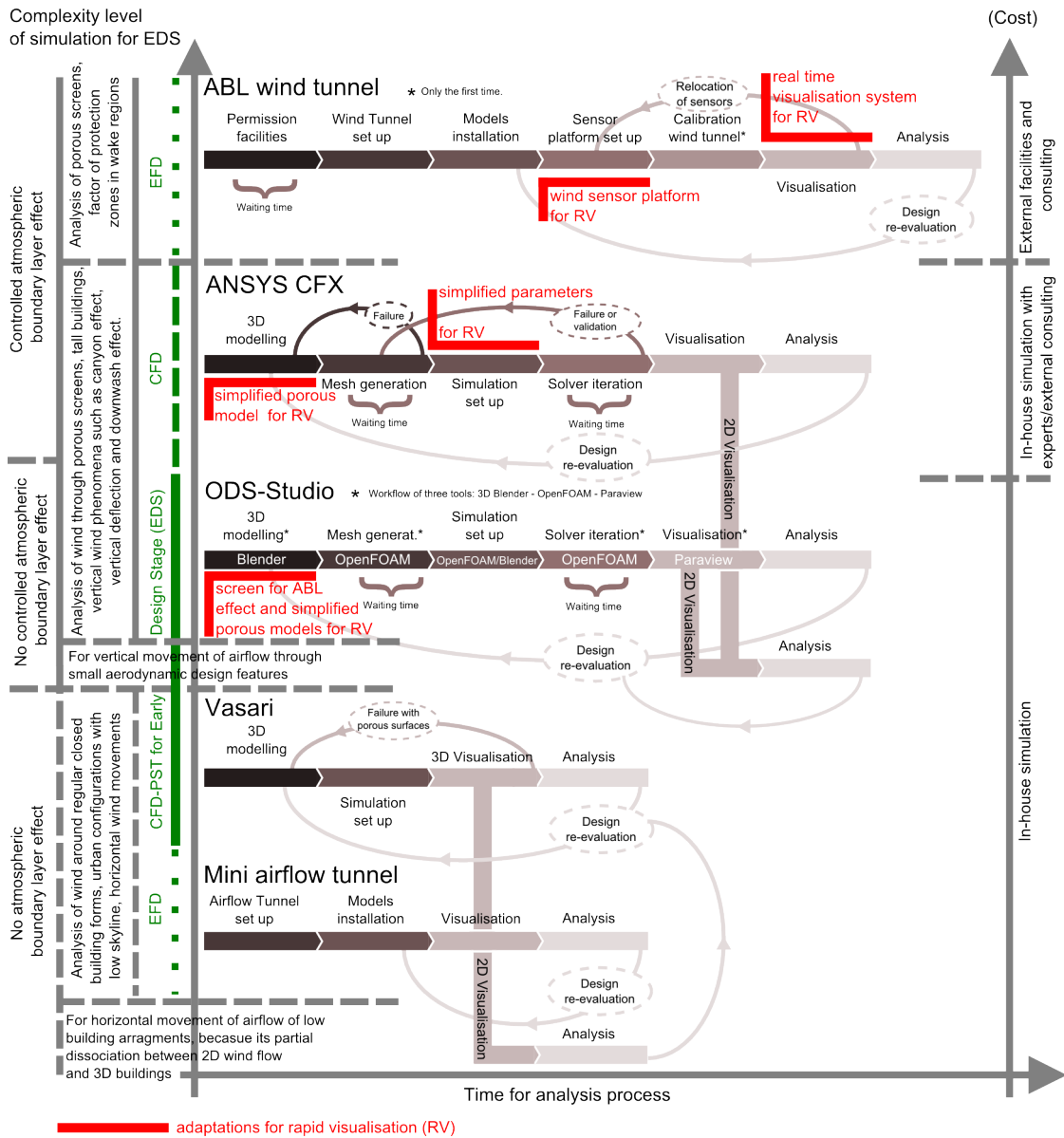
Figure 7.2: Evaluation diagram of wind analysis techniques used for rapid visualisation in the early design stage, with a ratio of time of analysis process and complexity level of simulation. The evaluation only applies for visualisation of outdoor airflow. From the bottom to the top the diagram shows the simplest tool tested in this research (mini airflow tunnel) to the most complex (ABL wind tunnel). The diagram includes the stages of each technique or program to resolve a wind analysis process, including the loops when the design is optimised and when there are failures or validations actions. The red marks indicate the features adapted in a program for rapid visualisation. (Source: author)

Thus, it is possible to observe that:

- the CFD-PST programs require few stages, and shorter loops of evaluation to com-

plete a process of analysis (less time processing), but results of visualisation of vertical wind phenomena are mitigated by simplified wind conditions (no ABL effect).

- CFD-PST programs produce visualisations with 2D wind flow that facilitate rapid graphical display, but this can be partially dissociated from other airflow movements produced around a 3D shape of a building. This means a difficult identification and comprehension of some wind phenomena near the base of buildings.

- CFD-PST programs are highly tolerant to geometries and digital mesh generation, so there are no failure loops in their analysis processes (difficulties in generating quality meshes or cessation of the simulation process), which means the visualisations can be generated quickly, allowing more tests with different designs in a short period.

- the CFD-PST produce quicker visualisation processes. But the analyses are reliable and comprehensible for outdoor environments around closed building forms and low skyline buildings. For cases of wind analysis on porous structures it is necessary to use more complex programs with longer analysis processes.

- ODS-Studio is a transition tool CFD-PST program, and CFD program, to conduct rapid wind analysis with relatively complex wind conditions (ABL) and a good tolerance to complex digital meshes, which facilitates the analysis of wind through porous structures.

- The use of more complex CFD programs requires more simplification and adaptation of parameters to conduct rapid wind analysis: simplification of geometries and porous patterns in models to facilitate the digital mesh generation and simulation (ODS-Studio and ANSYS CFX), and the use of a platform of multiple sensors, with a real-time graphical interface of visualisation in an ABL wind tunnel.

The diagram and the findings presented show how these techniques can be used by architects in the early design stage. Therefore, the best strategy to conduct rapid wind analysis for pedestrian comfort with these tools should first define the complexity for the simulation cases and the tempo of feedback in the analysis process. Thus, with simplified

wind conditions, for cases where the variation of wind velocity with height is not relevant and the observations are focused on horizontal movements of wind, CFD-PST programs like Vasari can be used for analyses of windy environments around isolated, regular and low buildings. Also, Vasari can be used in cases where the analysis considers urban configurations of several buildings with low skylines (no differences of height between buildings) where the more significant phenomena are associated with the wind channel effect. This positive performance was clearly observed during the second investigation, where the visualisation of 2D wind flow was useful to quickly identify potential areas with levels of discomfort produced by high airstreams horizontally flowing through the streets of a configuration of buildings. In addition, for rapid visualisation of several and different design alternatives, it should be more efficient to use a CFD-PST because they have a shorter analysis process (Vasari) and high tolerance to complex digital meshes (ODS-Studio), facilitating the repetition of the analysis processes.

For rapid but more complex wind visualisation, including aerodynamic phenomena related to the ABL effect, it would be more suitable to use CFD-PST programs similar to ODS-Studio to analyse wind conditions around tall buildings, groups of buildings with different heights, and any case where it is important to visualise vertical wind deflections, canyon effects, downwash effects and the rapid visualisation and analysis of the wind interaction with structures of porous screens and aerodynamic design features. The good performance of this program (with its associated software) on these tasks was observed during the experiments in the last two investigations.

When more detailed or reliable results are required, it is recommended that highly controlled ABL conditions in the rapid visualisation process are incorporated. However, this will require more sophisticated tools such as ANSYS CFX, which may not be the best tool for the early design stage, but with a geometrical simplification of the models and the use of standard wind parameters, it is possible to facilitate the rapid visualisation process (see the third and fourth investigations). On the other hand, for similar requirements, ABL wind tunnels are tools that would need to be set up and adapted with special hardware (sensors) and software (graphical interface) to generate rapid visualisation of wind phenomena. Without these features, incorporation in the early design stage is very

difficult.

To make clearer the differences between wind analysis programs and for a better knowledge of their capabilities and limitations for tool selection, the pros and cons of Vasari, ODS-Studio and ANSYS CFX, observed through my investigations (see the tables of evaluation at the end of each chapter) were gathered in a table, with the above mentioned approach of rapid visualisation for the early design stage. This table organises the advantages and disadvantages into four groups: user, workflow, parameters and results (Table 7.1).

The table shows that, under requirements of rapid visualisation, Vasari presents more favourable observations in the categories of "user and workflow" (pre-visualisation), while more unfavourable observations are found in the group "parameters and results" (pre-post visualisation). This does not mean that the program is failing in these categories, but the program did gather more unfavourable observations towards the end of the four investigations, with experiments of progressive complexity level. On the other hand, for a rapid process of visualisation, the sophisticated tool ANSYS CFX gathered more unfavourable observations in the areas of pre-visualisation (user, workflow, parameters) and several favourable observations in the category of "results" (observed at the end of the last two investigation projects). ODS-Studio is a tool that presents many advantages in each category for the rapid visualisation process. Therefore, both CFD-PST Vasari and ODS-Studio can be considered as parallel tools for wind visualisation when the timing and simplicity of the analyses are most relevant for the early design stage. ANSYS CFX can be used as a method of validation or judgment at the end of the early design stage when there is a disparity of results generated from different CFD-PST programs.

The table identifies several difficulties associated with different stages of the analysis process, that an architect can find using CFD-PST for rapid wind analysis in the early design stage. Based on this information the user can develop better strategies of use and understand the main differences with respect to other, more sophisticated tools that are not commonly used by most architects at the beginning of the design process.

This evaluation of tools has established a relationship based on qualitative perceptions for these techniques, rather than a comparison based on a rating of accurate results, which

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		PROS (EDS)	CONS (EDS)
CFD-PST VASARI	USER	1) Very easy to set up and operate for EDS simulation. 2) It only requires a short tutorial for learning. 3) More accessible than traditional CFD software or wind tunnel facilities. 4) Suitable for users without a strong theoretical background in fluid dynamics.	1) Beta version with expiry date of one year.
	WORKFLOW	1) Short analysis process. 2) Rapid visualisation, feedback. 3) It allows several analysis processes of different design alternatives in a short period. 4) Integrated workflow between 3D modelling, CFD simulation and visualisation. 5) It allows an easy transference of digital models from CAD programs for simple and complex geometries. 6) Well integrated in the design process and with other BPS tools.	1) 3D wind flow visualisation requires a slow analysis process that can delay timing in EDS. 2) The visualisation cannot produced results to be extrapolated between different scale contexts for further simulations in a continuous workflow.
	PARAMETERS	1) It considers main wind parameters for wind comfort analysis in EDS. 2) It considers local geographical statistical wind conditions.	1) Method of visualisation with 2D wind flow produces limited airflow movement patterns which can be confusing. 2) Low grid resolution for large domains. 3) Does not consider methods of validation. 4) It does not simulate ABL conditions that mitigate downwash effects and lateral wind deflection. 5) It does not allow the incorporation of additional parameters of analysis.
	RESULTS	1) Visualisation of 2D and 3D wind flow. 2) Feasible to analyse horizontal wind movements around low buildings and channel effects. 3) Easy to identify horizontal separation zones, acceleration regions, lateral deflection, and wake regions.	1) Mainly for simulation of outdoor wind flow for pedestrian wind comfort. 2) Low level of accuracy in results. 3) Not reliable for detailed analysis of complex design. 4) With low resolution, aerodynamic feature effects are missing. 5) Useful only for analysis of low resolution designs, low buildings, and visualisation of horizontal wind movements. 6) Visualisation of downwash effect in tall building is lower, less significant. 7) Not reliable analysis with porous structures. 8) 2D wind flow cannot visualise ground level.
CFD-PST ODS-Studio	USER	1) It provides a relative rapid visualisation and feedback. 2) Relative easy set up and operates. 3) It only requires tutorial to be used. 4) More accessible than traditional CFD software or wind tunnel facilities (low cost). 5) Suitable tool to be fully incorporated to design process.	1) New program without many tutorials or community of users.
	WORKFLOW	1) Integrated workflow with strong programs of 3D modelling to visualisation. 2) The results can be shared with other programs. 3) It allows transference of digital models from CAD program. 4) Tool focused on the EDS.	1) It requires more time for analysis process and feedback than Vasari.
	PARAMETERS	1) It can be adapted to produce an approximated ABL wind condition. 2) Highly tolerant to geometries models for mesh generation and simulation. 3) Refined digital mesh of the domain for a more detailed visualisation. 4) It incorporates OpenFOAM as CFD engine.	1) It requires adaptation to get an ABL wind effect but it is not controllable.
	RESULTS	1) Useful to visualise 3D wind phenomena at the windward and leeward side of a model. 2) Useful to visualise vertical wind movements in urban configurations such as canyon effect and downwash effect on tall buildings and wind around groups of buildings with different heights. 4) The refined digital mesh of the domain allows a better observation of wind through small aerodynamic features.	1) Does not incorporate a method of analysis of protection factor and wind comfort level for analysis in EDS. 2) Does not consider methods of validation.
CFD ANSYS CFX	USER	1) Tool used by community of engineers.	1) It requires fluid mechanics knowledge, tutorials, guides and training for operation. 2) Few tutorials available for architectural simulations and architectural wind analysis in EDS.
	WORKFLOW	1) Integrated workflow from 3D modelling to visualisation. 2) It allows transference of digital models from CAD program. 3) It allows parametric modelling. 4) More integrated to design process than a wind tunnel.	1) It requires more time for analysis process and feedback in EDS. 2) Importation of geometries from other programs such as Rhino3D or Grasshopper is a complex task.
	PARAMETERS	1) Complete and controlled wind flow conditions such as ABL. 2) It allows refined digital mesh of domain for better visualisation. 3) It allows controlled ABL wind condition.	1) Sophisticated CFD program, it requires establishing a criterion of simplification of parameters for EDS. 2) It requires geometrical simplification with complex geometries such as porous surfaces. 3) To set up parameters and digital mesh generation can take a lot of time.
	RESULTS	1) Very accurate simulation tool. 2) Feasible to analyse vertical wind movements around tall buildings and canyon effects. 3) Good visualisation of windward and leeward wind phenomena 4) It considers validation methods. 5) The quality of results allows the use of ANSYS as verification method between CFD-PST.	1) More possible failures for lack of tolerance to parameter errors. 2) Results highly depend on parameters set up manually by the user.

Table 7.1: Table of the wind analysis programs used in this investigation, with their pros and cons under the approach of a rapid visualisation process.

would be too relative because of the complexity of simulations and for the differences of the analysis processes for each technique. The better strategy to evaluate these tools for the early design stage is the use of a criterion based on their properties as rapid visualisation tools that allow the identification and basic comprehension of wind effects rather than the replication of real wind flow or an accurate measurement. However, it is important to remember that all these observations respond to a specific approach of rapid wind analysis for pedestrian areas around buildings. These programs may have a different performance under other kinds of wind analyses.

7.2.2 Second group of deductions: Three proposals for rapid wind visualisation in the early design stage

The second statement about the research question is delineated from the visualisation methods displayed by these CFD-PST programs during this study. Based on the four investigation projects, I have discovered that for architects to have a rapid and more comprehensible feedback from wind visualisation around any design morphology more complex that simple 3D closed volumes, they require techniques that reveal three main things:

- for visualisation of wind around complex models, the perception of the global 3D spatial wind flow must be associated with the first visualisation stage of an analysis, establishing a logical association with the 3D form of the building and the further partial visualisations (visualisations of horizontal wind flow, vertical wind flow).

- In a workflow with different analysis stages and visualisation scales, the visualisation process must be a continuous operation through scales and contexts, using the first level of visualisation for large scales, and second and third levels of visualisation for local phenomena.

- For visualisation of wind around complex structures such as porous screens with aerodynamic features (windbreaks), it is necessary CFD-PST programs that visualise the protection regions produced, the limits and thresholds, thus identifying the

protection factor of these regions (to analyse levels of wind comfort). This will allow users to compare the results of their designs with other studies about windbreak screens (e.g. Gandemer's studies).

Currently, it is possible to state that there is no CFD-PST software that meets all of these three elements operating within the scope and knowledge base of architects, for rapid wind visualisation in the early design stage. Even though CFD-PST has facilitated the visualisation of scientific data for preliminary analysis, the feedback that architects require from wind visualisation may be hard to comprehend in cases of wind effects produced by porous windbreak screens or when the analysis workflow requires different scales of visualisation. Furthermore, the visualisation can be confused when analysis involves isolated and partial images dissociated from a global representation of a wind phenomenon. All these issues could make the early exploration of forms at the beginning of a design process slower.

Visualisation and perception of the global 3D spatial wind flow

The first main finding of these experiments is the dissociation between visualisations that show segmented regions of a wind phenomenon and the global complexity of the movement of wind around a 3D building. CFD-PST programs such as Autodesk Vasari tend to display, first, 2D visualisations of sections that show the dynamics of wind representing local and partial movement patterns; rather than a first global 3D visualisation of the wind flow. In contrast, the physical method of visualisation in a mini airflow tunnel, starts with a 3D representation of the air movement (fog test) and the observer, after that general comprehension of the wind phenomenon, can proceed to analyse the wind through partial visualisation using laser light or a post-process of photos with PIV. This association between global images and their derived partial visualisations is missing in the CFD-PST methods and it can be quite significant, when the observer does not have a previous knowledge about the different wind movement patterns around buildings (Figure 7.3).
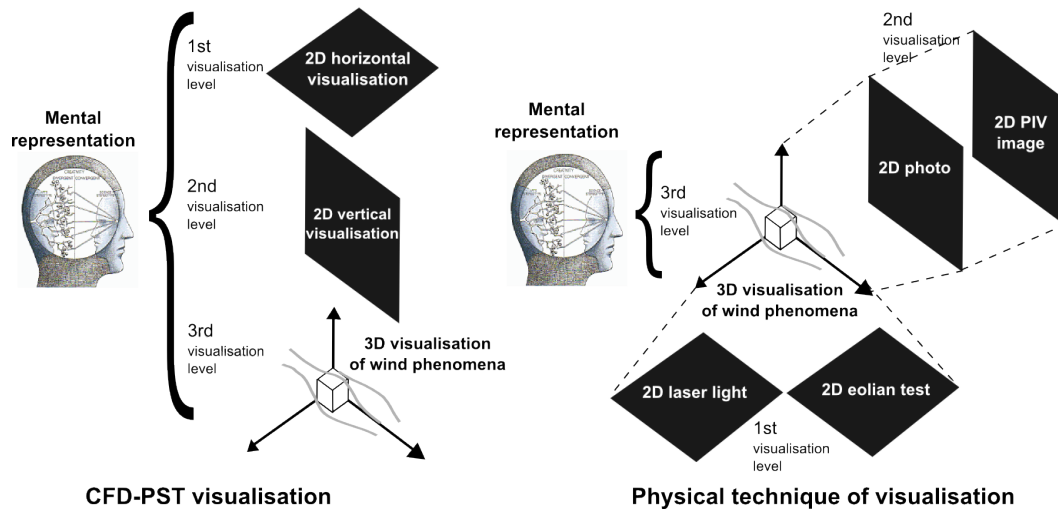
Figure 7.3: Diagrams of visualisation methods. Left: CFD-PST visualisation is generally represented with 2D graphical patterns of wind movements. The 3D visualisation is an option that is used for more accurate analysis. However, the analysis of 2D plots is difficult when there is not a previous mental representation of the global 3D phenomenon. Right: optical visualisation (mini airflow tunnel) where a 3D visualisation of the wind phenomenon is the first step. The visualisation techniques are derived from this first image, which facilitates the basic comprehension of each part of the general phenomenon. (Source: author).

I noticed this dissociation in the comparison between CFD-PST visualisations using Autodesk Vasari versus the direct observation with the mini airflow tunnel, during the first and second investigations. In those tests I observed that the visualisation of wind around single buildings and street configurations, using Vasari, showed that partial 2D visualisations of horizontal slices leaves the main part of the airflow movement unseen because these were in other levels or zones around of the model that cannot be noticed from this perspective, unless the observer is already aware of them. This is the case of vertical movements of wind at the top of models and vortex regions at the bottom, when the airflow has radical changes of movement. In fact, it is mentioned in the Vasari guidelines that 2D wind flow visualisations do not work near ground level, and a simulation with a 3D wind flow is necessary (Autodesk 2013b). The hidden phenomena can be underestimated if the observer is not well aware of their existence or when there is not a method to evaluate if the visualisation approach is sufficiently reliable.

Another condition that facilitates this dissociation is when a 2D wind flow is used

for visualisation of phenomena around 3D bodies. The 2D wind flow presents a restricted movement of wind through a bi-dimensional domain. I observed that the visualisation with 2D wind flow, around isolated buildings or through several buildings, will show different wind patterns and effects, compared with the pattern of movement visualised in a 3D wind flow. For instance, I observed in the first investigation that the CFD visualisation restricted to horizontal movements of airflow not only omits the vertical wind movement around a model, but also shows a wake of wind with unexpected wind movement patterns (osculating and irregular movements, even with regular and symmetrical building shapes). Because of this, the idea of symmetry in the movement of air, associated with the symmetry of the building shape, is not perceptible in these visualisations.

All these issues delay the comprehension of the global phenomenon, which may have an impact in the time line of the early design stage. The observation of partial and segmented regions of wind will provide an incomplete and underestimated comprehension of the general dynamics of wind phenomenon, leading the observer into limited conclusions and requiring more time for feedback to reach a good analysis.

In previous research, the positive impact of CFD-PST simulation and visualisation of wind in the early design stage has been widely recognised. However, observations about how the method of visualisation can affect the full comprehension of observers (designers or clients) is missing in the evaluation of these tools. There are no observations about strategies or order to put coherency in the method of visualisation of wind with CFD-PST, probably because it is seen as something subjective, but the current research has showed that CFD-PST can produce different visualisations and interpretations of phenomena if the tools are not used correctly. Thus, regarding the research question, I found that digital visualisation techniques, in the early design stage, facilitate the segmentation of a spatial phenomenon (something that in physical experiments has a slow set-up process), but also change the order of visualisation, starting with the parts before the global picture, which could be a barrier to comprehension for architects without a theoretical background. I think this aspect is crucial in the early design stage, because the confusion in the preliminary analysis can produce mistakes in the decision process that will only be noticed later, in the validation stage, rendering the early wind analysis in the design process useless.

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Therefore, considering that it is important to keep a direct association between the different partial visualisations and the global 3D movement of the wind flow, before proceeding with an analysis, some strategies can be suggested for developers to improve display methods in CFD-PST visualisation tools to assist the user, without slowing down the process of analysis:

- The 2D visualisation of wind flow around buildings could present a 3D pre-representation of wind movement regions based on several examples of wind profiles around different building forms taken from literature. The idea is to make visible the 3D form of the airflow from the beginning of the visualisation. This could be used as a neutral graphical map to represent the omitted regions of airflow. This representation of wind flow regions does not need to be a calculated simulation. It is just a reference for the observer, who can use it as generic representation to understand the segmentation that produces the CFD-PST visualisation. For instance, flow representation programs used on graphical game engines, such as Real Flow, can generate a generic 3D image of wind phenomena around a building that can be used as a generic pattern of airflow regions. In fact, this program has already been mentioned with respect to the re-creation of wind patterns for preliminary visualisations (Kirkegaard et al. 2008).

- The visualisation of 2D wind flow with CFD-PST programs should be associated with a strategy of use to produce more regular and symmetrical movement patterns for regular geometries of buildings. For instance, the 2D wind flow around a cube should produce a representation of a wake region similar to the actual wake region produced by a cube. In addition, this strategy should provide a guide to facilitate the choice between visualisations of 2D wind flow and 3D wind flow for a specific scenario. This means that the program should suggest when it is a good strategy to visualise 2D or 3D wind flow for a specific analysis.

Continuous workflow for the analysis process of wind phenomena through different scale and context

The second main finding is about the visualisation with CFD-PST through a workflow that presents gaps between the visualisation of wind in a large-scale context such as a built environment, and the small-scale visualisation of wind interacting with an artificial windbreak for pedestrian wind protection. CFD-PST does not consider a method to facilitate the extrapolation of parameters and outcomes from a first large-scale visualisation to conduct a second visualisation of a local context. This means that these wind visualisation programs do not facilitate a clear continuity of analysis between the cause of wind discomfort conditions in a built environment and the effect of a windbreak in a pedestrian zone. Therefore, the wind analysis process is a workflow with independent stages of visualisation and gaps between them, which makes it difficult to visualise the development of a wind phenomenon through the urban space.

I understood the relevance of a continuous workflow for an analysis process in my second investigation, when I observed that the program for wind analysis, used by a group of designers in an elective course, was not able to incorporate the results of the large-scale visualisation into the visualisation of a concept design with a smaller and local scale. The designer could only set up a simplified wind condition based on their perceptions. Any parameter had to be set up manually for each analysis, and this means that the CFD-PST is a tool that must repeat independent analyses rather than be a technological frame for the whole workflow process. In this context, the visualisation had to resolve three tasks: a large visualisation of an urban context, a local visualisation scale and the visualisation of the aerodynamic performance of an artificial windbreak installation. The lack of a sequenced method to link the outcomes between tasks affected the general rigour of the observations. This does not facilitate the comprehension of the global development of the phenomena from a large scale to a small scale, where each analysis is an approximate interpretation of the results from the previous visualisations (Figure 7.4).

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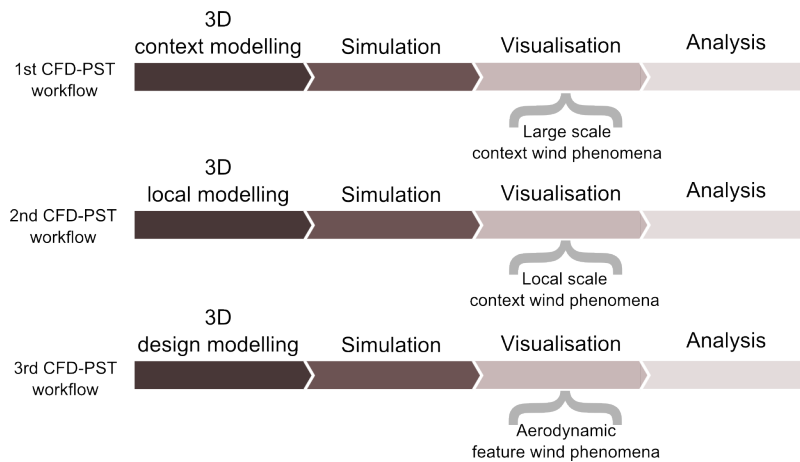
Figure 7.4: Comparison between wind analysis workflows, showing separate analysis processes for each spatial context when a workflow involves several stages with different scales of visualisation and different levels of design complexity. For each workflow the CFD-PST program is used for: 1) modelling the spatial context of the case; 2) numerical simulation; 3) generation of several visualisations; and 4) analysis. If the scale of the spatial context changes, the workflow must be repeated. This method may delay the analysis; besides, the results of a group of visualisations cannot be exported as parameters for other simulations. (Source: author)

Previous studies have not evaluated the role that CFD-PST programs play in a design process that involves visualisation and wind analysis from a large urban scale to a small local scale or between prototypes of designs that change from regular forms to more complex forms. Such a process means a workflow with several stages of visualisation. The literature is generally focused on individual and defined tasks that are not always representative of processes of more random explorations and stages. Through the second investigation I observed that CFD-PST programs work as individual components in a workflow, generating more segmentation in the analysis. These programs should provide a methodology of analysis through workflows with several visualisation stages. The process of visualisation should generate a wind map that can be used as a link to connect one stage to another, helping to define the more significant wind conditions for the next visualisation stage. The importance of a wind map as a valuable instrument was observed empirically in the second investigation. In addition, a good practice for the user should be to work with three visualisation levels that are more suitable for specific wind phenomena: visualisation of horizontal airflow movements for urban context, visualisation of vertical

airflow movement for local context, and spatial 3D visualisation for wind phenomena around an artificial installation (Figure 7.5). In summary, this is an evolved and improved version of the structure for CFD application in the early design stage, elaborated by Lau and Tsou (Lau and Tsou 2009).
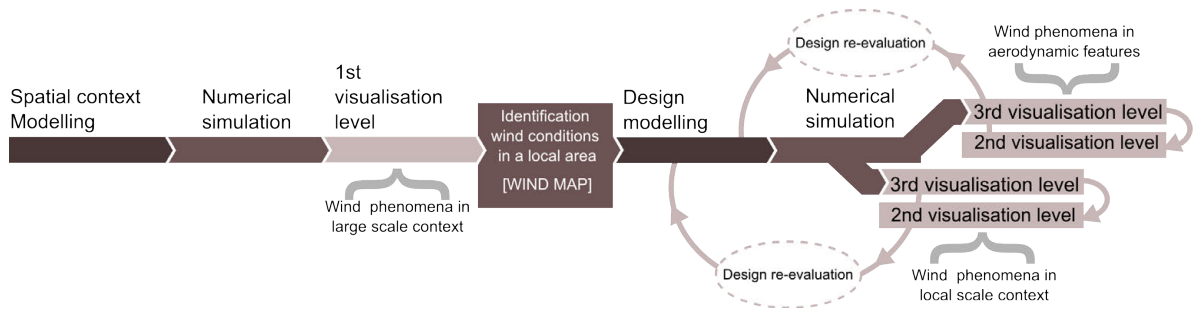
Figure 7.5: Proposition for a continuous workflow through several analyses where the parameters for a simulation are extrapolated from a previous visualisation process. This method facilitates the comprehension of wind through different scale contexts to test alternatives of windbreak designs. It represents an evolution from previous structure elaborated by Lau and Tsou. (Source: author)

With this approach, some strategies are suggested to improve the performance of these CFD-PST programs in complex workflows:

- To extend CFD-PST visualisations, extrapolating the results and parameters of a visualisation of wind in an urban area (urban scale) to a new visualisation oriented to the analysis of a local context (project scale). For instance, after a first wind visualisation in an urban context, the user should be able to select a particular area as a wind map and define it as a new domain for further visualisation, importing automatically the main parameters of wind from the previous visualisation (multiple wind directions, speed variation, etc.), to run a new analysis (Figure 7.5).

- To include in the visualisation of the wind flow, complementary data from an automated analysis, such as comfort factor, or from other platforms, as additional overlapped layers of information, to integrate them as a graphical wind map for architects, with different patterns of information to complement the analysis.

- To stablish a standard for a methodology of visualisation when several stages are involved in a workflow. It is recommended that users follow a plan of visualisation

based on three levels of representation: visualisation of horizontal airflow movements for urban context, visualisation of vertical airflow movement for local context, and spatial 3D visualisation for wind phenomena around an artificial installation.

Wind visualisation for aerodynamic features of screens and porous structures

The third main empirical finding was the unclear wind visualisation of porous screens produced by CFD-PST, which makes difficult the further use of these tools as aids for the analysis of strategies of wind control based on windbreak screen concepts. This refers to difficulties for CFD-PST to conduct wind analysis of protection levels and wind mitigation regions generated by artificial membranes with thin and porous surfaces, or screens with aerodynamic features such as gaps, fins, slots and variation of porosity density, which are passive systems of artificial barriers for wind mitigation used in outdoor environments. In general, some CFD-PST programs did not produce clear visualisations, or the results were not very reliable. Therefore, it is not possible to evaluate or compare the level of wind comfort for windbreaks with different porosity patterns or screen arrangements.

During the last three investigations, I found that visualisation tests of CFD-PST Vasari with models of artificial windbreaks based on porous surfaces or screens with aerodynamic features (the Pneumosenser project in the first investigation, multi deflector screens in the third investigation and the urban shelter for a tram stop), showed visualisations of wake regions (protection regions) with distorted patterns of wind speed and non-reliable results which made difficult the interpretation of conditions in the areas of protection produced by these shelter designs. In the last investigation, the CFD-PST visualisation of a group of screens with different aerodynamic features, different sizes and in a large area, provided different results from each visualisation tool, which made it difficult to evaluate the configuration of these shelters to develop a better arrangement.

Moreover, these programs do not provide rapid and direct results about protection factor or variations of wind protection regions. It is only possible to make an analysis based on wind speed intensity and airflow direction. However, these results may not be very reliable. For instance, Vasari visualisations showed high wind velocity that affected the comfort level in the shelter zones of pedestrian windbreak concepts for a tram stop. In

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contrast, ODS-Studio showed efficient wind deflection that produced regions of protection with low airflow velocity (something clarified in further analyses in an ABL wind tunnel). Furthermore, ODS-Studio provided a clear visualisation of wind phenomena through each aerodynamic feature of the windbreak installation, while Vasari could not provide that level of visualisation. In fact, when several screens are installed in complex configurations, involving several elements in a large area, the resolution of the visualisation using Autodesk Vasari decreased, affecting the visualisation of small details and features on the screens. This restricts the analysis by architects when they are exploring windbreak designs for a more sophisticated interaction with the wind, such as membrane morphologies and porous structures. As explained in the interlude chapter, the complexity of concept designs used as windbreak screens and other strategies for mitigation of wind discomfort issues is increasingly based on more sophisticated features for wind flow control, such as screens with porous surfaces, slots and fins. However, the investigation shows that CFD-PST programs do not display measurable and comprehensible rapid visualisation to compare, analyse and interpret quickly the level of wind protection produced by these screens. This means they are not yet fully suitable for this kind of task.

This statement opens a critical line of argument for the further development of these kinds of wind analysis tools that previous studies about CFD-PST have not addressed. The fascination with the possibilities of wind analysis for architects must move to define requirements about how preliminary and rapid wind visualisation techniques provide information about protection and wind comfort related to wind speed regions. This is especially necessary for the exploration of more sophisticated designs with permeable screens, studied as architectural designs for artificial windbreaks in pedestrian areas.

Wind analysis programs for the early design stage must be able to visualise the wind flowing not only around an object, providing information of wind velocity and direction, but rather flowing through mixed structures of thin surfaces and porous screens, with clear information about the level of protection in the regions of comfort produced. To facilitate the evaluation of these regions of protection, the definition of a topological group of screens that classify windbreak designs could be a valuable source with which to compare performances. Therefore, I suggest an evaluation associated with Jacques Gandemer's

studies, which presents an analysis of different configurations of screens and wind protection factors. The Gandemer's work can be a base of evaluation criterion to explore, compare and improve designs of pedestrian windbreaks. CFD-PST would be the wind analysis tool to conduct a design process with this evaluation criterion.

In summary, as suggestions to facilitate the definition of a criterion, I propose:

- To establish a method of visualisation and evaluation of protection regions (wake regions) with CFD-PST programs to generate data in a format that can be compared with results from literature and others studies.

- To facilitate a comparison of pedestrian windbreaks concepts, for which I suggest the use of the classification of artificial windbreak screens, elaborated and studied by Jacques Gandemer. His work about configurations of screens to work as windbreaks, and the aerodynamic analyses about protection regions (thresholds), is valuable knowledge with which to establish a general criterion for strategies of design and evaluation of design performances (Figure 7.6).
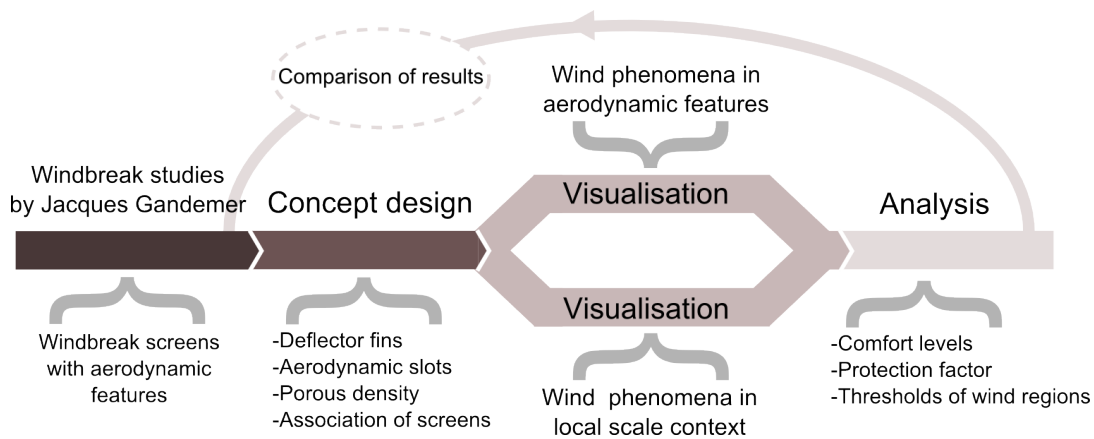
Figure 7.6: The techniques of rapid wind visualisation must be able to produce comprehensible analyses of the protection factor and levels of comfort produced for designs of windbreaks with porous structures and screens with aerodynamic features. These aerodynamic features could be designs already studied by Jacques Gandemer for artificial windbreaks screens, such as screens with deflectors, accelerator slots and porous screens. The visualisation plots generated by a CFD-PST program should be able to measure the condition of comfort and protection in the outdoor environment, thus to be compared with the previous studies of Gandemer. (Source: author)

7.3 Theoretical implications

With respect to the research question about how CFD-PST programs accomplish the wind visualisation and analysis for conceptual design exploration, my investigation has found that CFD-PST programs allow visualisation with a qualitative approach that is useful for quick observation, basic comprehension and dynamic design exploration by architects. However, the previously synthesised findings establish an indispensable criterion, necessary for complete feedback in a qualitative wind analysis of more complex conceptual design explorations than regular and closed building forms. These are the basic elements of a criterion for the use of wind visualisation techniques by architects, which have not been developed in the features and functions of the CFD-PST programs evaluated through the investigations conducted in my research. This lack in the definition of a criterion for wind visualisation practice reduces the potential of CFD-PST programs as analysis platforms to evaluate conceptual designs, and affects the quality of wind phenomena analysis for architecture. In addition, it restricts the function of CFD-PST as tools to support communication between architects, clients and wind experts in the first stage of the design process.

These findings could be used to develop norms for adequate selection of tools and acceptable qualitative wind analysis that can complement discussions in the literature about the use of CFD-PST in the early stage of the design process. They open a critical review of CFD-PST programs' performance as instruments of visualisation for architects to identify wind phenomena associated with design concept development. These criticisms of CFD-PST have been noted in F. Farias' study and during his interviews with architects, where they insinuate some critical opinions about BPS programs and wind analysis. The aspects developed here work as clear specifications that could orient strategies of improvement, for issues such as the lack of knowledge about the limitations of these programs, which would be useful for the election of the best tool for a specific wind analysis; the difficulty in the correct interpretation of data visualisation and analysis results for architects; and the knowledge of what variables affect reliability of these programs, making them a more effective design tool. This knowledge is useful in guiding designers in their work with

CFD-PST, when the elaboration of complex wind simulations in the early design stage with more sophisticated programs is not seen as the best strategy of work (Farias 2013).

On the other hand, the findings presented here remark on the qualitative approach of wind analysis for the early stage of the design process, based in visualisation techniques rather than instruments of measurement of data from accurate simulation of the airflow. The results of these investigations suggest CFD-PST is a technique with the potential to bridge the field of knowledge about the complexity of wind dynamics (describing wind phenomena around geometrical patterns of buildings), and architects' design-centric knowledge to conduct more creative exploration through the concept design stage that can be communicated and shared as ideas with other experts in further stages of the design process. For this reason, the CFD-PST is a suitable platform to establish a "shared image" and "shared knowledge" of wind dynamics, between designers, clients and engineers, something that Aynsley proposed some time ago in his paper "Shape and flow" (Aynsley 1999).

In the literature, several authors have mentioned the constant development and improvement of numerical simulation techniques for wind flow. This means that in the next few years, direct numerical simulation (DNS) technology will present better performance and accuracy levels and will be able to resolve, visualise and predict wind behaviour around buildings with precision in feasible time scales. How this will affect current CFD-PST programs and rapid visualisation in the early design stage is an open question. But there is no doubt about the potential impact, which could mean new approaches for rapid wind visualisation in the early design stage. However, this study shows that rapid visualisation with CFD-PST is not only related to precision, but also involves a subjective approach of protocols for rapid and better comprehension and identification of aerodynamic phenomena in the outdoor environment. To follow a method for wind analysis in the early design stage would enhance the exploration of more sophisticated architectural strategies of interaction with wind. In summary, the future direction of wind analysis in the early design stage will be influenced by the improvement of technology and how it is used in the creative process by architects.

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7.4 Gaps and further research lines

My research has developed an experimental investigation focused on some lines of action, while other paths have been postponed. Also, the complexities of a particular task and the time required have conditioned the approach and the extension of the study. Consequently, the research at this stage is limited in many of the topics and has left uncovered several potential branches related to wind visualisation in the early design stage. In the following sections I explain the main aspects that are not covered in the present study, as well as recommendations for future research.

Quantitative evaluation of digital wind visualisation techniques

The current study presents a first qualitative approach to evaluate the outcomes of the experiments. However, it is necessary to conduct tests to gather numerical data to analyse aspects of these tools with more accuracy, and compare quantitative results of Vasari, ODS-Studio and ANSYS CFX in the areas analysed through these investigations. Moreover, the classification of artificial windbreaks with aerodynamic features developed by Jacques Gandemer has not been quantitatively tested with the programs studied here. Thus, it would be useful, for a better evaluation of the current performance of these programs, to make a comparison between the outcomes gathered in Gandemer's work and new CFD-PST wind analysis tests for each model of windbreak. This work will provide valuable information that detects the limitations and issues in these visualisation tools.

Wind analysis of windbreaks based on porous membrane morphology

For the study of screens with aerodynamic features, as a passive method for wind discomfort mitigation, the original forms of the screens were translated from literal representations of these features with regular non-porous surfaces. This interpretation was a strategy to facilitate the elaboration of the digital meshes with CFD software, and prepare physical models for experiments in a boundary wind tunnel. However, the wind analysis tests conducted with the CFD programs did not consider the morphology of screens based on membranes with porosity, because of the complex pre-process to set up experiments

for wind analysis with those models, under this technology. In this sense, the idea to conduct wind analysis tests with porous surfaces for screens and membranes, using the set of CFD-PST programs, is a next stage that extends a research line of exploration probing more deeply into passive design strategies of wind mitigation, using porous structures as artificial windbreaks in public spaces.

Wind visualisation on physical tests using mini airflow tunnel technology

For this research I needed to build two visualisation tools to analyse the dynamic phenomena of wind. These tools were models of physical mini airflow tunnels. However, these mini airflow tunnels were used for preliminary wind visualisation and they did not consider standards for wind analysis in architecture such as ABL conditions in the airflow. Thus, the research of a platform of wind visualisation, based on a new "do it yourself" version of the mini airflow tunnel, integrating the conditions of controlled wind flow for more representative visualisation of the wind and with a sensor system, is a next research objective. A preliminary example of this mini airflow tunnel was developed for the Private Microclimates cluster of the Smart Geometry workshop 2014[1], following design parameters for low-cost wind tunnels (Bruce et al. 1974). A second version of this mini airflow tunnel is presented as part of the final project and examination of my research.

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[1]Smart Geometry 2014, Urban compaction, Chinese University of Hong Kong, China.

CHAPTER 8

Conclusion

8.1 Overview of research

My research has critically explored the performance of some wind analysis techniques for visualisation of outdoor wind conditions around buildings, analysing their functions through several exercises of rapid visualisation with different contexts and scale models, and with a focus on two specific CFD-PST (computational fluid Dynamics - performance sketch tools), in order to evaluate their efficacy as rapid wind visualisation tools for architects' practice in the early design stage.

Despite the technical challenges, wind visualisation and analysis tools have been increasingly incorporated in the early stage of the architectural design process, changing the paradigm of tools as validators of a design in the middle of the process, to the role of assisting in the exploration of form-making at the beginning of the design work (Lima et al. 2012). However, the study of the literature about wind simulation and architectural practice reveals a gap between the strict requirements of wind analysis practice and the conditions of architects' work at the beginning of a design process. In this context, the development of CFD-PST programs represents an approach that tries to fulfil the early design stage of architects for rapid wind analysis (for outdoor wind environments), but with differences with traditional techniques. The general literature on the subject of tools for wind analysis in the design process (see Emanuele Naboni (2013) and Fernando Farias

(2013)) is inconclusive on their evaluation of how CFD-PST programs resolve the issue of wind visualisation in the early design stage, specifically the performance of these tools in scenarios of wind phenomena around design topologies more complex than closed form buildings.

In order to understand in depth the feature boundaries of these tools in the work of architects, this study sought to answer the question: *To what extent has CFD-PST technology contributed solutions to the problem of wind visualisation and analysis for architects in the early design stage?*

8.2 Final conclusions

The outcomes from my investigations (and the discussion presented in the previous chapter), have identified three main conclusions in response to the research question. These are: (1) what is actually solved by the use of CFD-PST, (2) what is not quite resolved yet and (3) what should be done to improve performance.

First

Independent CFD-PST programs can facilitate rapid wind visualisation in the early design stage, providing a qualitative dimension that is useful for quick exploration, basic comprehension and dynamic design exploration by architects. However, a workflow of representative programs (Vasari and ODS-Studio) can simplify the visualisation process with their associated functionalities, for more cases of large phenomena observation and design exploration. Thus, the best strategy to conduct rapid wind analysis (for pedestrian comfort) with these tools should first define the complexity of the simulation cases and the tempo of feedback in the analysis process. When the variation of wind velocity with height is not relevant and the observations are focused on horizontal movements of wind, CFD-PST programs with a low digital grid control like Vasari can be used. CFD-PST programs with sufficient digital grid control, similar to ODS-Studio, are more suitable for visualisation of wind conditions around tall buildings, groups of buildings with different heights, any case where it is important to visualise vertical wind deflections, the design ex-

ploration of porous screens and aerodynamic design features. When more detailed results are required, the use of highly controlled wind conditions to simulate the ABL and digital grid domain with more sophisticated CFD tool is recommended. However, flexibility and tolerance of complex geometries, by the programs, is needed in this case to facilitate the generation of digital grids, for the rapid visualisation process in the early design stage.

Therefore, a CFD-PST workflow could consider: 1) programs with limited grid control (Vasari) as observation tools of large scale wind phenomena; 2) programs with sufficiently controlled digital grid domain (ODS-Studio) for exploration of design features; and 3) sophisticated CFD tools (ANSYS CFX) for validation of results.

Second

There are aspects of rapid visualisation in the early design stage that are not fully resolved by CFD-PST programs, limiting their potential as design exploration tools for architects. Firstly, digital visualisation techniques, facilitate the segmentation of a spatial phenomenon. The hidden phenomena in a partial and segmented visualisation can be underestimated if the observer has no theoretical background in wind dynamics. Secondly, CFD-PST does not included a method to facilitate the extrapolation of parameters and outcomes from a large-scale visualisation, on order to implement the values into a second visualisation of a local context. The lack of a sequenced method to link the outcomes between tasks does not facilitate the comprehension of the global development of the phenomena from a large scale to a small scale. Lastly, CFD-PST programs do not display measurable and comprehensible rapid visualisations to compare, analyse and interpret quickly the level of wind protection produced by screens with porous surfaces, slots and fins. This means they are not yet fully suitable for this kind of task.

Third

Therefore, for rapid and more comprehensible feedback from quick wind visualisation in the early design stage, the techniques should include: 1) visualisation and perception of the global 3D spatial wind flow; 2) continuous workflow for the analysis process of wind

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phenomena through different scales and contexts; and 3) wind visualisation for aerodynamic features of screens and porous structures.

The outcomes also lead to the recommendation of a protocol based on the three display levels of visualisation (horizontal section, vertical section and 3D visualisation): 1) horizontal section for observation of large spatial contexts; 2) visualisation of horizontal, vertical section for local context observation; 3) and combination of the three levels for design exploration of artificial windbreaks with aerodynamic features.

8.3 Contribution

The prior literature about CFD-PST that focuses on the early design stage is limited regarding rapid visualisation methodologies and is inconclusive about their performance in complex scenarios of design exploration. This study identifies the potential of two representative CFD-PST programs to be used in the early design stage, to identify wind phenomena and improve designers' comprehension of airflow movement patterns around windbreak structures. These findings establish useful criteria for selection of appropriated tool. They also suggest that qualitative wind analysis can usefully complement the discussions in the literature about the use of CFD-PST in the early stage of the design process. They open a critical review of CFD-PST programs as instruments of visualisation for design concept development.

The future direction of wind analysis in the early design stage will be influenced by the improvement of technology and how it is used in the creative process by architects. In particular, CFD-PST has the potential to bridge between the field of knowledge about the complexity of wind dynamics on one hand, and architects' design-centric knowledge on the other, to conduct more creative explorations.

8.4 Further research stage

The physical mini airflow tunnels allowed a comparison and evaluation of CFD-PST for preliminary wind visualisation. The integration between this technique and CFD-PST

has the potential to complement visualisation of numeric analysis an analogue and visual approach. Thus, the research of a platform of wind visualisation, based on a new "do it yourself" version of the mini airflow tunnel, is the next research objective. This new investigation will integrate the conditions of controlled wind flow for more representative visualisations of wind in the airflow tunnel, models of aerodynamic design features to explore wind interaction, rapid CFD-PST visualisation and measurement devices to complete a unified experience of rapid learning about airflow phenomena around artificial structures (see appendix).

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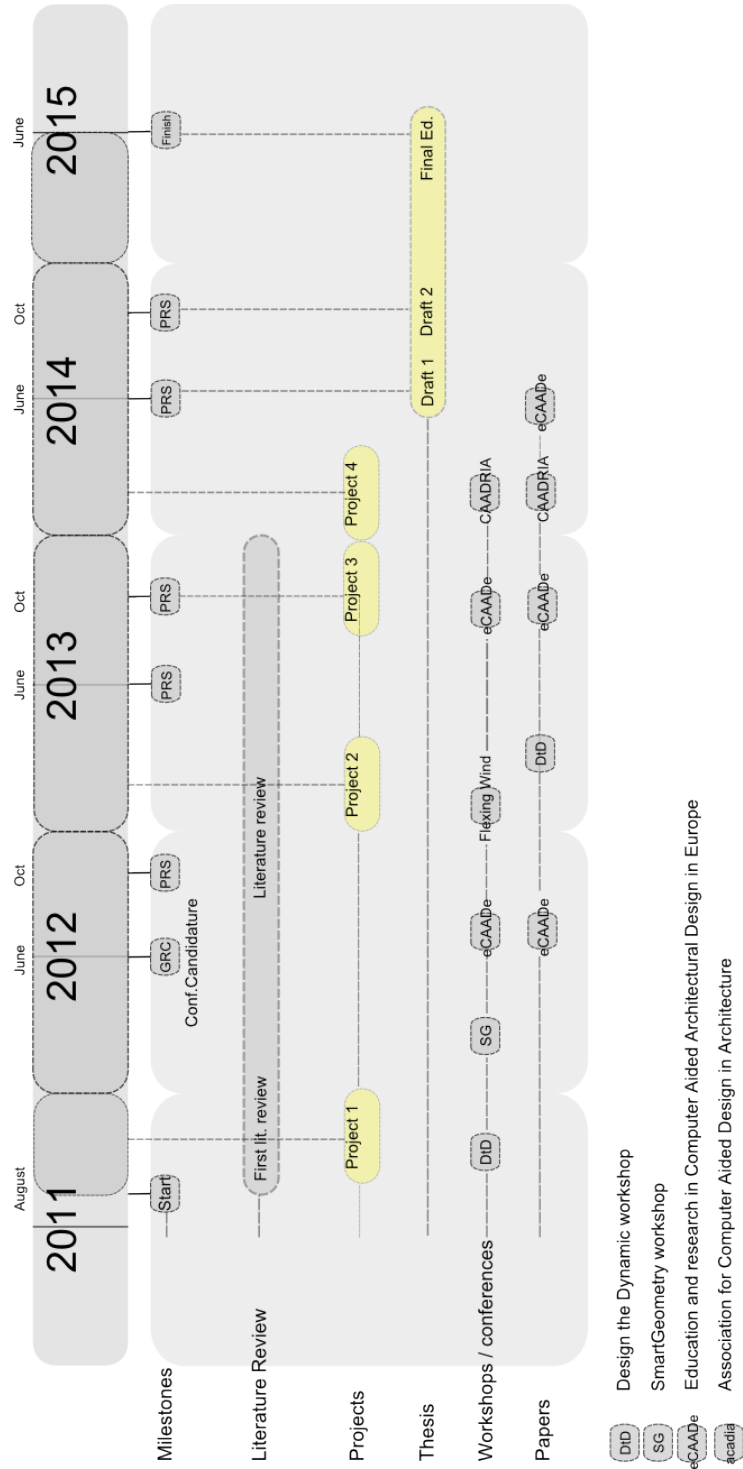
Appendix

Research timeline

Figure 8.1: Research time-line. (Source: author)

Research ethics approval

RMIT Design and Social Context College Human Ethics Advisory Network (CHEAN)
UNIVERSITY Sub-committee of the RMIT Human Research Ethics Committee (HREC)

Notice of Approval

Date: 8 February 2013

Project number: CHEAN A-2000822-1-13

Project title: Flexing wind elective course

Risk classification: Low Risk

Investigator: Dr Flora Salim

Approved: From: 24 January 2013   To: 24 January 2016

I am pleased to advise that your application has been granted ethics approval by the Design and Social Context College Human Ethics Advisory Network as a sub-committee of the RMIT Human Research Ethics Committee (HREC).

Terms of approval:

1. **Responsibilities of investigator**
   It is the responsibility of the above investigator/s to ensure that all other investigators and staff on a project are aware of the terms of approval and to ensure that the project is conducted as approved by the CHEAN. Approval is only valid whilst the investigator/s holds a position at RMIT University.

2. **Amendments**
   Approval must be sought from the CHEAN to amend any aspect of a project including approved documents. To apply for an amendment please use the 'Request for Amendment Form' that is available on the RMIT website. Amendments must not be implemented without first gaining approval from CHEAN.

3. **Adverse events**
   You should notify HREC immediately of any serious or unexpected adverse effects on participants or unforeseen events affecting the ethical acceptability of the project.

4. **Participant Information and Consent Form (PICF)**
   The PICF and any other material used to recruit and inform participants of the project must include the RMIT university logo. The PICF must contain a complaints clause including the project number.

5. **Annual reports**
   Continued approval of this project is dependent on the submission of an annual report. This form can be located online on the human research ethics web page on the RMIT website.

6. **Final report**
   A final report must be provided at the conclusion of the project. CHEAN must be notified if the project is discontinued before the expected date of completion.

7. **Monitoring**
   Projects may be subject to an audit or any other form of monitoring by HREC at any time.

8. **Retention and storage of data**
   The investigator is responsible for the storage and retention of original data pertaining to a project for a minimum period of five years.

9. **Special conditions (if applicable)**

In any future correspondence please quote the project number and project title.

On behalf of the DSC College Human Ethics Advisory Network I wish you well in your research.

Grace Wijnen
Ethics Coordinator
College of Design & Social Context
RMIT University
Ph: (03) 9925 2974
grace.wijnen@rmit.edu.au

Design exploration of a windbreak barrier
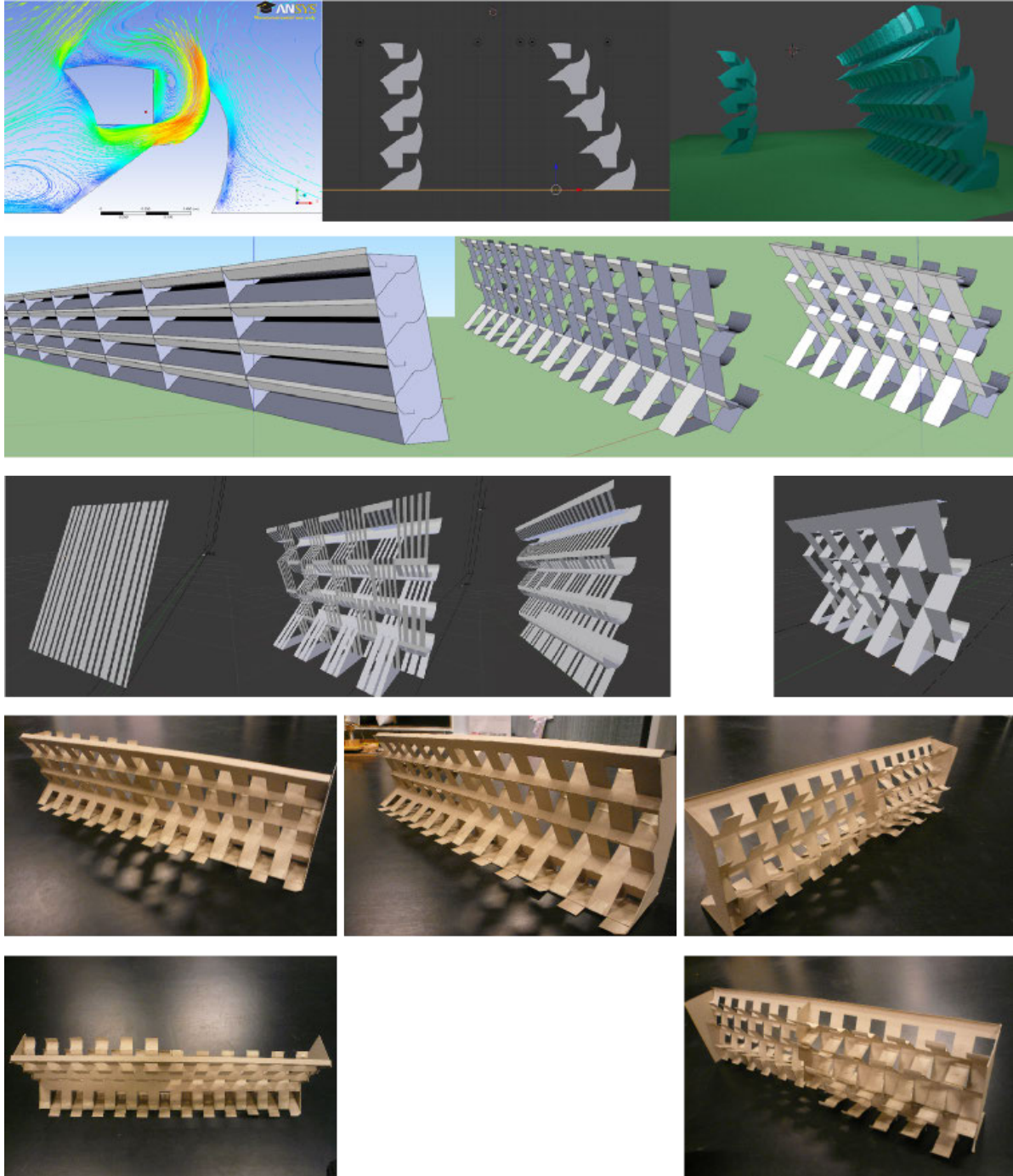
Figure 8.2: Design exploration of a wind barrier with multiple deflector fins. (Source: author)

Design exploration of membranes for windbreak screens

Figure 8.3: Design exploration of screens with membrane morphology. Deflectors and slot concept. (Source: author)

Windbreak shelter concept
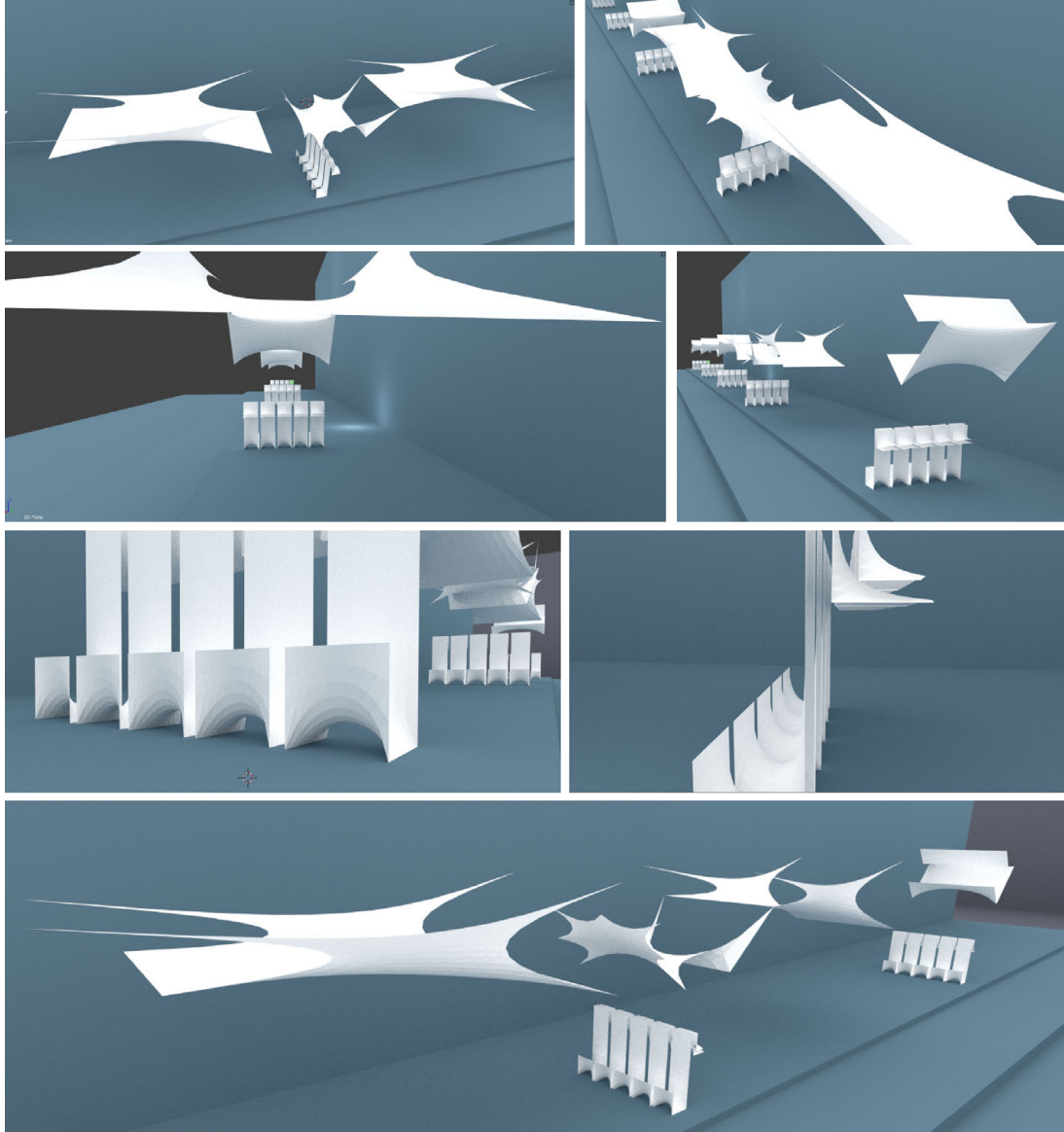
Figure 8.4: Windbreak shelter concept for tram stop. Screens and canopies with a membrane morphology. (Source: author)
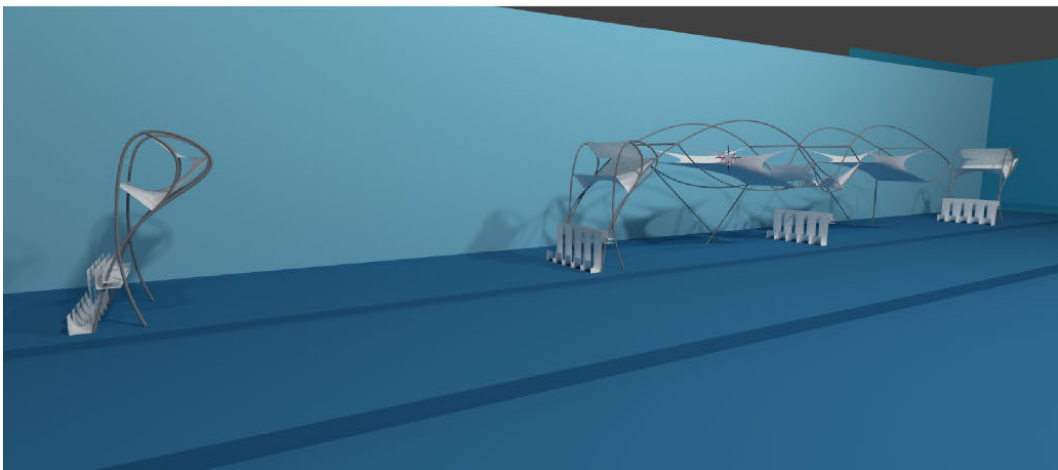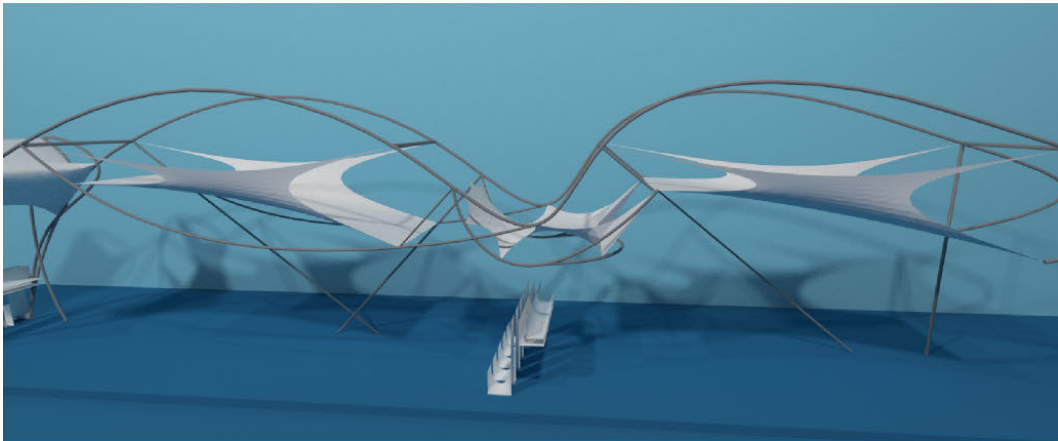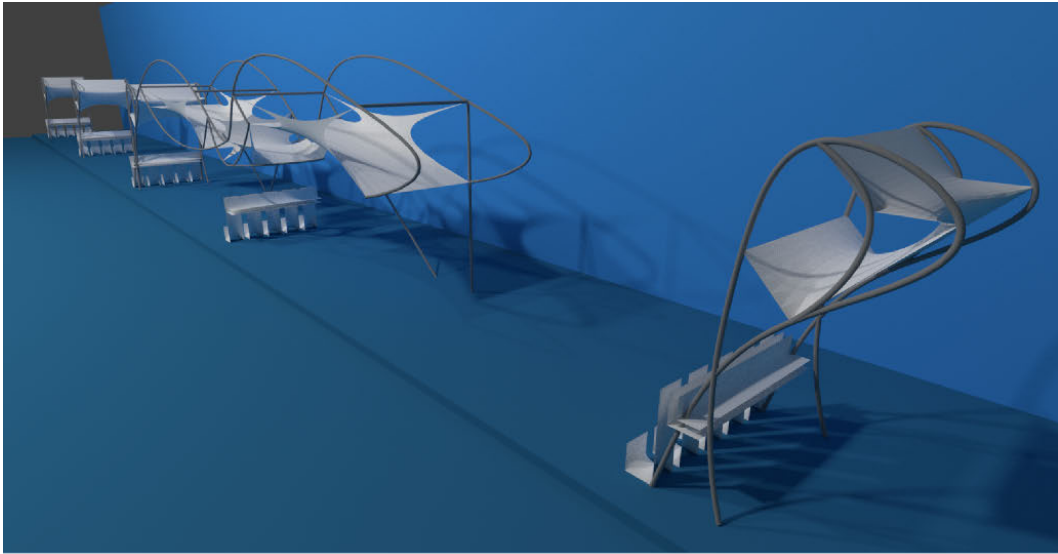
Figure 8.5: Windbreak shelter concept for tram stop. Screens and canopies with a membrane morphology. (Source: author)
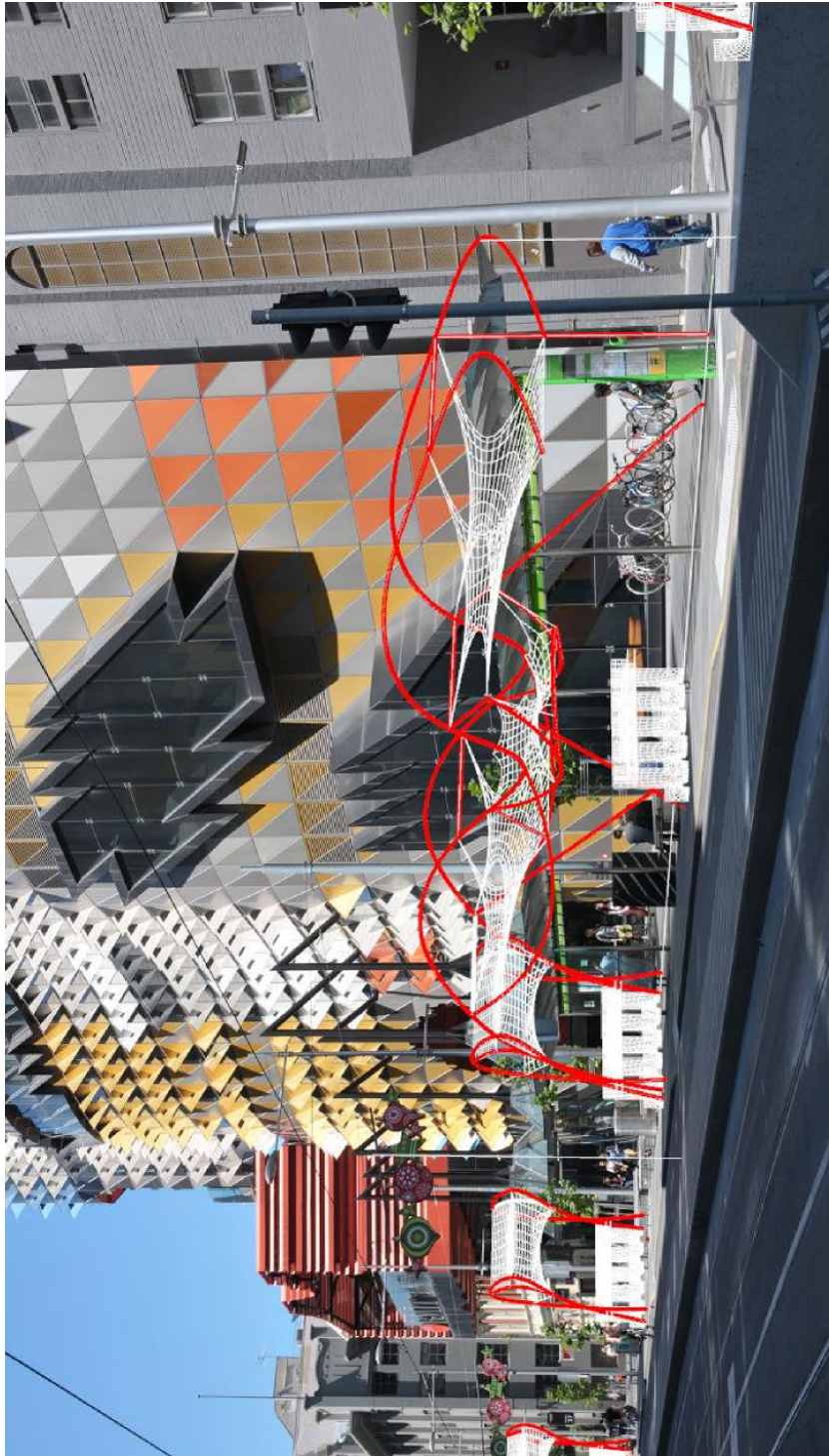
Figure 8.6: Windbreak shelter concept for tram stop. Screens and canopies with a membrane morphology. (Source: author)

Rapid visualisation with ANSYS CFX
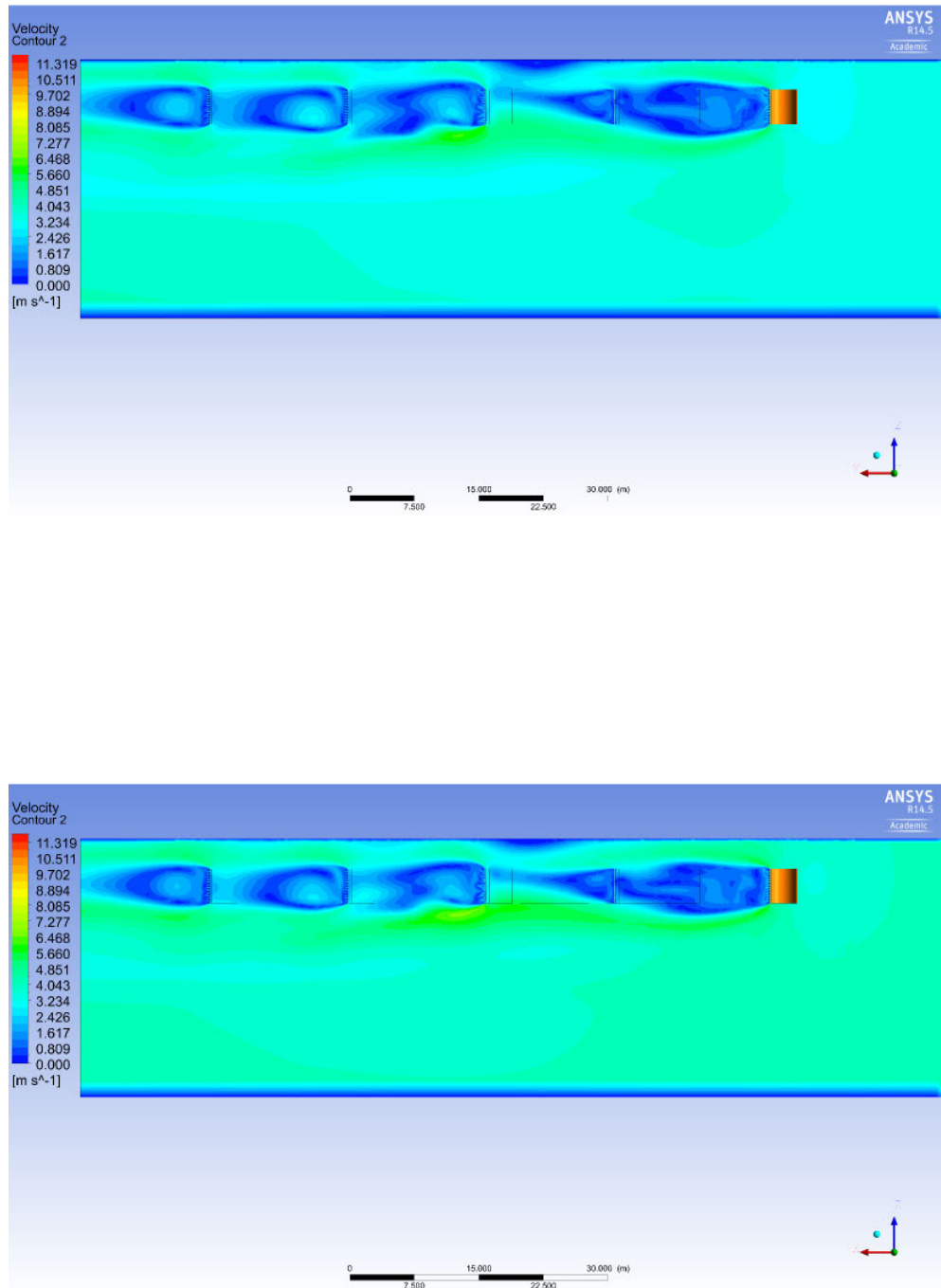
Figure 8.7: Rapid visualisation of a windbreak shelter concept, including screens and canopies with regular geometries and the façades of the street (footpath). Horizontal visualisation of protection bubbles section. Top: 60 cm height. Bottom: 90 cm height (Source: author)
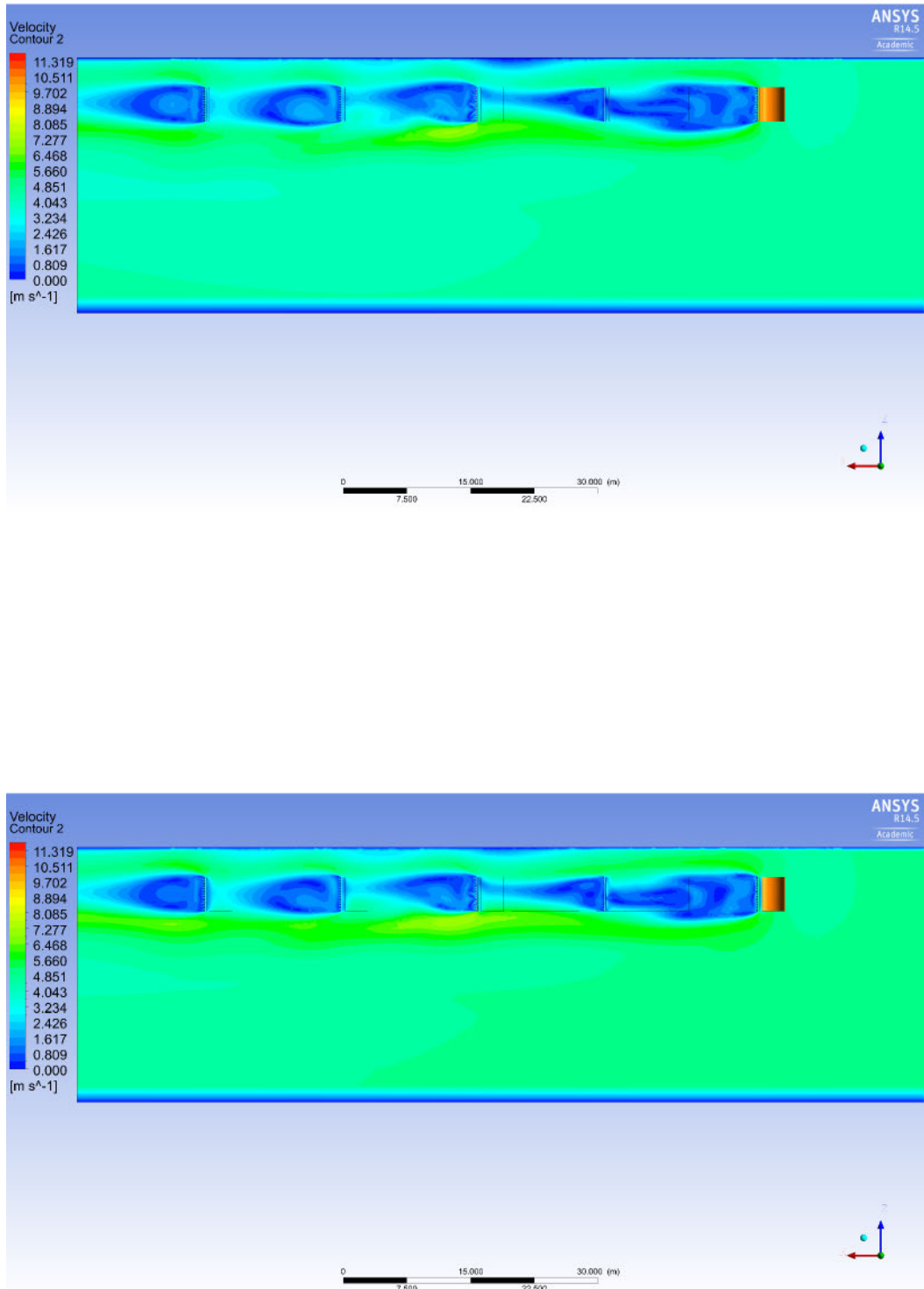
Figure 8.8: Rapid visualisation of a windbreak shelter concept, including screens and canopies with regular geometries and the façades of the street (footpath). Horizontal visualisation of protection bubbles section. Top: 120 cm height. Bottom: 150 cm height (Source: author)
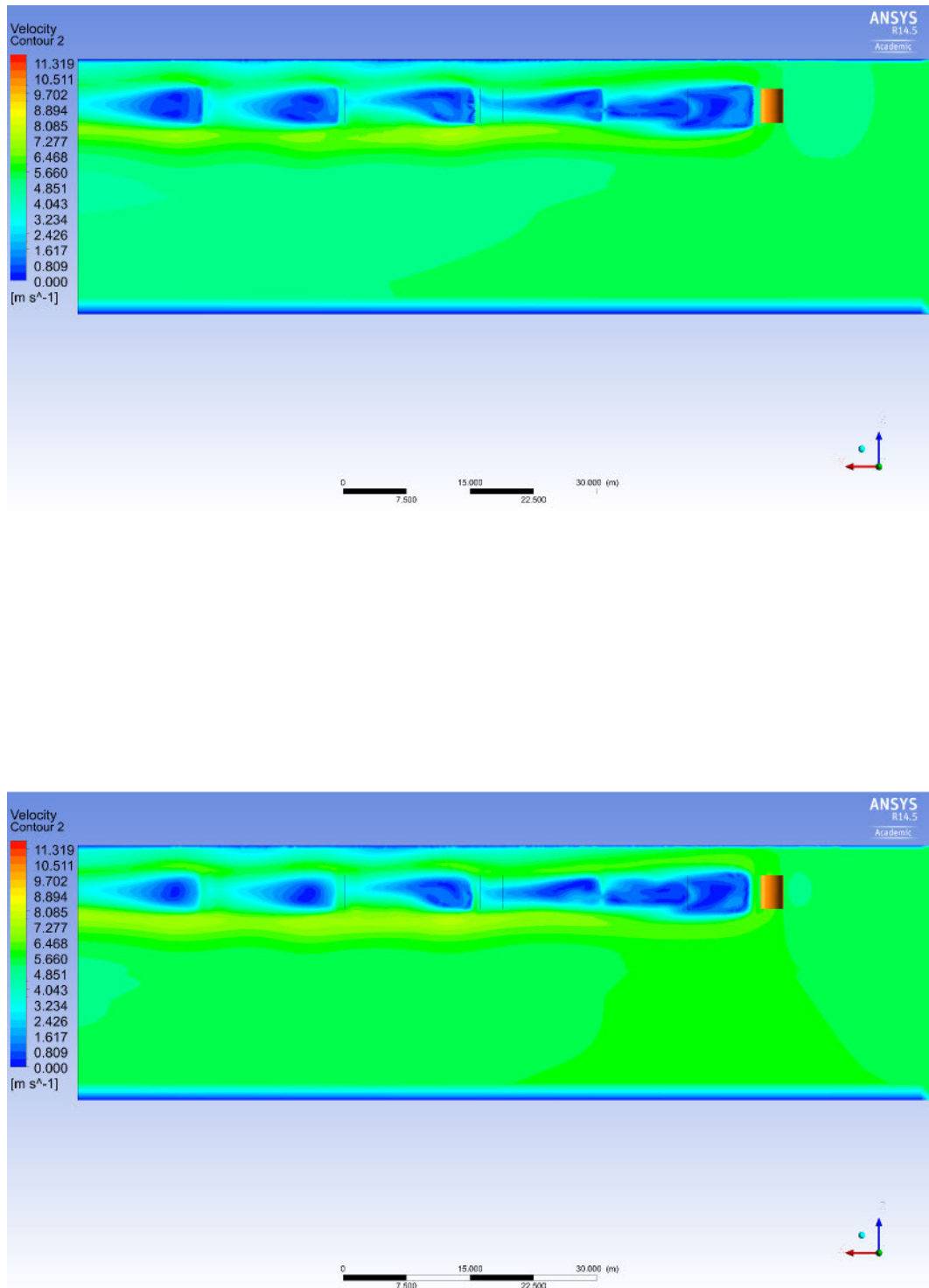
Figure 8.9: Rapid visualisation of a windbreak shelter concept, including screens and canopies with regular geometries and the façades of the street (footpath). Horizontal visualisation of protection bubbles section. Top: 180 cm height. Bottom: 210 cm height (Source: author)
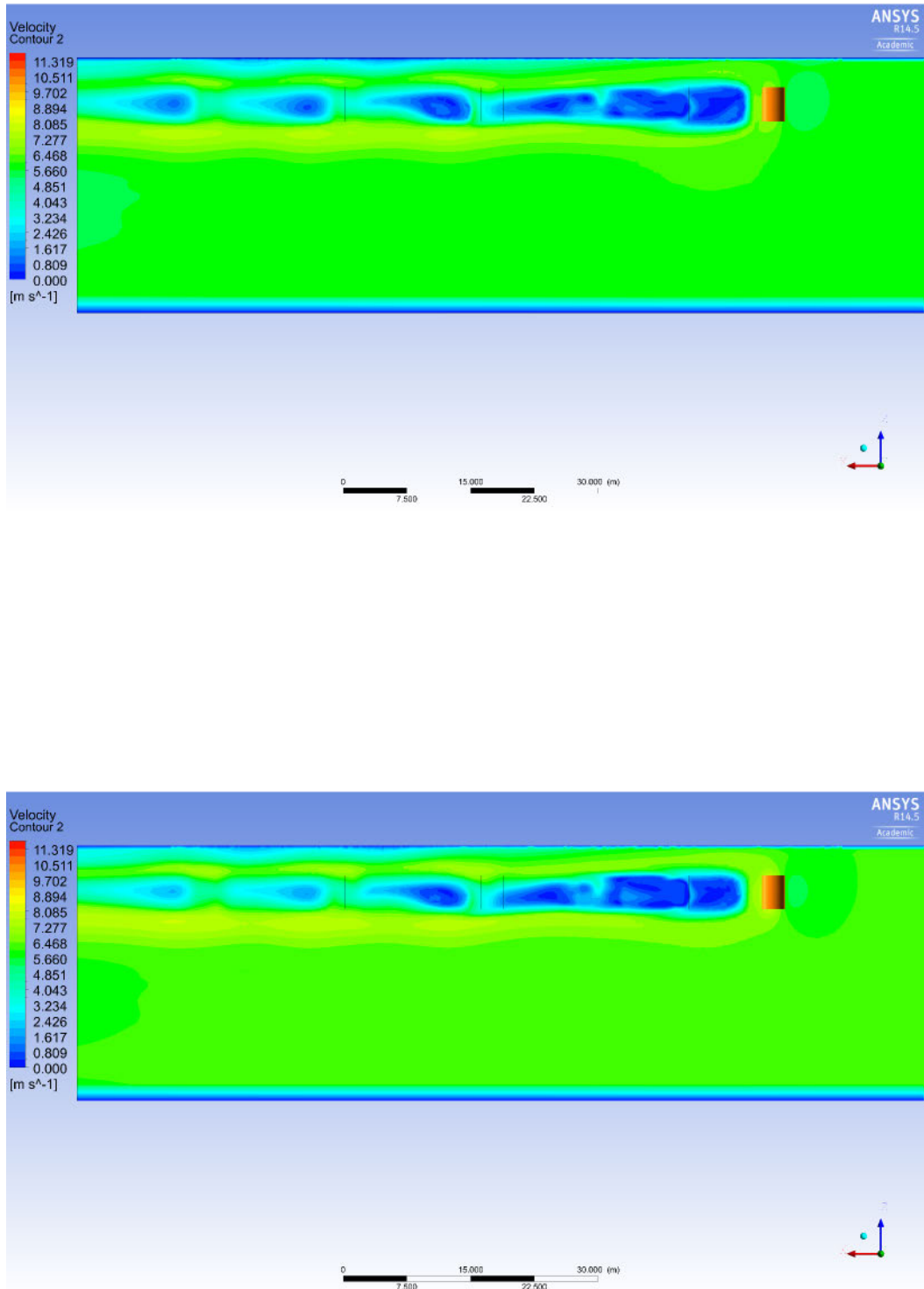
Figure 8.10: Rapid visualisation of a windbreak shelter concept, including screens and canopies with regular geometries and the façades of the street (footpath). Horizontal visualisation of protection bubbles section. Top: 240 cm height. Bottom: 270 cm height (Source: author)
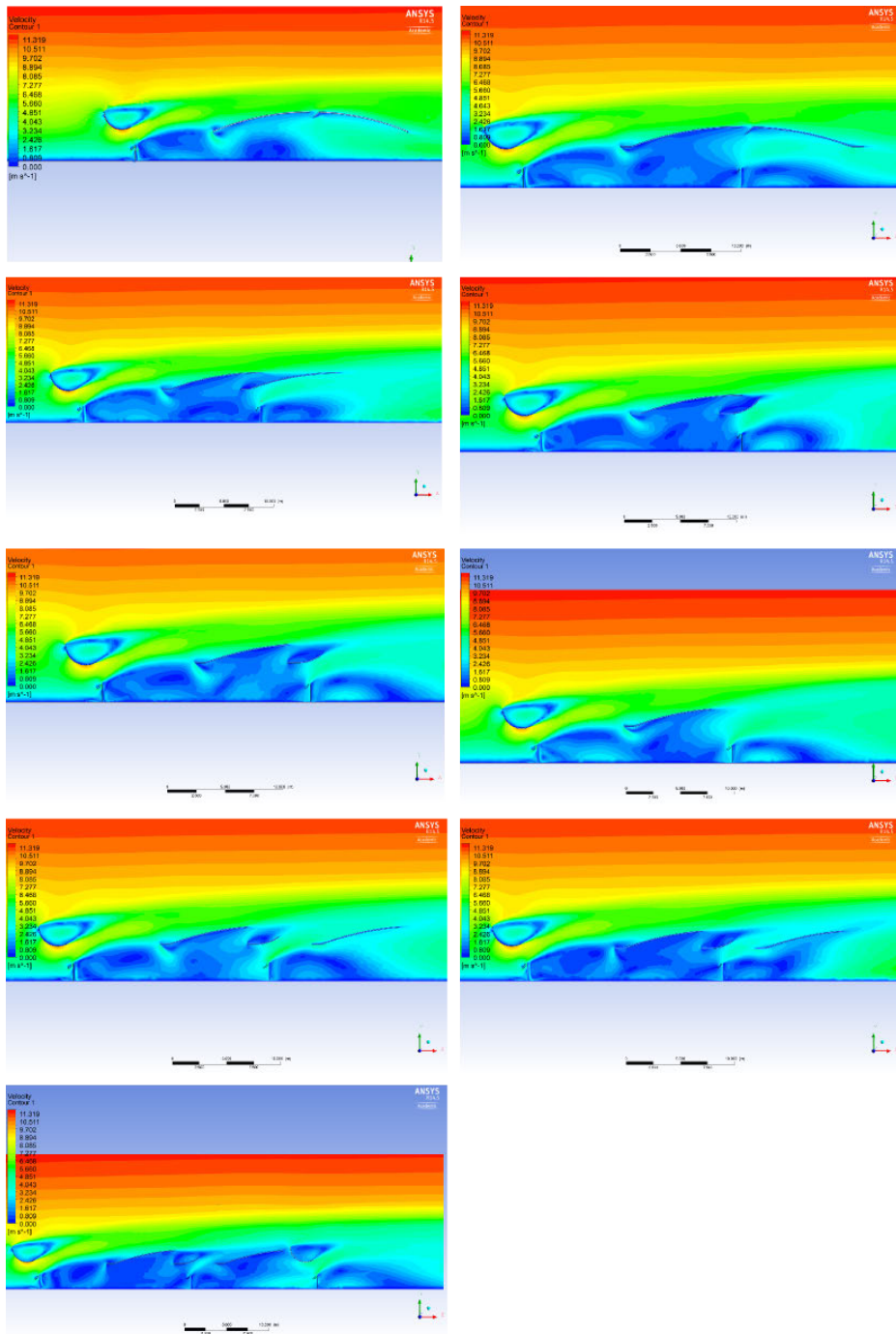
Figure 8.11: Rapid visualisation of a windbreak shelter concept, including screens and canopies with regular geometries and the façades of the street (footpath). Lateral visualisation of protection region with different roofs configurations. (Source: author)

ABL wind tunnel experiments
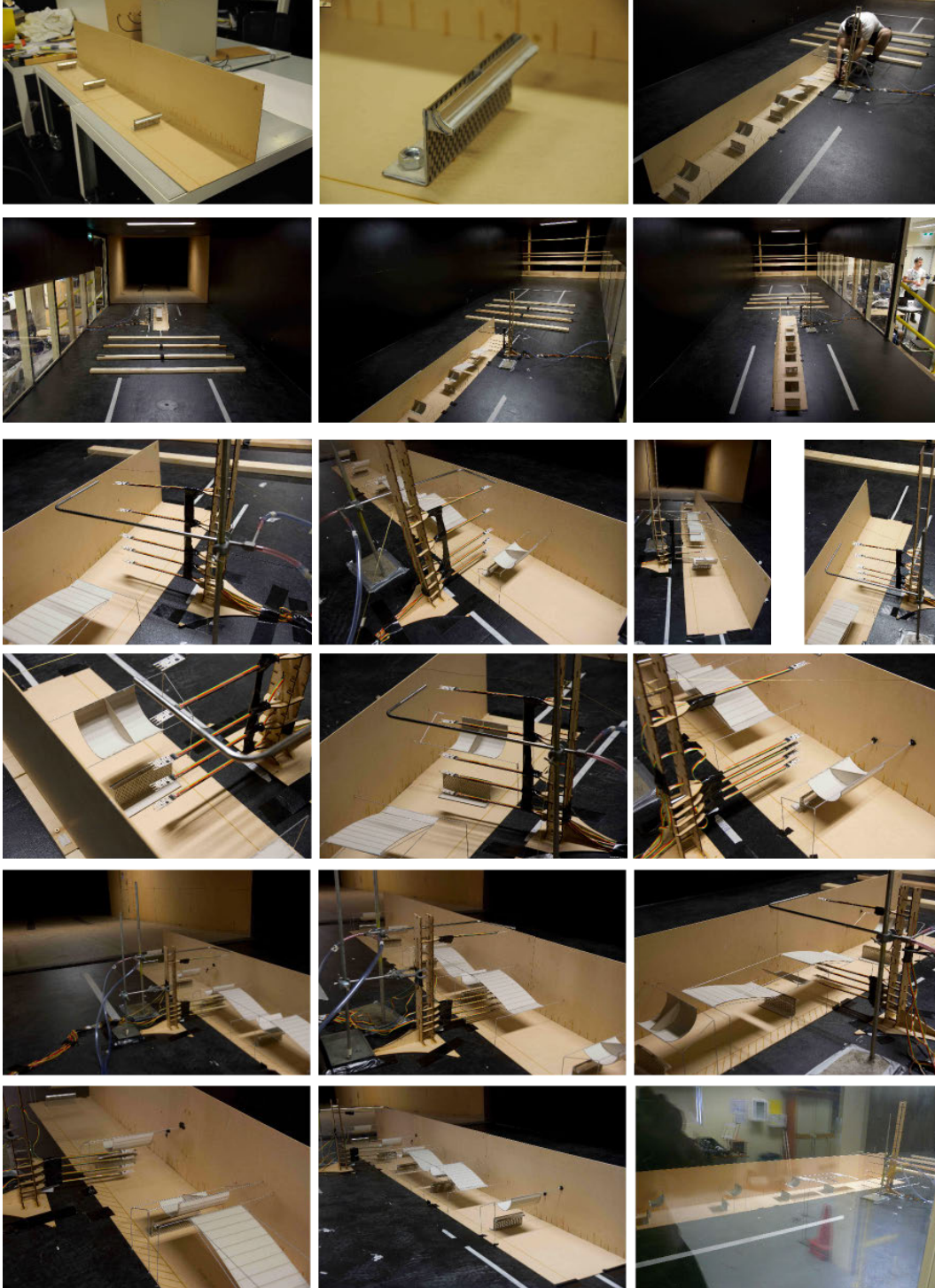
Figure 8.12: ABL wind tunnel experiments for rapid visualisation. A 1:30 scale model was installed, including screens and canopies with regular geometries and the West façade of the street (footpath). (Source: Daniel Prohasky and Rafael Moya's work)
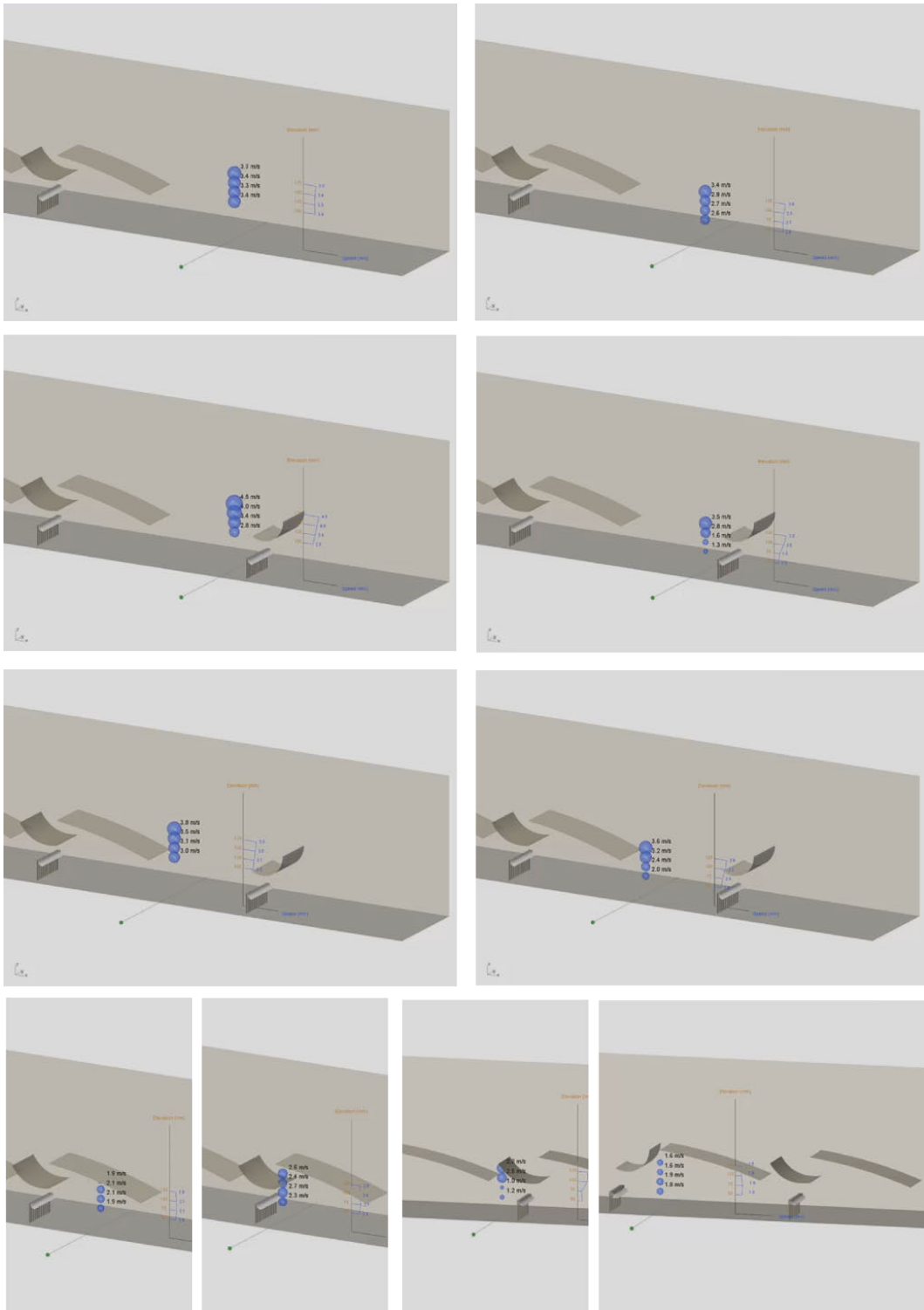
Figure 8.13: Rapid visualisation in ABL WT of a windbreak shelter concept. Screens and canopies with regular geometries. (Source: Daniel Prohasky and Rafael Moya's work)
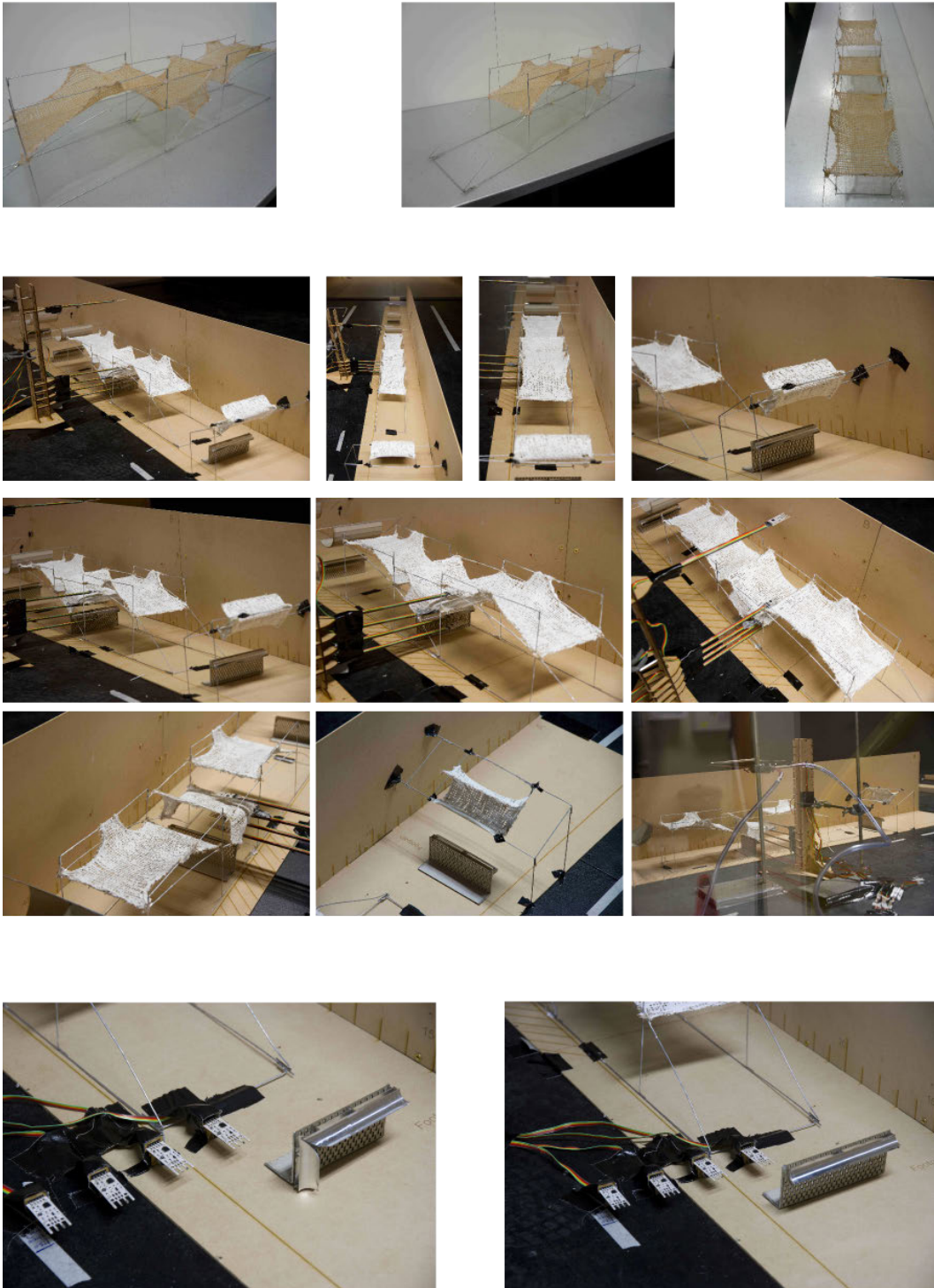
Figure 8.14: ABL wind tunnel experiments for rapid visualisation. 1:30 scale model including screens and canopies with membrane morphology and the West façade of the street (footpath). (Source: Daniel Prohasky and Rafael Moya's work)
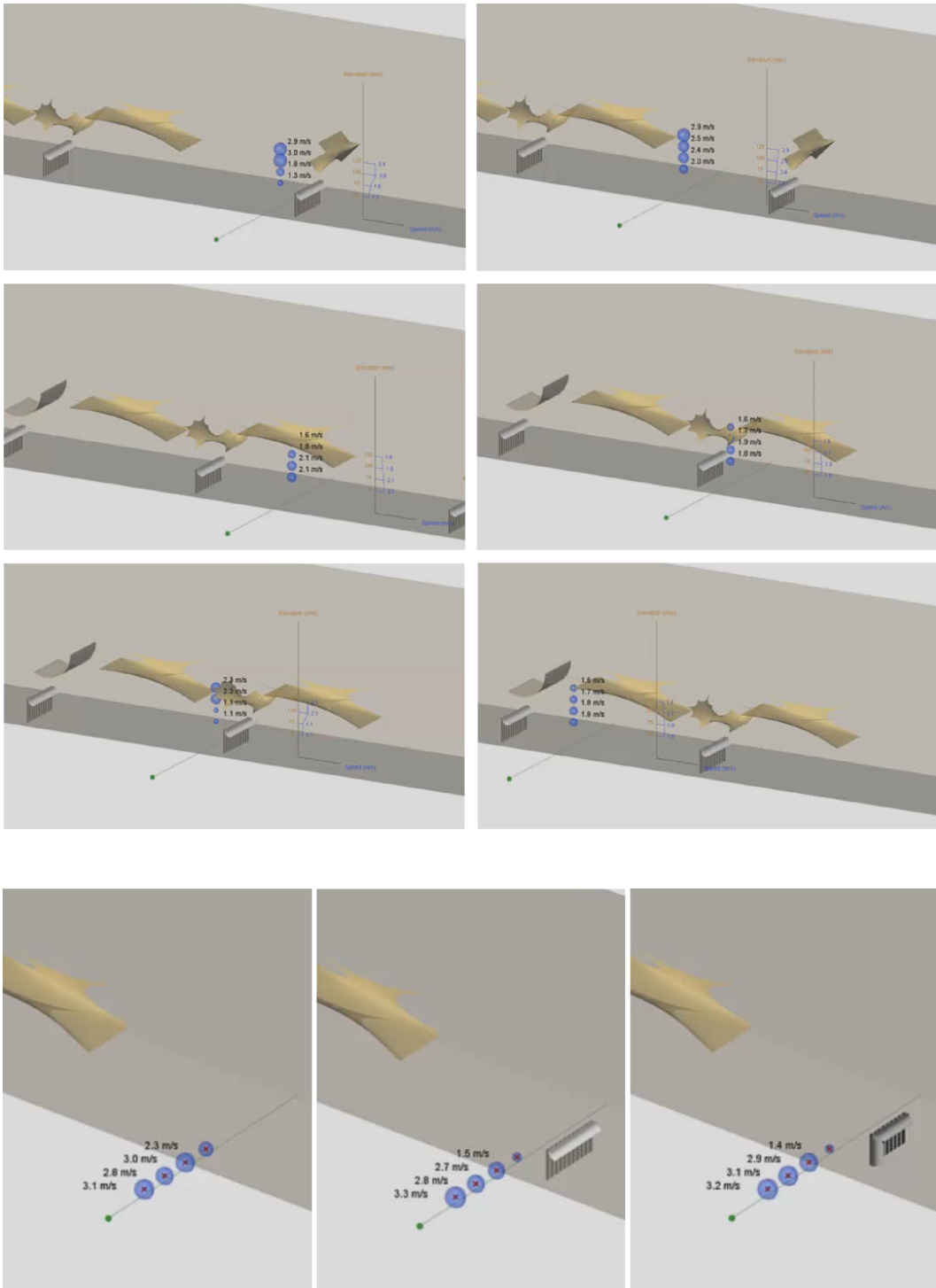
Figure 8.15: Rapid visualisation in ABL WT of a windbreak shelter concept. Screens and canopies with membrane morphology. Bottom row: visualisation of a lateral deflector in a screen. (Source: Daniel Prohasky and Rafael Moya's work)

Evolution and new version of a mini airflow tunnel
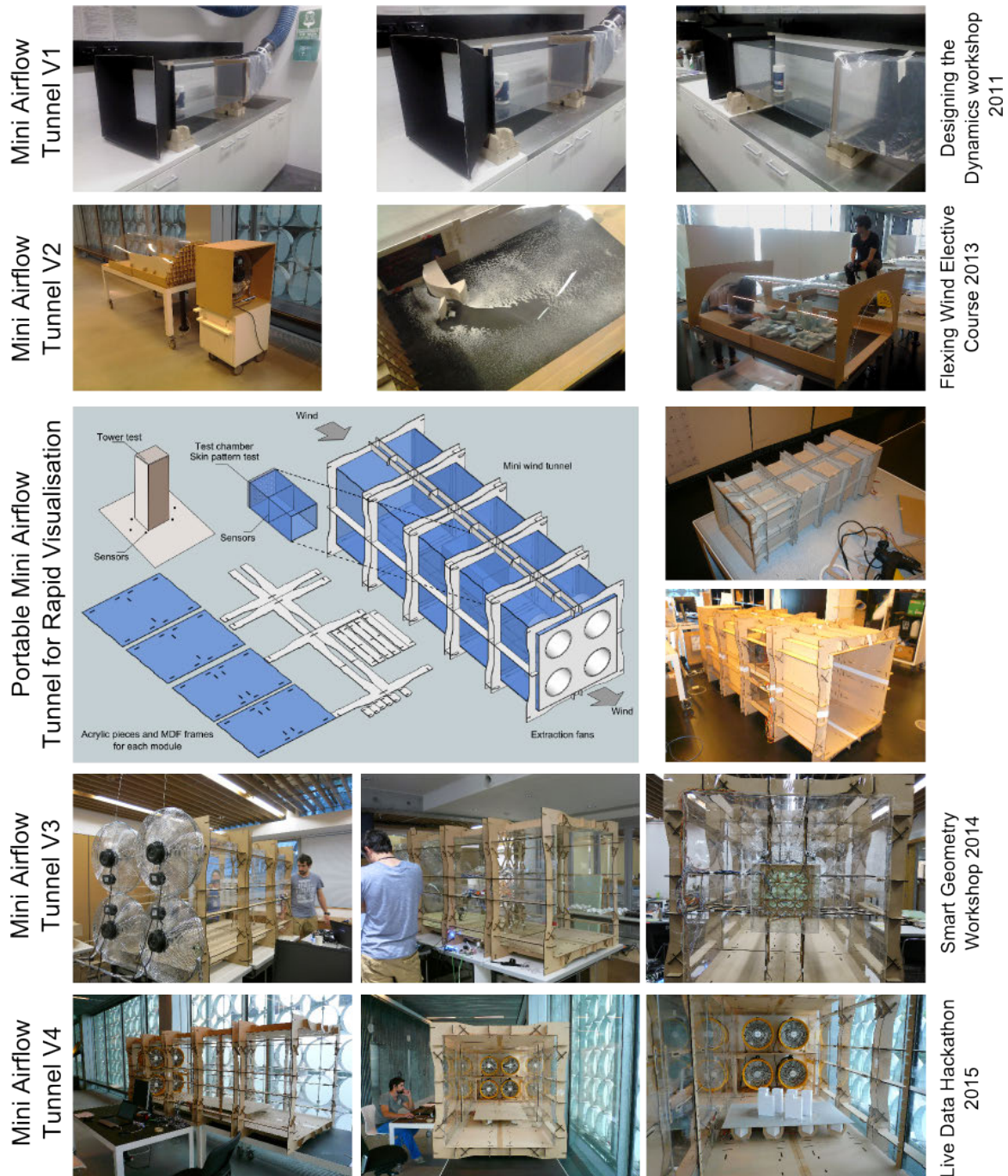
Figure 8.16: Different versions of mini airflow tunnels for rapid visualisation: first and second version of mini airflow tunnel for isolated building visualisation; third version of mini airflow tunnel for visualisation of screens in Smart Geometry 2014; fourth version of mini airflow tunnel for Live Data Hackathon 2015. (Source: author)

Rapid visualisation in a mini airflow tunnel (Version 1)
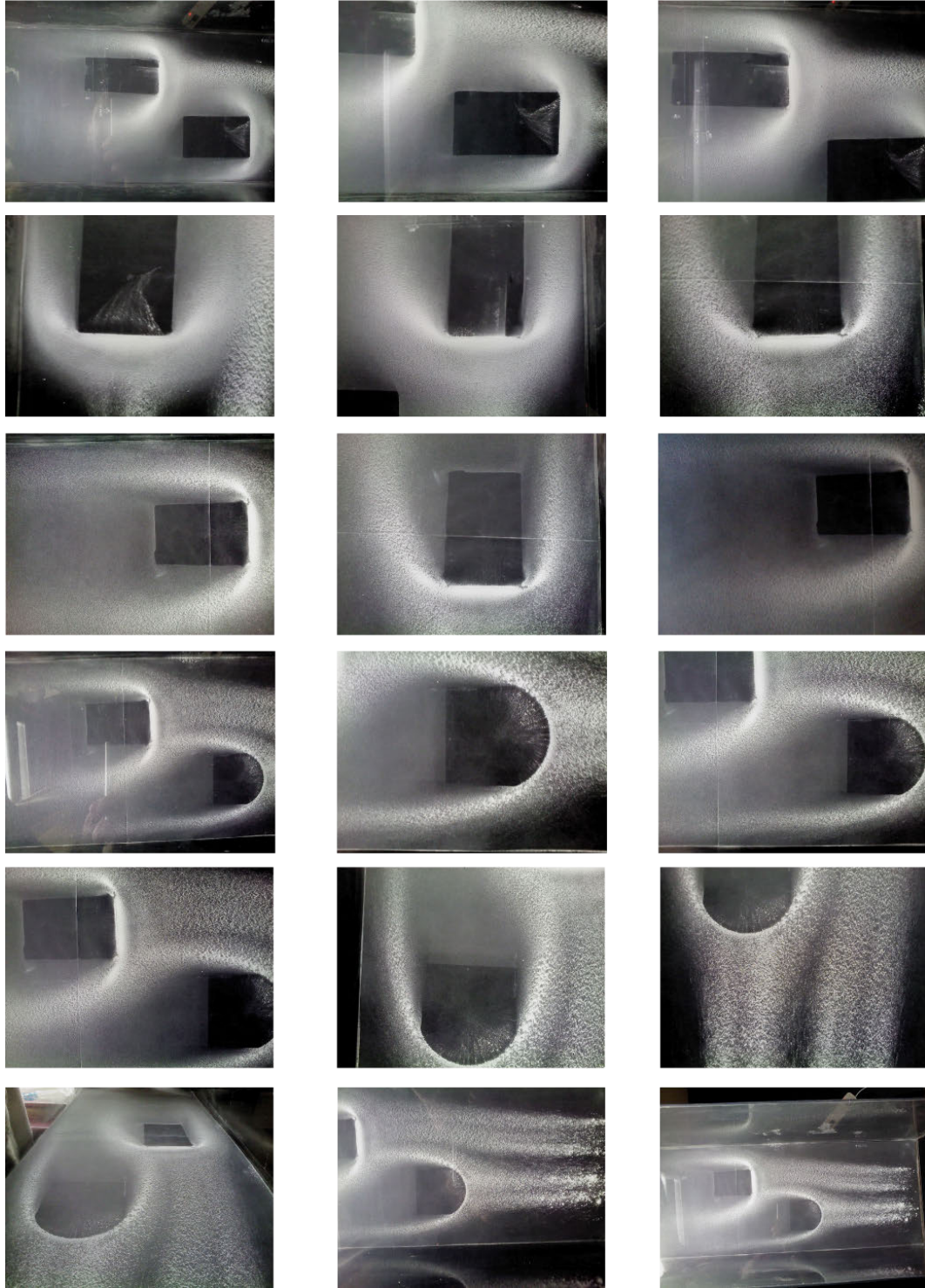
Figure 8.17: Rapid visualisation of airflow around close building forms, in the mini airflow tunnel, with erosion technique. (Source: author)
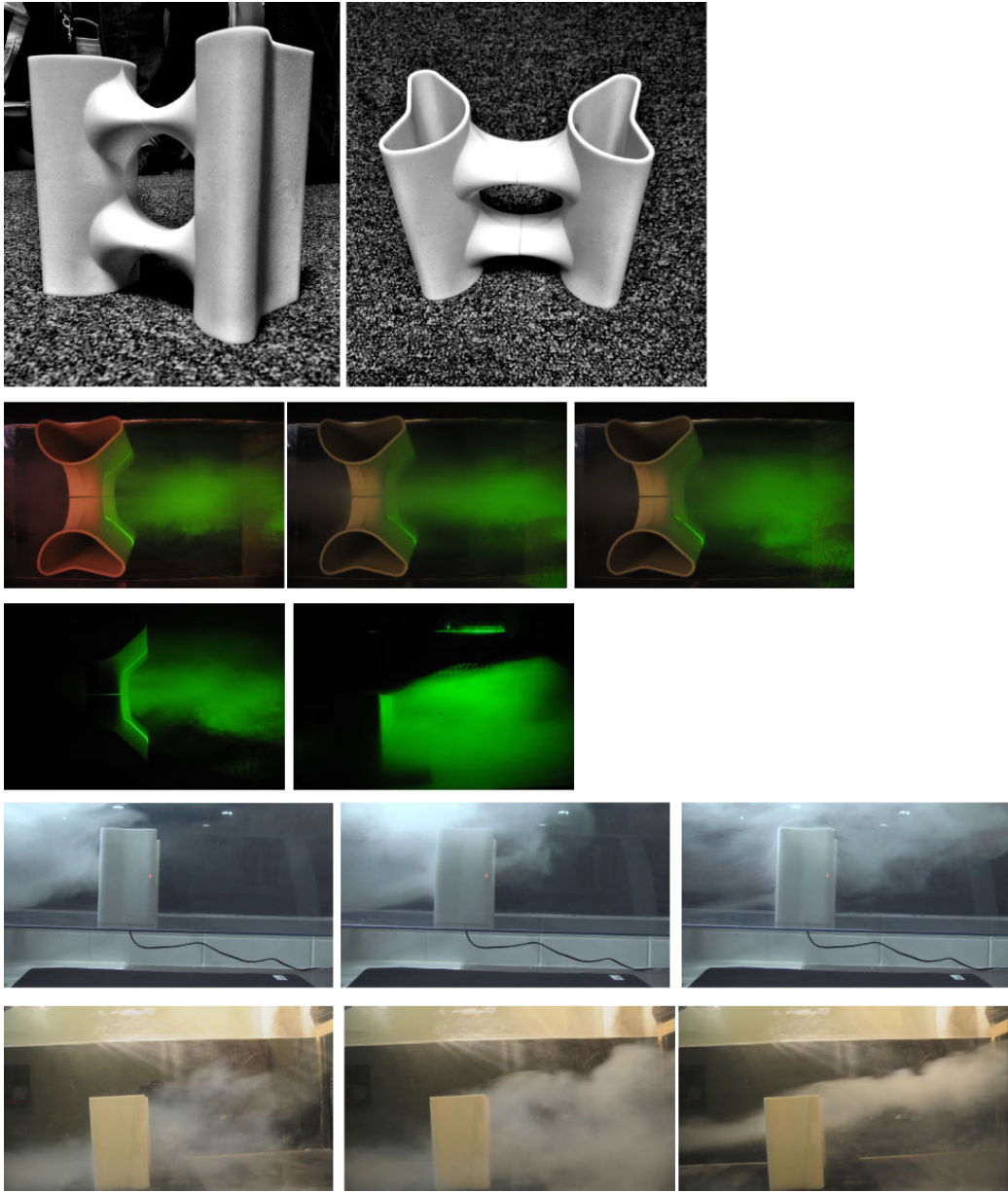
Figure 8.18: Rapid visualisation of airflow around irregular building forms, in the mini airflow tunnel, with fog technique. (Source: author)

Rapid visualisation in a mini airflow tunnel (Version 2)

Figure 8.19: Rapid visualisation of airflow through a deflector barrier, in the mini airflow tunnel, with erosion technique. (Source: author)

Rapid visualisation in the mini airflow tunnel (Version 4)
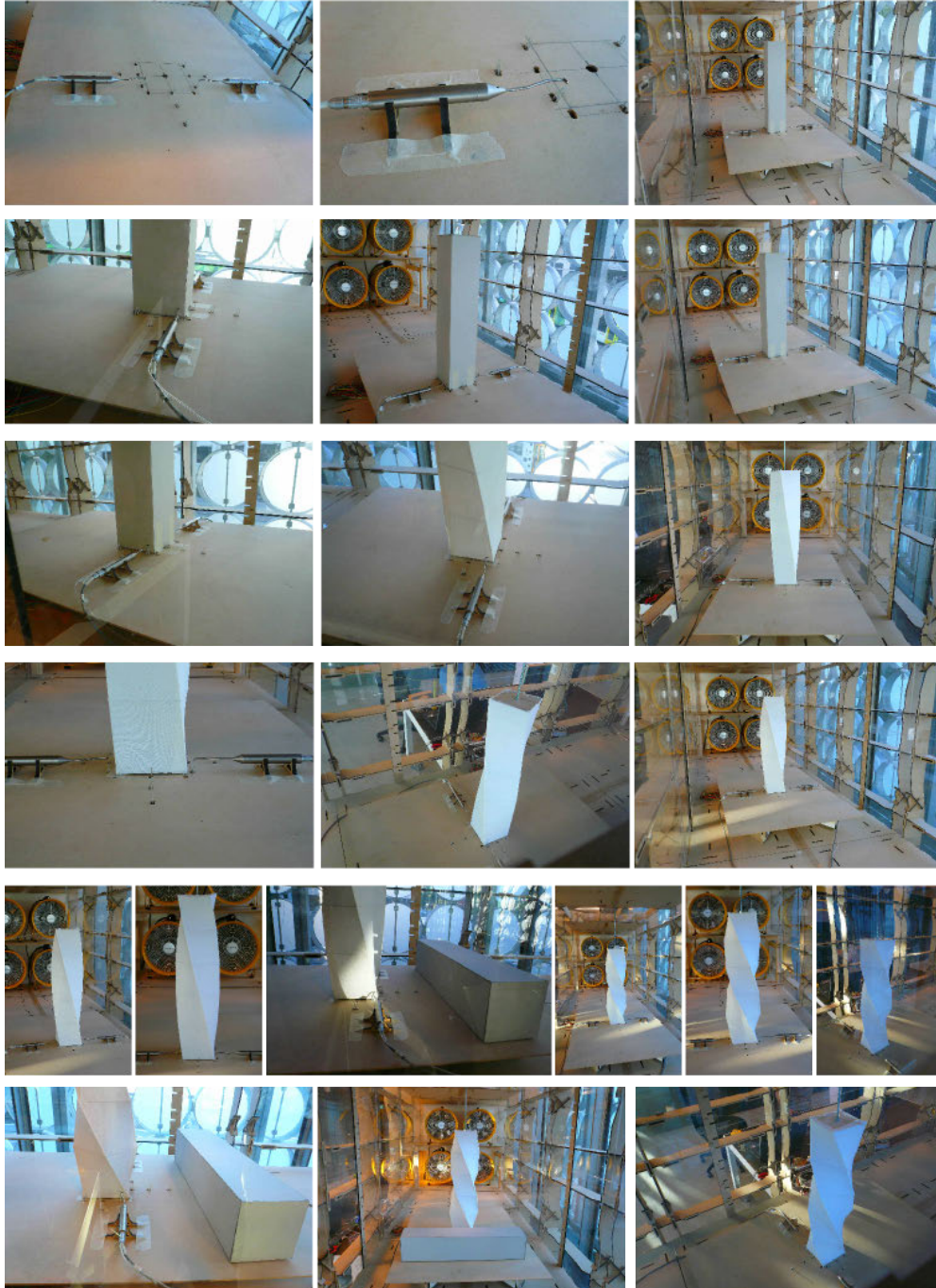
Figure 8.20: Experiments with geometrical configurations of a isolated building in a mini airflow tunnels, for rapid visualisation. The building presents three grades of torsion: 0, 60, 120 and 180 degree. The surrounding space has nine sensors to measure airflow deflection levels. (Source: author)

Rapid visualisation of airflow at the bottom of a twisted building
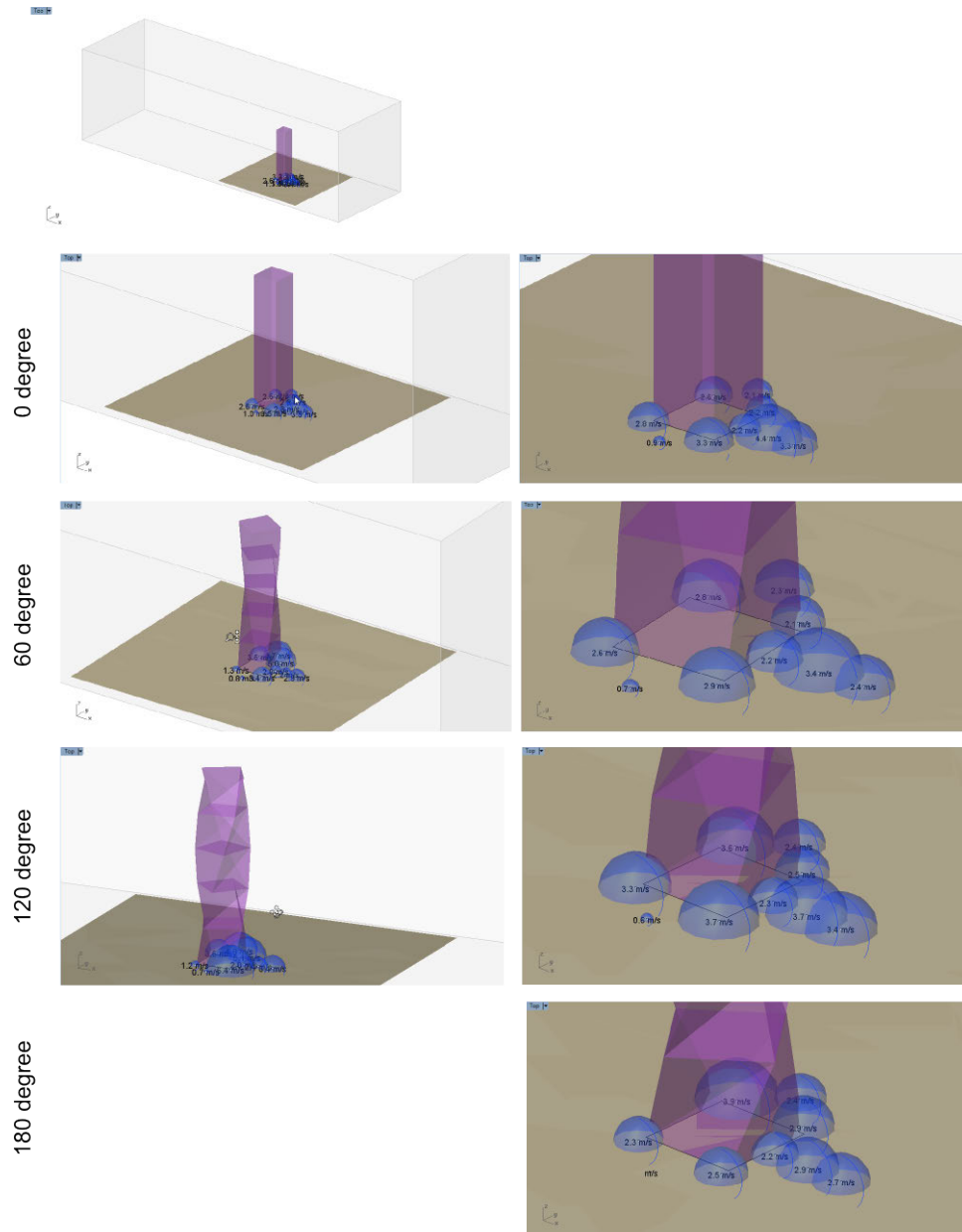
Figure 8.21: Rapid visualisations in airflow tunnel with graphical interface. Results of wind speed around buildings with four grades of torsion: 0, 60, 120 and 180 degree. (Source: Daniel Prohasky and Rafael Moya's work)

Rapid visualisation processes (comparison)

Workflow diagrams of four visualisation processes using technologies of wind analysis:

- Investigation project 1

- Investigation project 2

- Investigation project 3

- Investigation project 4

Investigation project 1

Rapid visualisation of 3D wind condition

Mini airflow tunnel

Airflow Tunnel set up | Models installation | Visualisation | Analysis

Design re-evaluation

Vasari

3D modelling

Simulation set up

3D Visualisation | Analysis

2D Visualisation

Design re-evaluation

Analysis

Level of comprehension for 3D condition of the airflow

Rapid wind visualisation process (RV)

Investigation project 2

Rapid wind visualisation through different analysis scales

Ideal rapid wind analysis workflow

Spatial context Modelling | Numerical simulation

Analysis in large scale context

Identification of wind conditions [WIND MAP]

Numerical simulation

Visualisation in local scale context

3D modelling

Simulation set up

Visualisation aerodynamic design feature | Analysis

Design re-evaluation

Vasari

3D modelling

Failure with porous surfaces

Simulation set up

3D Visualisation | Analysis

Design re-evaluation

Level of comprehension for wind phenomena along several visualisation scales

Rapid wind visualisation process

Rapid wind visualisation processes

Process and performance comparison

Investigation project 3

Performance through three design complexity levels

ODS-Studio ★ Workflow of three tools: 3D Blender - OpenFOAM - Paraview

3D modelling* | Mesh generat.* | Simulation set up | Solver iteration* | Visualisation* | Analysis

Blender | OpenFOAM | OpenFOAM/Blender | OpenFOAM | Paraview

Waiting time | Waiting time

Design re-evaluation

Visualisation of wind phenomena associated to multiple and complex aerodynamic design features with porous surfaces

ANSYS CFX

3D modelling

Failure

simplified parameters for RV

Failure or validation

Visualisation | Analysis

non porous model for RV | Mesh generation | Simulation set up | Solver iteration

Waiting time | Waiting time

Design re-evaluation

Visualisation of wind phenomena associated to multiple and complex aerodynamic design features

Vasari

3D modelling

Failure with porous surfaces

3D Visualisation | Analysis

Simulation set up

Design re-evaluation

Visualisation of wind phenomena associated to single aerodynamic design feature

Rapid wind visualisation process (RV)

Investigation project 4

Rapid wind visualisation process for architectural exploration

ODS-Studio ★ Workflow of three tools: 3D Blender - OpenFOAM - Paraview

3D modelling* | Mesh generat.* | Simulation set up | Solver iteration* | Visualisation* | Analysis

Blender | OpenFOAM | OpenFOAM/Blender | OpenFOAM | Paraview

Waiting time | Waiting time

Design re-evaluation

ABL wind tunnel ★ Only the first time.

Permission facilities | Wind Tunnel set up | Models installation | Sensor platform set up | Relocation of sensors / Calibration wind tunnel* | Analysis

real time visualisation system for RV

Waiting time

wind sensor platform for RV

Visualisation

Design re-evaluation

Rapid visualisation of wind phenomena associated to aerodynamic design features changes

Rapid visualisation of wind phenomena associated to membrane morphology

Vasari

3D modelling

Failure with porous surfaces

3D Visualisation | Analysis

Simulation set up

Design re-evaluation

ANSYS CFX

3D modelling

Failure

simplified parameters for RV

Failure or validation

Visualisation | Analysis

non porous model for RV | Mesh generation | Simulation set up | Solver iteration

Waiting time | Waiting time

Design re-evaluation

Visualisation of wind phenomena variation by complex aerodynamic design features

Rapid wind visualisation process (RV)

Rapid wind visualisation processes

Process and performance comparison

Published papers

Flexing wind. Aerodynamic study of architectural windbreak

Rafael Moya, Flora Salim, Mani Williams, Kamil Sharaidin

Published in 31st eCAADe Conference Proceedings. 18-20 September 2013, Delft (the Netherlands).

Pneumosense project. A flexible kinetic windbreak

Rafael Moya, Flora Salim, Mani Williams

Published in 19th CAADRIA Conference Proceedings. 14-17 May 2014, Kyoto (Japan).

Aerodynamic features as Auxiliary architecture

Rafael Moya, Simon Watkins, Yan Ding, Jane Burry, Mark Burry

Published in 19th CAADRIA Conference Proceedings. 14-17 May 2014, Kyoto (Japan).

Aerodynamic features applied in an urban shelter design

Rafael Moya, Daniel Prohasky, Simon Watkins, Yan Ding, Jane Burry, Mark Burry

Published in 32nd eCAADe Conference Proceedings. 10-12 September 2014, Newcastle upon Tyne (England).

Empirical evaluation of three wind analysis tools for a concept design of a urban wind shelter

Rafael Moya

Published in 20th CAADRIA Conference Proceedings. 14-17 May 2015, Daegu (Korea).

(2nd author) Parallel analysis of urban aerodynamic phenomena using high and low-tech tools

Flora Salim, Rafael Moya

Published in 30th eCAADe Conference Proceedings. 12-14 September 2012, Prague (Czech Republic).

(2nd author) Wind sensing with real-time visualisations for Designers

Daniel Prohasky, Rafael Moya Castro, Simon Watkins, Jane Burry, Mark Burry
Published in 32nd eCAADe Conference Proceedings. 10-12 September 2014, Newcastle upon Tyne (England).

(2nd author) A physical and numerical simulation strategy to understand the impact of the dynamics in air for the design of porous screens

Mani Williams, Rafael Moya, Daniel Prohasky, Mehrnoush Latifi Khorasgani, Simon Watkins, Mark Burry, Jane Burry, Philip Belesky
Accepted for publication in 6th SimAUD Conference Proceedings. 12-15 April 2015, Washington, DC (USA).

Flexing Wind

Aerodynamic study of architectural windbreak

Rafael Moya[1], Flora Salim[2], Mani Williams[3], Kamil Sharaidin[4]
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[4]kamilsharaidin@gmail.com

Abstract. *The aims of the Flexing Wind project, investigated in an intensive cross-disciplinary course, were twofold. First was to learn about aerodynamic phenomena around buildings. Second was to explore ways to observe, measure, and control the negative effects of wind around specific pedestrian areas, tram stops, and public sites in Melbourne City. Using tools such as a weather station to collect data and CFD software to simulate aerodynamic phenomena students could study the wind conditions in one of the windiest areas in the Melbourne downtown. Various do-it-yourself tools such as mini wind tunnels, handheld probes and sensors were used to evaluate the performance of potential design options, which lead to prototyping full scale adaptive architectural windbreaks.*
Keywords. *Urban aerodynamics; windbreak; wind tunnel simulation; Computational Fluid Dynamics; architectural prototype.*

INTRODUCTION

A better understanding of urban aerodynamics will positively influence design decisions in architectural and urban projects. The wind flow and dispersion through a city determine environmental air quality, wind pressures on buildings, urban heat islands, pedestrian comfort, and ambient noise level in the surrounding environment (Boris, 2005; Zaki et al., 2010). However, only a few existing techniques have been developed to deal with the habitability and comfort issues due to strong wind conditions on pedestrian areas (Cochran, 2004). These are mainly done on the urban planning level or by introducing trees and shrubs as vernacular shelterbelts. Studies have been done on how aerodynamic characteristics of windbreaks can be used to resolve pedestrian comfort is-

sues (Gandemer, 1981).

This project was conducted as an intensive three-week cross-disciplinary elective in the School of Architecture and Design, RMIT University, offered to architecture, landscape architecture, and engineering students. The outcomes of the explorations include:
- Wind maps of the sites (a major intersection located at the northern axis of Melbourne and the alleyway at the rear-entry of the RMIT University Design Hub building), derived from data captured using handheld probes and a weather station
- Analysis and evaluation of the performance of a series of windbreak options designed for

each particular site performed using a small-scale wind tunnel test and Computational Fluid Dynamics simulation.

• Three prototypes as a system of mitigation for conflictive wind environments (deflector and diffuser devices). Two of these prototypes are reported in this paper.

The main task was to investigate the design and performance of architectural windbreaks as design interventions on the prevailing wind conditions (directions, pressure, speed) by controlling eddy areas around a building. Eddy is a turbulent wind condition caused by the changes of wind pressures [1]. The key outcomes were design prototypes of adaptive architectural windbreaks, which were installed on public footpaths. Feedbacks were gathered around issues such as the performance of the proposed windbreaks and the impact of installing the windbreak on the windy sites.

METHODOLOGY

The research and design aspects of the elective projects was conducted by a group of students (11 masters and undergraduate students) and highly guided by investigators (the teaching staff in the elective, authors of the paper). At the beginning, the students had access to a wide range of literature on the theory of windbreak design. Topics included studies about aerodynamics in urban contexts and wind comfort using Beaufort scale criteria where wind is considered as a function of speed and sensations felt (Gandemer, 1978); and systems to wind control such as windbreaks (Cochran. 2004). The students were also presented with introductory lectures on the technical aspects of the project by the teaching staff as well as an external industrial expert. During this stage the students learned about causes and effects of more common aerodynamic phenomena in cities produced by the wind flow interacting with buildings and affecting public areas.

In the second stage, students were introduced to the methodology and tools on windbreak design. The literature included the authors' earlier research projects, such as the parallel wind analysis method and the mini wind tunnel (Salim and Moya, 2012) and methods of designing kinetic façade prototypes (Sharaidin et al., 2012). Digital technologies such as Computational Fluid Dynamics (CFD) were also used to simulate the aerodynamics of the external environment. Additionally, using a mini wind tunnel, physical experiments such as erosion test (wind flow visualization using particles on a dark-coloured background) and smoke test (Salim and Moya, 2012) were applied to evaluate the different designs of the windbreak systems. Through these methodology and tools the students could run different experiments focused on the analysis of wind phenomena.

The proposed methodological experiments were divided into several tasks:

1. Build a system to quantify and visualise wind data (wind speed). The tools made available to the students were: a low-cost commercial weather station, scientific indoor condition measuring probes, low-cost electronic sensors and development platform (Arduino). Through a selection of the above tools, the students will develop a system to collect and visualise the data from the public space. The intention is to develop a wind map of the urban zone using instruments to measure the movement of wind.

2. Construct both a physical and digital module of the selected site. Conduct simulations to understand the effect of wind in an interactive fashion.

3. Design an artificial windbreak prototype for public space (passive or kinetic structures). Students were encouraged to test their design iteratively through both physical and digital simulations.

4. Build and install a full scale windbreak prototype. Students built a representative part of their design in a scale one by one. This prototype was installed in a windy site in the city to evaluate impact on public space and performance to mitigate wind problems.

5. Evaluate the wind mitigation achieve after of the prototype installation.
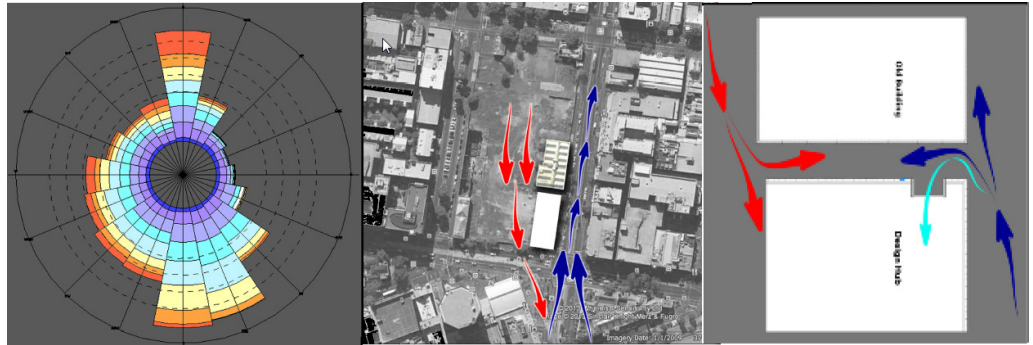
PROJECTS: ANALYSIS, DESIGN AND OUTCOMES

The two main approaches to develop a wind control structure were the exploration of porous patterns as a wind filter and the concept of a shell as a wind deflector. The challenge was to not only design a structure to control the negative effect of wind detected in the site, but also produce low impacts in the surrounding space. This meant that the aesthetics is an important element alongside the functional aspect of the windbreak.

Milk.Crate.Break Project (by Tamara Cher, Xuan Son Nguyen, Romy Peterfreund)

The site for prototype 1 *Milk.Crate.Break* is at the rear entry of the RMIT Design Hub (Swanston Street entrance). It is a narrow alleyway close to an alcove with an operable door opening. Through a study of the historic data of the site it was found that there is a prevailing wind blowing through the site, direction alternating depending on the season (Figure 1). When the door is opened the sudden pressure difference produce a noticeable wind gust into the building.

The study of the site (Figure 1) was focused on the investigation of the differences of wind conditions between summer and winter seasons, as well as analysing the impact in this area.

The first finding of this study showed that wind has two predominant directions (north and south). This meant that wind passing through the pas-

sage leading to the entrance changes its direction throughout the year. The effect on the entrance is the same but the design of the windbreak should deal with both wind directions.

Using Vasari as CFD software it was possible to visualise how the gust of wind had a curved movement producing two separation zones with low pressure areas. One of these areas coincided with the entrance of the building, producing an input of wind when the gate was opened. These simulations were validated with measurements of the wind speed using the anemometer on the low-cost weather station. On the day of data collection it was found that the wind coming closed to the façade had an average speed of 3.7m/s at 2m height, but this velocity increased up to 4.4m/s when was blowing through the passage (Figure 2).

The first approach was to use a shell or canopy to deflect the wind to maintain the low pressure area in front of the entrance. Later the design process progressed to the design of a skin with some kind of porosity to control the wind speed. This porosity concept evolved from a surface with simple patterns of holes to different patterns with a variable density of porosity (Figure 3), following the indications of the studies by Gandemer (1981) on windbreaks.

As part of the project the students were required to construct a section of their design in full size and install it on site. The *Milk.Crate.Break* team decided on the front section of the design to be constructed
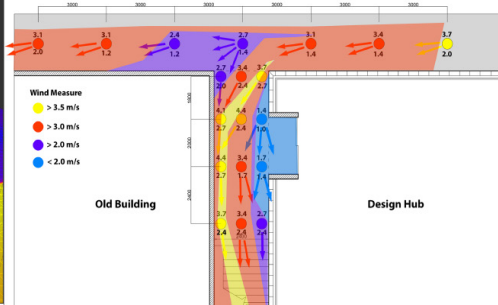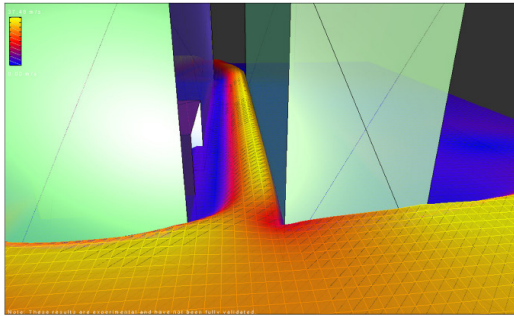
at the full scale. This had the implication that a new structural system is required for the design. Through further exploration the students decided on using milk crates as the main building material, factors influenced their decisions included: structural (modular self-supporting, easy to assemble and disassemble), sourcing (free and readily available), a cultural significance (Melbourne's laneway). The inherent structure and porosity of the milk crates also offered the students additional design possibilities: The design was adapted to take advantage of the crate volume to produce a design with a double skin. The students explored several options of patterns for an adaptable second skin through CFD analysis. The first option had a pattern of Venturi funnels working as a diffuser to decrease the wind speed in the outcome side of the wall. The second version was a pattern of triangular petals with a more simple system of petals aperture for the density control. The final design was a pattern of triangle flaps based on the shark skin. This was the options chosen because the parallel triangular surfaces deflected the wind

more efficiently to produce an upward air through the wall. The experiments compared these different patterns with 20%, 40% and 60% of porosity. For each case, the pattern moves depending on the pressure of the wind, where used to deflect the wind upwards as well as absorbs a fraction of the wind energy (Figure 4 and 5).

The final concept was a structure with a double layer of porous skin. The first porosity layer was a regular graph design which ameliorated the wind speed. The second shark-skin pattern layer reduced the wind flow close to zero. Between both layers, the internal chamber in the structure was designed to deflect the wind vertically. In this way the pressure on the structure was reduced to maintain the structural stability.

The students' final design was a windbreak that spans the full width of the alleyway, 2.5 meters in height, offering protection for a large area in the proximity of the door. The design form is symmetrical to work with both wind directions. There is one opening at each end to allow access through the

Figure 4
From the left to right: Venturi
funnels, petals and shark skin.

Pattern 1: VENTURI FUNNELS   Pattern 2: PETALS   Pattern 3: SHARK SKIN
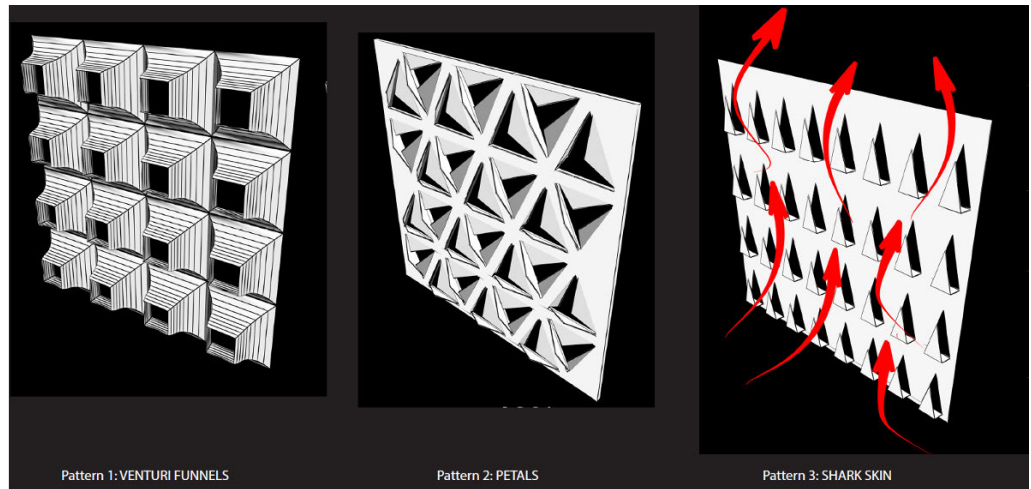
site and into the building. The porosity system is designed for the surface of the windbreak, with lower density at the lower part the design to offer more protection (Figure 6).

Further testing (both simulation and in the physical mini wind tunnel) were conducted to confirm the functionality of the adapted design. Measurements were taken to evaluate the design.

Lyrebird Project (by Mikhail Kochev, Sara Metanios, Daisy Leung, Rico Shuyuan Zhang)

The site of prototype 2 *Lyrebird* is located close to a street level entrance to RMIT University Building 14 (Swanston Street). The onsite data measurements revealed a predominant wind direction from the south to north. The students noticed a strong and

Figure 5
From the left to right: porosity
variations and effect of wind
passing through the structure,
final installation.
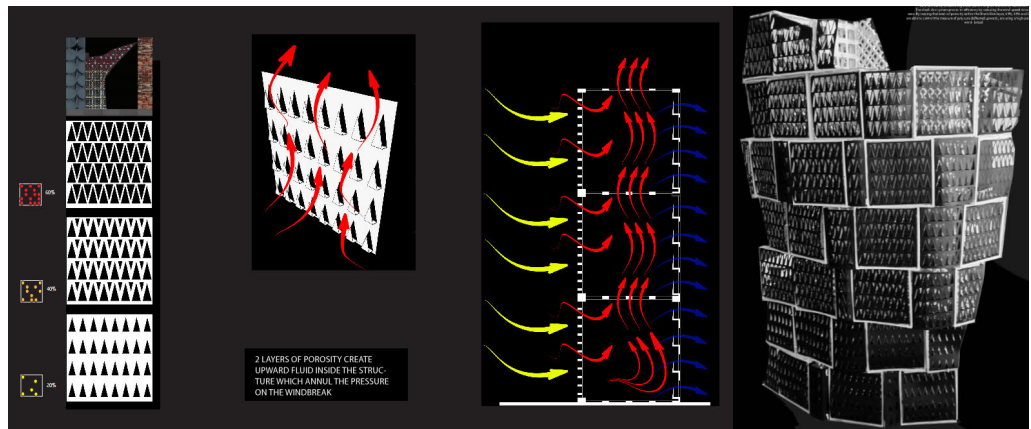
2 LAYERS OF POROSITY CREATE
UPWARD FLUID INSIDE THE STRUC-
TURE WHICH ANNUL THE PRESSURE
ON THE WINDBREAK

turbulent wind close to the building facades side of the pedestrian sidewalk. Although a number of trees are present on the street near the site, it was evident that the wind conditions were not improved for pedestrians. Erosion test of the site model was conducted in the mini wind tunnel to reproduce the more relevant phenomena. The phenomena observed were: the wind blowing along the street, the wind effect around the corner on the building, and the effect that could be produced by placing structures over the entrance (Figure 7). These simulations demonstrated a channel effect occurring in this area with a high level of turbulence from the friction with the buildings' walls. This was identified as an issue for the building entrances and other points around the pedestrian circulation routes. The design objective was to protect the street level entrance from the prevailing and local wind conditions.

The student drew their design inspiration from bird feathers, in particular the fan-like tail of the Aus-

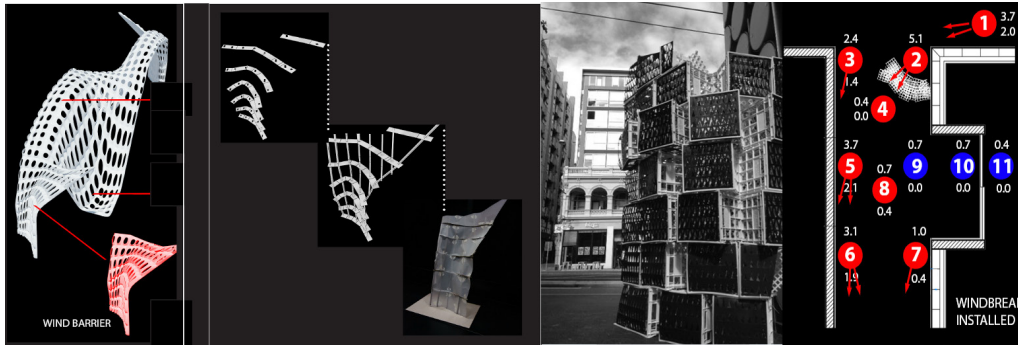tralian Lyrebird. The idea was to mimic the natural curvature of the feather to form a curved shell for the entrance (Figure 8). Design iteration of the form and dimension of the windbreak was mainly conducted through physical wind tunnel tests and CFD experiments. These digital tests were focused to find the more efficient curvature for this roof to deflect the wind. This exploration found that a double curvature performed a very good protection rather a single curve (Figure 9).

In the wind tunnel test, a simple curved canopy shows a good performance to deflect the wind without significant loan on the structure: the arched shape was able to deflect and guide the wind over the building opening. This final version was chosen as the structure shown to be a more effective windbreak. These tests demonstrated that the structure does not produce lateral strong gusts and the protection area was large enough to provide shelter against strong winds around the entrance of the

building (Figure 10).

Detailed porosity exploration was also carried out using smoke test to study the best sequence of gaps and thickness of the barrier with different wind velocities (Figure 11).

The final design was a frame and infill system with triangular "slot-in" panels on vertical structural frames. Each triangular panel contains a movable flap with functions similar to prototype 1. As these panels are more visually prominent compare with prototype 1, the students worked to adapted them as a visual wind indicator to increase public interaction with the windbreak. This was done through installing an Arduino controlled LED display, where the display was driving by wind data from an electronic sensor (anemometer). This was not installed
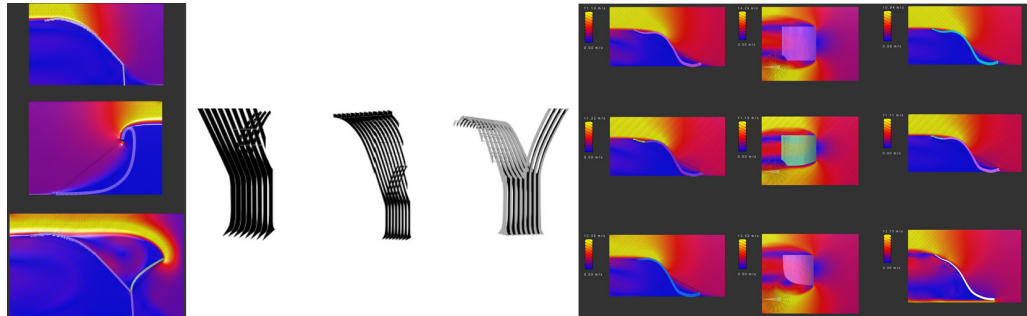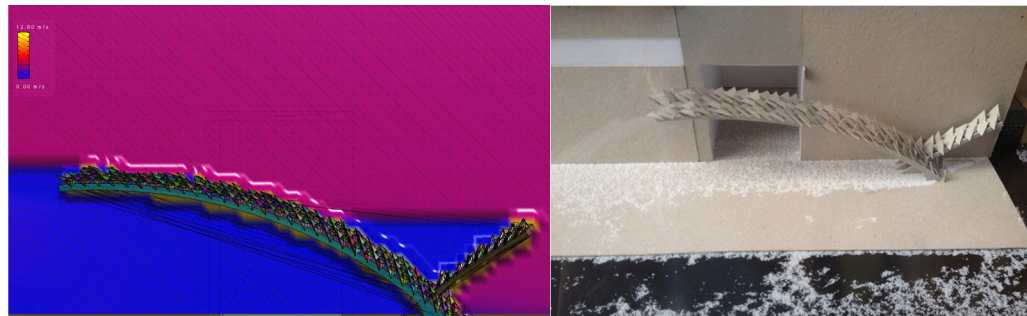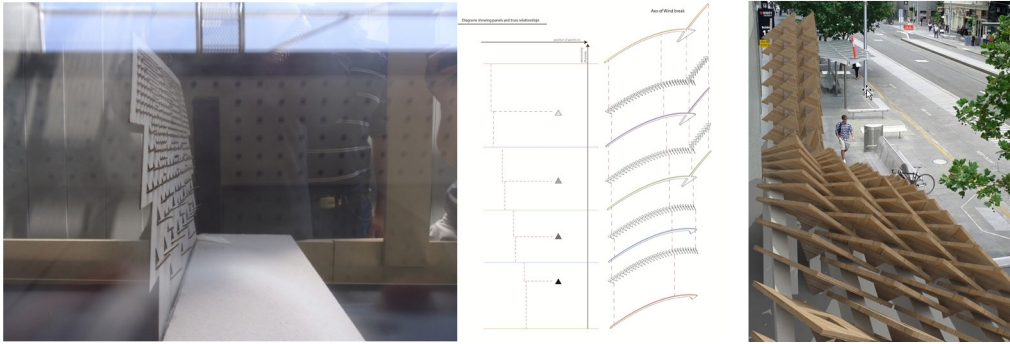
Figure 11
From the left to right: smoke test, axonometric of panels and final render.

on the final installation due to time constraints. Many factors such as site permit restriction and fabrication constraints dictated that only approximately 2 meters by 2 meters by 2 meters of the design was constructed and evaluated on site. The students applied bright paint to observe how colours have a relevance to intensify the visual aesthetic of the structure in the public area (Figure 12).

GENERAL EVALUATION

One positive outcome of this academic project was the opportunity to share knowledge from different fields that conduct work on the city and its current problems. The use of technology helps us to understand the dynamic phenomena like wind in cities, through collecting data (both in the physical and virtual realm, on site and through simulations) and make sense of that information. This was the inten-

tion of this project: to teach students to work with methods and technological tools to study complex phenomena.

This first part of the objective was fully complete for the students. In the short three weeks, through the study of the literature available in the field of wind engineering and the tools such as Vasari CFD and a low-tech mini wind tunnel, the students were able to gain a good understanding of the basic aerodynamic effects to begin their own design exploration in this field. The potential of these tools for pedagogic purposes was evident. The visual interactive feedback helped the students to gasp with the comprehension of these complex phenomena, and as a platform for discussion the design performance. The visual documentation of the design testing process (both still images and videos) formed a large part of the presentation material for the students
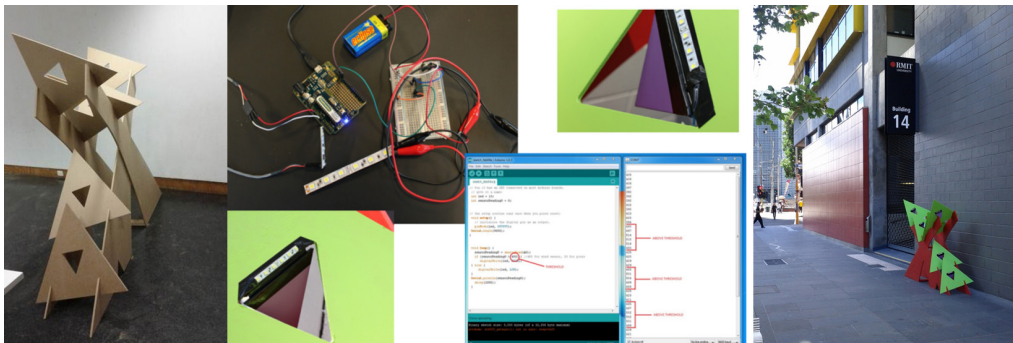
Figure 12
From the left to right: prototype, Arduino platform and installation.

to communicate their design intent to the teaching staff and invited critiques.

The ready-to-go low-cost commercially available weather station, with its simple interface, was quick to be adapted by the students to be used for site analysis and to prototype performance evaluation tool.

Arduino Platform and electronic sensors have proven to require a learning curve too steep for most of the students to be able to utilise them in their design. The Arduino and sensors induction were provided as part of the course material, but whether to incorporate it within the design was a choice left for the individual student team. All of the students welcomed the half day hands-on session exploring Arduino sensors and motors. The students were guided through a series of selected examples that introduced the concept of Arduino microcontroller and a collection of electronics. With each example its possible application to the windbreak design was discussed. Following the demonstration, a proportion of students actively sought additional equipment and assistance to experiment it further. This demonstrated that new technology was easily taken up students when it is presented as a useful resource to extend the possibilities for their design proposal.

Apart of the design aspect of the windbreak, the challenge of a built prototype was a very positive learning process because students were encouraged to deal with physical problems and technical solutions. Even if the prototype was not a fully functional model, many issues concerning scale, materials, and cost were considered and evaluated for each project. This dialog of material and constructability also opened up new design exploration. Take the intention of the *Milk.Crate.Break* project to use recycle plastic boxes as an interesting example. The decision to use milk crates as a building material led the team to explore the features of a double-layer windbreak. This project studied the performance of different porous patterns when a simple plastic mesh may be functionally sufficient. This demonstrated that performance and constructability should inform each other in design.

The task of constructing a physical prototype and installing it on site helped students to understand how an urban intervention can also have a visual impact in the space. For instance, the colour in the structure of *Lyrebird* project was considered as a parameter of communication. Additionally, the project also considered to use an anemometer driven LED display which could be activated with the wind, sending a live visual signal to the passers-by when the wind speed increases over the comfortable levels. Thus, the performative aesthetics of a windbreak as an urban element can also have a functional aspect that informs people of the surrounding environmental conditions.

CONCLUSION

Wind around buildings and in public spaces can produce negative effects that are necessary to mitigate. This paper reports on a design-construct cycle of a site specific architectural windbreak, conducted in the form of a design studio taken place over an intensive three-week period at the RMIT University, Melbourne Australia. After a detailed study of the site, the students successfully incorporated aerodynamic theory into their design thinking and demonstrated the use of CFD simulation tools and physical wind testing to assist their design process. The impact of the windbreak on the site was quantitatively measured and evaluated. This is done by assimilating the studies of local wind conditions and vernacular systems and testing the design in wind tunnel simulations.

The results and prototype designs are preliminary, however they demonstrated the possibilities of designing windbreaks that have aesthetics features as well as the functional capacities to provide comfortable pedestrian areas.

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PNEUMOSENSE PROJECT

A flexible kinetic windbreak

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Abstract. The study of wind conditions in the urban context has multiple application areas such as for cleaning pollution through ventilation, analysing wind pressures on building façades, and improving pedestrian comfort. In this context, the Pneumosense project is a student's project focused in the design of a kinetic system to ameliorate negative impact of wind conditions in pedestrian areas in the city of Melbourne. Its development considers several stages including site analysis, analogue wind tunnel testing, digital simulations with Computational Fluid Dynamic software, material explorations, kinetic component design with Arduino, and rapid prototyping.

Keywords. Urban aerodynamics; windbreak; wind tunnel simulation; computational fluid dynamics; architectural prototype.

1. Introduction

The aim of this project was to design an adaptive windbreak system to improve the habitability and comfort in a building's external space, which is prone to strong prevailing winds.

Studies about human discomfort produced by wind in environments near buildings (Gandemer et al., 1978) provide a broad information about more common aerodynamic issues in built environments. Existing techniques to ameliorate wind conditions on pedestrian areas (Cochran, 2004) consist mainly in urban planning and low scale interventions, like the use of natural windbreaks, such as trees or shrubs, and artificial windbreaks, such as porous screens. These solutions often incorporate very little aesthetic design considerations.

This paper presents an alternative proposition for wind control, a kinetic and adaptive artificial windbreak called Pneumosense, capable of sensing the current wind conditions, deflecting and reducing wind speed, and helps to improve pedestrian comfort of a site of the north boundaries of Melbourne CBD. This approach extends the existing methods to deal with the dynamics of wind conditions on public areas.

This project was a successful conceptual design developed in an intensive three-week cross-disciplinary elective course in the School of Architecture and Design, RMIT University. The course was offered to architecture, landscape architecture, and engineering students. The Pneumosense final design is a proposition presented by the team of Marta Sophianti, Lazuardy Laisuhanta, Vera Raquel dos Santos and Zin Mee Zin Win. Reports on other student projects of the same course can be found in Moya et al (2013).

The project was designed and developed after performing site analysis, material explorations, and technical experiments with Arduino. The wind conditions of the site was analysed using analogue measurements, physical wind tunnel simulation, and digital simulation. The data gathered from the site analysis was visualised and compared to inform the design of the adaptive windbreak. The explorations with the materials, sensors, and actuators lead to a new design of a kinetic windbreak. The windbreak model was tested in the digital simulation to achieve the desired intervention prior to the fabrication of the model. Finally, the prototype was installed and tested on site to evaluate the impact it has on the wind conditions on site.

2. Precedents

Existing research on responsive and kinetic architecture have mainly focused on its application for facades to improve the energy performance of buildings (Sharaidin et al., 2012). The main considerations for designing kinetic facades or structures in architecture have been to improve natural daylight or regulate indoor temperature.

To develop a concept for a kinetic structure which adapts to ambient wind conditions, some precedents were studied includes a study of contraction and expansion of fabrics through embedded frames and an electronic control. Another reference considered was the "Responsive Surface" by Michell Johanna Cardona from Cornell University's College of Architecture, Art and Planning (Cardona, 2011). Here, an artificial skin with a porosity pattern was explored as a potential responsive building envelope to improve their energy performance (Figure 1, left). Sensing and computation were used to gather data about the environment and actuate on those surfaces to

improve the building's internal conditions. However, those projects are mainly focused on exploring daylight and designing shading devices.

Except one concept design, the Blow Wall/ Urban Wind-Vibro-Power screen (2013), to our knowledge, there is no existing research or development into kinetic or adaptive architectural windbreak. The Blow Wall is an artificial urban windscreen for public plazas which controls wind and harvests wind energy with small elements vibrating with the wind flow (Figure 1, right).

These precedents show approaches which were presented as challenges in the course and were integrated into the Pneumosense project: a windbreak device to be placed in outdoor pedestrian areas, with kinetic features that are capable of adapting to the changes of the wind conditions.
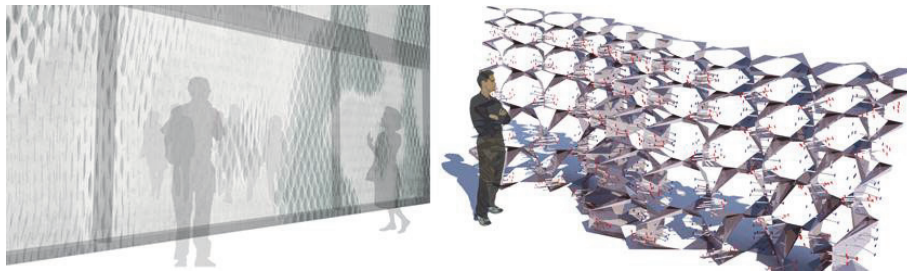
Figure 1. Left: Responsive Surface by Michell Johanna Cardona (take from Cardona, 2011). Right: Blow Wall (taken from adaptivecomponentsystems.wordpress.com)

3. Site data analysis and simulation

The course integrated approaches from architectural design, engineering, and computing to achieve the two main tasks of the project: 1) analysis of wind and environmental conditions in outdoor space; 2) design and evaluation of an artificial windbreak in public space. Therefore, the Pneumosense team had to collect site and historic contextual data, understand the underlying wind phenomenon, run scientific experiments and digital simulations to inform the iteratively design process and the performance evaluation. Computational Fluid Dynamics simulation, a wireless weather station for analogue measurements and a mini wind tunnel (Salim and Castro, 2012) were used simultaneously. Different wind analysis tests were run. The goal of these explorations was to map and visualize the shelter areas and wind speed areas around buildings.

3.1. COMPUTATIONAL FLUID DYNAMICS (CFD) SIMULATION

Using Vasari software for CFD simulation (Figure 2, left), physical erosion test using the mini wind tunnel, and visual observation with a weather station, it was possible to draw a wind map of the area showing different pressure areas, direction of the wind flow and wind speed. This analysis identified three regions within the chosen site: main incident wind areas and directions, turbulent areas and a diffuse airflow area. These aerodynamic phenomena are produced by canyon effect, a well-known phenomenon that occurs in cities (Ahmad et al., 2005).

3.2. SITE DATA COLLECTION AND VISUALISATION USING A WEATHER STATION

The wind speed, pressure, and directions around the site were captured, monitored, and logged using a weather station. The data was then analysed, and compared with the analysis from the digital simulation.

The turbulent wind effect on this area was evident through simulation and data collection (Figure 2, right), the pedestrian discomfort was also observed while on site. The turbulent area in the zone was chosen as the site of the kinetic architectural windbreak installation to improve the pedestrian comforts.
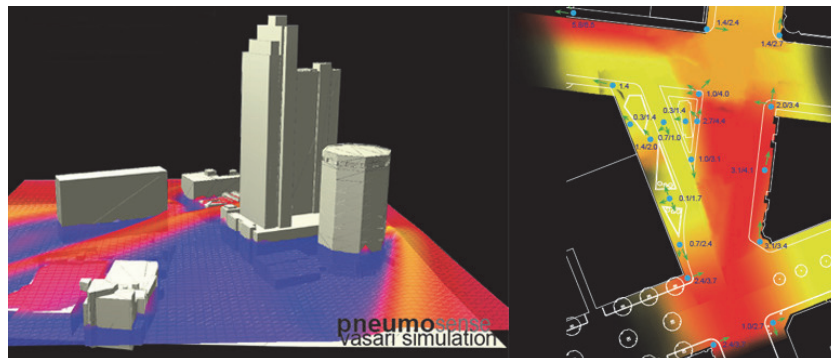
Figure 2. Left: CFD Simulation of the urban area. Right: weather station wind map, with areas of wind speed (grey colour is more intensive)

3.3. ANALOGUE WIND TUNNEL TEST

The first test was done in the analogue wind tunnel constructed and a small-scale urban model of the site was placed in this wind tunnel. Using the simulated wind and salt particles to visualize erosion contours around the physical models, the impact of the wind on the pedestrian areas affected by the

topological configuration of the group of buildings and wind behaviours could be better understood (Figure 3).

Figure 3. Erosion test. Experiment in a mini wind tunnel.

4. Concept and design process

During the design process of the Pneumosense project, two options were developed. The first one was a flexible and porous screen system with horizontal blind-like frames operating in a vertical movement (Figure 4).
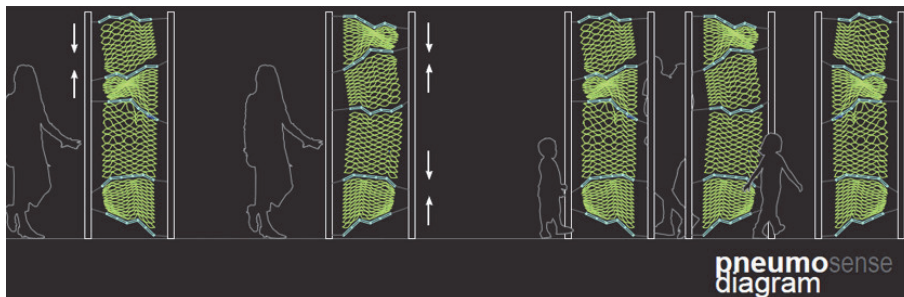
Figure 4. Pneumosense first concept (screens).

However, this first version generated only a small region of protection, had a poor structural resistance to the overload produced by the wind and had a high operational complexity.

The final alternative was a cylindrical mesh with two types of porosities: a structural porosity and a layer of adaptive porosity (Figure 5). Even though both alternatives were different, the concept behind them was the same: a skin with an adaptive porosity which responds with the variation of wind speed measured by the wind sensors. Porosity can filter and diffuse high wind speed more efficiently than opaque barriers; with the variation of the

porous density as controlling factor (Gandemer, 1981). Based on these facts, the proposed windbreaks could produce a sheltered area that mitigated strong turbulent wind. The idea was to consider the necessary flexibility and the structural stability in the presence of the wind drag force. The final concept was a tree-like three-dimensional mesh that can adapt to unpredictable wind conditions, such as the variation of the flow direction.
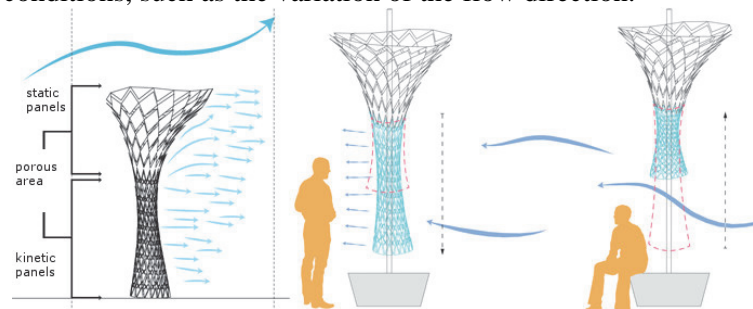
Figure 5. Pneumosense final concept.

The concept was developed in Rhino Grasshopper to explore different options and variations of the panel configuration and porosity patterns.

4.1. MATERIALITY

Using flexible material resolves the need for porosity and flexibility without elaborated complex mechanical system. Working only with the flexibility of the material this skin can be stretched producing different sizes in the porosity pattern. Different kinds of geometric topography made of silicone material were tested to select a good configuration for the mesh pattern. In the end, a simple leaf-like sheet with small cuts was chosen in order to be stretched from each vertex. Those panels were assembled into a mesh to be controlled by a simple mechanism.

A further possibility was to use smart materials, such as Smart Memory Alloys (SMA), to stretch and control the expansions of the material structure without the need of electric motors. A solar system could be designed to power the system.

4.2. TECHNICALITY

The unpredictable condition of wind requires an automatic responsive system to adapt automatically to these changes. An electronic platform was

used to sense, quantify, evaluate and respond to the wind conditions. The Pneumosense project integrated readings from wind sensors, running on an Arduino board, to actuate servo motors. The wind sensors measured the wind speed and this data was processed by the Arduino to control a servo motor producing three grades of tension on the flexible mesh, increasing or decreasing its porous density at the level of pedestrians when the wind is blowing (Figure 6).
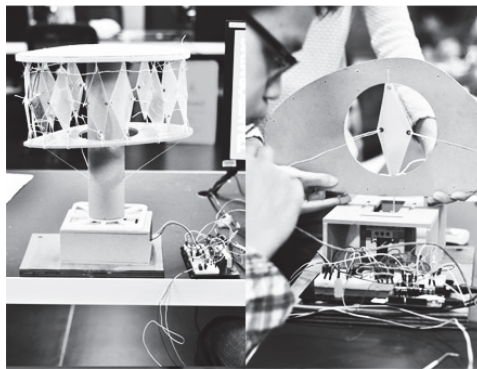
Figure 6. Arduino Platform and test of porosity control with flexible material.

5. Prototype

The final step of the students' work was to build a full scale prototype of the Pneumosense project which replicates some features of natural windbreaks. The result was an improvement of the aesthetic design, and its performance as artificial windbreak. However it was not a simple simulation of a tree, rather a kinetic device which could respond through a process of adaptation to deflect the wind and reduce wind speed under multiple wind directions.

This prototype had two sections with panels to create a porous surface. The top section had static panels to work as a filter and a deflector of the downwind, constructed as a structural mesh. The second part of the windbreak was a cylindrical section of kinetic panelling at the bottom of the structure working at the pedestrian level. This motor controlled mesh could change its porosity density from 0% (unstrech) to 5-8% of porosity (stretched) when operated vertically.

The general shape of this kinetic windbreak had the form of an inverted cone mesh (Figure 7). This conical design resolved one of the most significant problems related with the wind: the unpredictable wind directions. Generally, static windbreaks as a screen need to be orientated to the prevalent wind direction. However, changes in the pressure zones caused by seasons or new buildings that modified the urban configuration will produce variations

in the direction of wind, affecting the windbreak performance. The students' windbreak design is based on a cylindrical structure rather a simple screen or flat barrier, hence, it does not have problems in facing different wind directions.
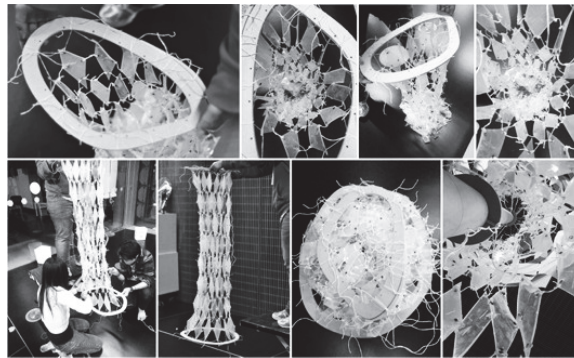
Figure 7. Pneumosense, prototype assembly.

6. Evaluation

There are two stages to evaluate the proof-of-concept prototype: first, a digital simulation with CFD software (Vasari) and second, a quantifiable testing of the physical model on site using a weather station.

The digital design was tested with the Vasari simulation software to evaluate its performance. Firstly, it was studied as individual element. The test showed a significant reduction of the wind speed when the wind passed through the structure and we observed a lower wind speed around the windbreak's edges. This is a significant improvement compared with an opaque barrier. On the other hand, a natural screen such as a tree produces mitigation by its foliage at the top, but not at the branch level, where wind still produces discomfort in pedestrian areas. This concept of a complete porous structure can deal with this issue. Secondly, the students experimented with a group of windbreaks to select the arrangement with the best performance in terms of dealing with different wind directions and wind speeds, as well as to increase the shelter area (Figure 8).
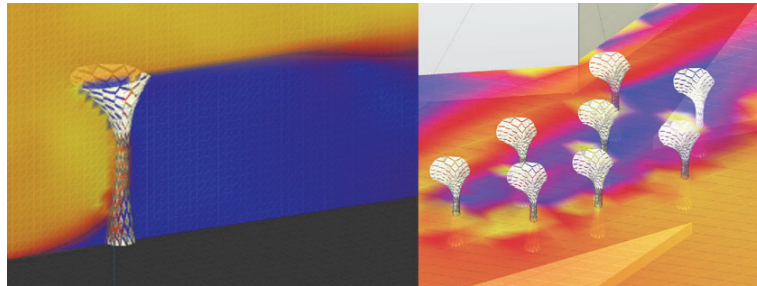
Figure 8. CFD test of protection region (dark colour represents slow speed wind)

The porous density of this artificial windbreak regulated by a mechanism opened several possibilities. For instance, the aperture of the porous could respond to the temperature conditions of the environment, increase or decrease the wind speed as required depending on the variations in temperature.

Due to limitations of time, materials and cost, it was not possible to build a group of fully functional prototypes. However, the students installed a proof of concept model on site and carried out qualitative observations about the visual impact of this structure on the site, as well as limited quantitative evaluation of the wind speed around the model using a weather station (Figure 9).
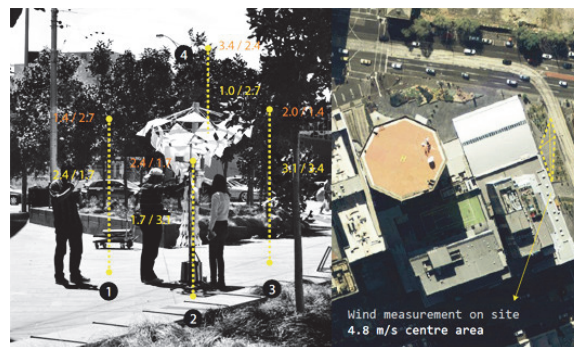
Figure 9. Prototype installation and wind measurements around the model

7. Conclusion

The Pneumosense is a students' project conducted during an intensive elective course. However, it was designed following a workflow that involved a multidisciplinary approach, allowing students to define environmental problems, analyse the wind condition factors and design potential solutions with a new approach. This concept that integrates kinetic system design with per-

formance-based design of windbreaks is an original contribution of this paper, which deals with windy pedestrian areas in outdoor environments. The general concept of the Pneumosense project integrated a smart design with efficiency and aesthetics. With a more complete development this design could be a contribution to the field of wind architecture, where there are not many tools to resolve the negative impacts of strong wind effects in the urban context, kinetic devices can be an interesting alternative to deal with the unpredictable nature of the wind.

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AERODYNAMIC FEATURES AS AUXILIARY ARCHITECTURE

Design and analysis of protection regions for wind discomfort in a local urban context, using CFD simulations

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Abstract. This paper presents the experimental study of aerodynamics phenomena in built environments, focused on explorations of environmental wind flow near buildings, pedestrian wind comfort issues and methods of mitigation of wind speed. In addition, it is an overview of an aerodynamic analysis with CFD software for a hypothetical urban shelter design, based on aerodynamic features. The aim is to evaluate the feature's performance to control wind flow in protection regions for pedestrians.

Keywords. Urban aerodynamics; CFD simulation; wind discomfort.

1. Background

The habitability and comfort in a building's external space, where the atmospheric dynamics (wind) are affected by the urban context generating wind phenomena around buildings (Figure 1), has received a lot of attention in recent years by researchers (Stathopoulos, 2011). In many cases, the public space requires mitigation methods for local wind issues at the ground level. Even though existing options to change or ameliorate pedestrian wind conditions have been documented in the literature (Cochran, 2004), methods of control and mitigation of local wind discomfort in pedestrian areas are difficult to be implemented, because of the inflexibilities associated with the built environment. In general, it has promoted the use of vegetable screens as

a main classic element of mitigation and wind control, thanks to their positive performance and good aesthetic condition. However, the question about how to improve the outdoor environments for pedestrian comfort remains as a field of exploration of technical solutions and new designs of architectural elements.
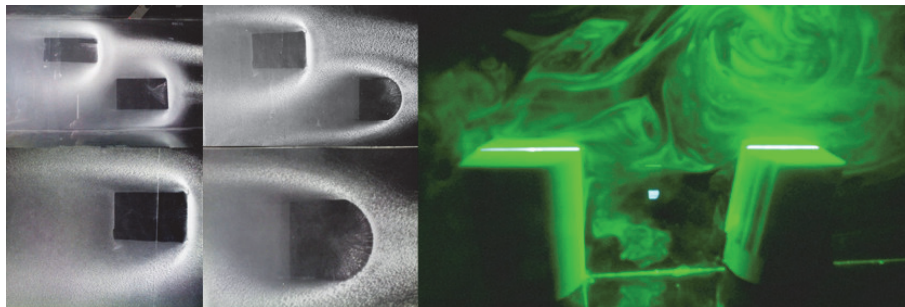
Figure 1. Turbulence around buildings (Designing the Dynamic Workshop, 2011).

Porous membranes and permeable structures are being explored with new morphologic approaches for designers to provide conditions of comfort. Because of their possible architectural applications such as auxiliary elements for buildings to deal with the wind conditions, Michael Hensel (2012) has called them as a "Supplementary Architecture".

However, the control of wind phenomena and the improvement of regions of comfort provided by architectural solutions need an additional approach. The aerodynamic studies of Jacques Gandemer about wind comfort, windbreaks and their aerodynamic features are relevant to determine ways of manipulation for wind condition and wind mitigation methods. His experiments of particular interest are about porous screens and aerodynamic features. These features allow changes in the wind flow pattern produced by porous forms and permeable materials when they are strategically integrated and associated to work as windbreaks.

This research proposes the convergence of the auxiliary architectural elements and the aerodynamic features, as a strategy of design to be used for the mitigation of wind issues in outdoor environments near buildings.

2. Research aims

The first objective of this research is focused on an aerodynamic analysis of wind effects produced by aerodynamic features in a shelter prototype. These aerodynamic features are based on the studies of Jacques Gandemer about artificial porous screens (Gandemer, 1981). Gandemer explored different

configurations of fences used as windbreaks. These studies, realised with wind tunnel experiments, evaluated several possible barrier designs and the protection factor produced, respectively. After several tests, screens with a 20-30% porosity were found to have the best performance (Gandemer, 1979). However, Gandemer also found that some auxiliary features produce particular aerodynamic effects when these are integrated to the porous screens, increasing the region of protection at the leeward side of the barrier.

Four of these features are defined as more significant for further experimental models: graduated pattern of porosity, auxiliary curve deflector, double slot of acceleration, and parallel screens (Figure 2). Thus, these can be studied as potential design components of architectural prototypes with more complex forms or in contexts with different wind phenomena (like local wind in a built environment).
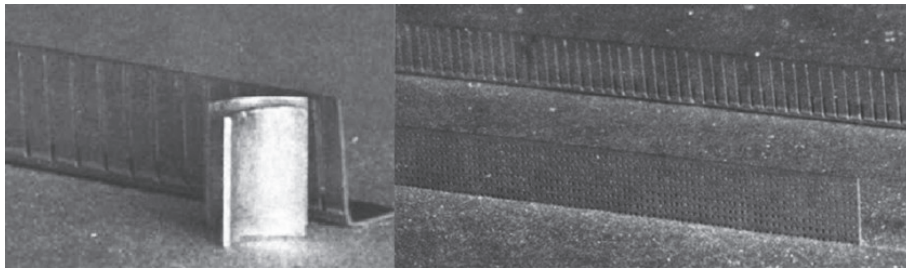
Figure 2. Gandemer's experiments of windbreaks and aerodynamic features. Left: deflector and porous screen. Right parallel screens (taken from Gandemer, 1979).

The relevance of these the features for wind control is verified with aerodynamic experiments with the intention to use them to create wind deflections in substitution of physical region boundaries for an urban wind shelter (tram stop). These wind deflections increase the protection region of a windbreak, to be referred to as *wind thresholds* in this paper.

2. Experimental methodology

The methodology is based on empirical evaluations and experiments on a hypothetical project of shelter for a tram stop of the city. These experiments involve simulation and analysis using Ansys CFD (Computational Fluid Dynamics) software to verify the location of the eddy regions and protection areas generated by the wind mitigation feature. These experiments with digital technology link parameters of aerodynamic phenomena in urban context, local wind issues and aerodynamic feature performance. Additionally, in the first stage, to simplify and to facilitate the further experiments: all models

studied and tested are simple geometries representing individual screens or roofs, where their condition as porous surfaces is more significant and easy to evaluate.

1.2. URBAN WIND PHENOMENON

To facilitate the aerodynamic experiments and analysis, the Authors selected a specific urban wind phenomenon presents in an urban context: a phenomenon caused by the seasonal prevalent wind in the Melbourne City (North to South). The high wind speed along a narrow street (Figure 3), known as the Channel Effect (Gandemer et al., 1978), can cause discomfort to the pedestrians in the region.
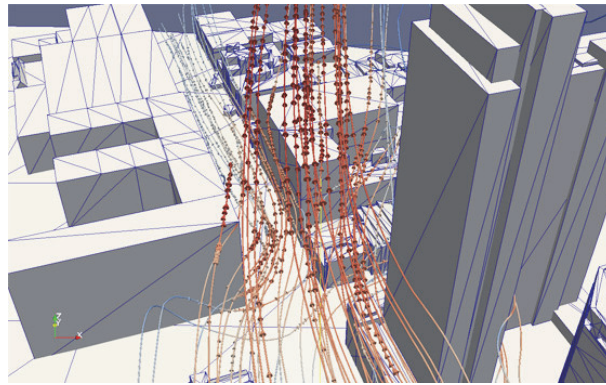
Figure 3. CFD test. Visualisation of channel effect phenomenon.

The space previously described involves two areas: the street space and a tram stop site. The street runs from South to North and has 30m width and includes a tram track of the Public transport system. This tram stop is an area of 4.5m width and 69m length on the west sidewalk. It considers urban furniture and a roof to protect the pedestrians while they are waiting for the public transport.

The statistics shows a trend of prevalent winds from North to South during the second half of the year (Bureau of M, 2013). In a windy day, with wind blowing from the north, the channel effect is produced along the street, with more intensity around a tram stop area near the street's intersection. Here, there is no protection from natural foliage of trees and the wind flows at ground level with high velocity along the sidewalk and the tram stop (probably intensified by corners of facades) causing discomfort on pedestrians that are waiting for public transport (Figure 4).
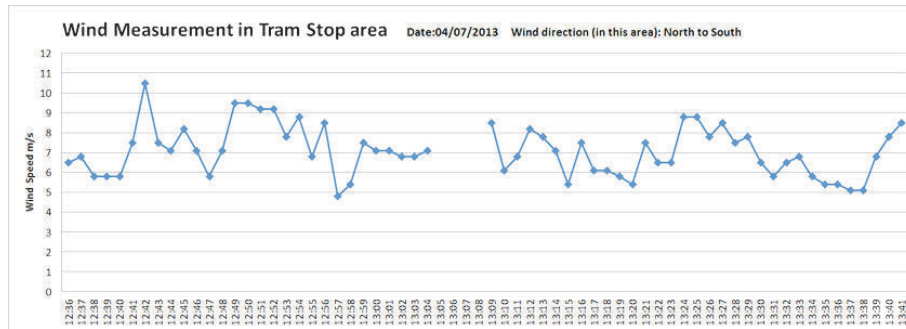
Figure 4. Fluctuation of wind speed in the tram stops area.

1.3. STANDARDIZATION OF PARAMETERS FOR CFD SIMULATIONS

Because of the limitation of instruments, data and time, it is not possible to replicate the real wind conditions of the place for the purpose of these experiments. To simplify the simulations, standard conditions are used as parameters. Thus, for the digital simulation, the urban context is represented as a simple and regular geometry of a channel. The standard of wind discomfort used is a speed of 5m/s at 1.5m height (head level) (Wisse, 1988). Wind flows only in one direction (main characteristic of a channel effect). The acceleration from corners is omitted, but other wind conditions are considered such us the atmospheric boundary layer based on the power law equation (Aynsley et al., 1977). The turbulence intensity is fixed to a low level (5%).

The Fluid Domain is where the channel effect is recreated. This has 30m width (similar to the distance between opposite facades), 16m height and a 69m length. The bottom face represents the ground, the front and back sides are street facades. A low grade of roughness is given to these surfaces to simulate the friction of facades and ground.

The second digital mesh is the tram-stop domain with 10m height, 15m width and 46m length which represents a part of tram stop region. This small domain has more density of the digital mesh for a more detailed simulation of the wind around the model: the wind effects at the windward side, leeward side and along the wake region (Figure 5).

Figure 5.Left: Fluid Domain and tram stop domain. Right: digital mesh.

3. Tram stop design

The design process involves the definition of a group of regions of protection based on the observation of conditions of use for pedestrians, and a group of CFD simulations to define the installation of each aerodynamic feature. In addition, the first design of the tram stop is based on a literal interpretation of the windbreak shapes and aerodynamic features studied by Gandemer. They are adapted as physical installations to produce these wind thresholds and protection regions.

The definitions of protection regions and the regions consider 3 basic programs in the site. The first one is a shelter area with a roof for pedestrians who wait for the tram. The second program is an area in front of a private building entrance. Finally, there is the main entrance to the same building with more traffic of people. These three spaces overlap the activities and functions of a private building with a public space. Therefore, the general plan of the tram stop has 4 regions (Figure 6).

Figure 6. 3D model of the tram stop. Simple geometries represent the street and installations.

The installations are designed to generate wind thresholds. These thresholds can be understood as vertical wind deflections to replace a physical bar-

rier. To achieve this, these elements must create a layer of low pressure above the tram stop area. With the association of three basic elements: a porous screen with 20% porosity, a horizontal curved surface as a deflector with a double slot system and a convex deflector above the barrier, which provides a region of protection for each area of the tram stop. The main requirement is to keep a low vertical porous barrier (1.6m height); the protection must be generated by the wind threshold effect.

3. Preliminary results

The CFD simulation of these aerodynamic features shows in the first installation a strong vertical deflection (wind threshold) and protection region of 3.5m height. This means a double height of the barrier itself. This vertical deflection is defined as a free shear layer that separates the free-stream flow from the recirculating region, increasing the protection area behind the barrier. The effect can be controlled by manipulating the position of the deflector elements (concave and horizontal deflector). With this wind threshold, it is possible to reduce the height of the vertical porous barrier to not interrupt the view of the pedestrians (Figure 7). Additionally, based on this first simulation it is possible to define the distances for the position of each screen and deflector.
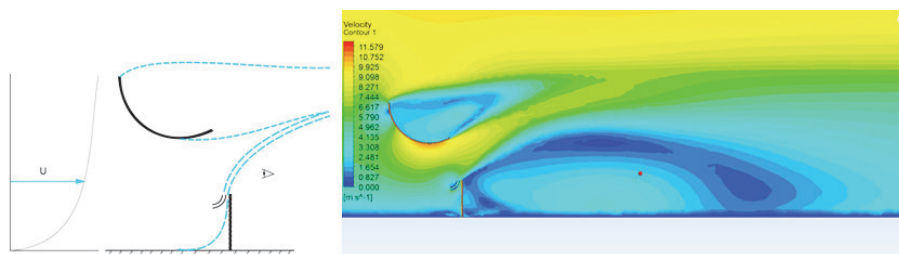
Figure 7. Left: highly vertical deflection as wind wall to increase height of wake region. Right: Aerodynamic effect: wind velocity contours from CFD simulation.

Moreover, a second aerodynamic simulation tested the effects produced for a roof profile for the tram stop. This roof is installed with a curvature to catch the threshold projected to the leeward side and deflect it up over the upper surface of the roof. With a ventilation gap at the top of the curvature it is possible to reduce the acceleration of the wind in this shelter. However, an acceleration of the wind at the outlet area of the roof region is detected. To avoid this, a second porous barrier under the roof is installed. These parallel barriers are other of the aerodynamic features mentioned. The CFD visuali-

sation shows the whole protection region generated (Figure 8). With the second porous screen installed, an additional phenomenon is produced between both regions: the second screen produces a change in the direction of the wind, moving back to the inlet region and produces a neutralisation of incoming wind. This effect is in the first part of the roof region.

Figure 8. Top: areas of wind acceleration under the curved roof. Middle: aerodynamic features are included to change the wind flow pattern. Bottom: the roof is adapted to facilitate a vertical deflection of the wind.

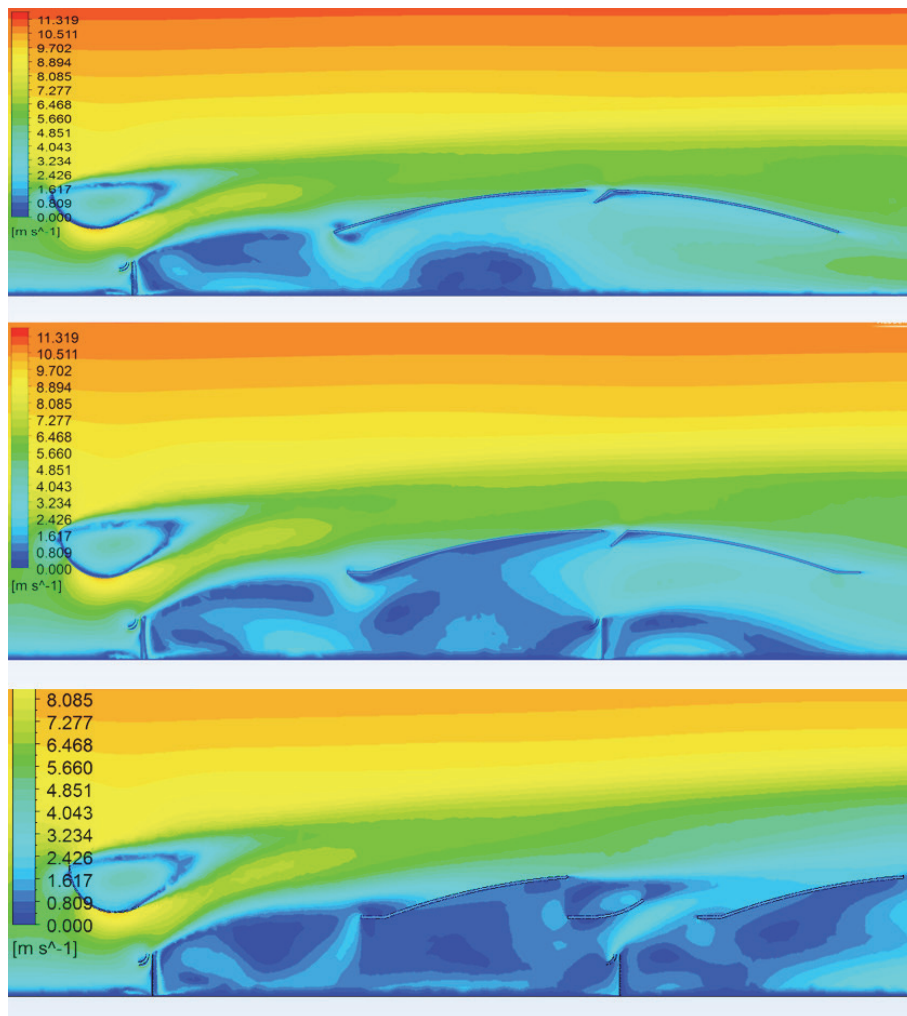Also, the second porous screen extends the protection area of the first porous screen increasing the protection region along the tram stop area (Figure 9, left).
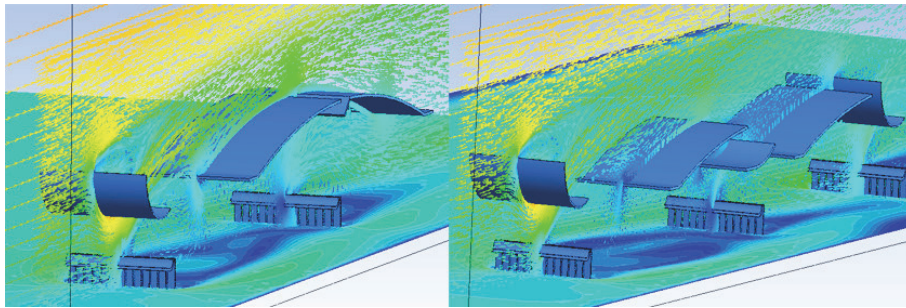

Figure 9. CFD simulation: wind velocity vector plot. Left: extension of the protection region with a second porous barrier. Right: adaptation of the roof for the vertical wind deflection.

Finally, this visualisation shows that it was necessary to include a new design for the second part of the roof profile. By splitting the roof in three parts this avoided the acceleration of wind at the outlet area.

4. Conclusion

The aerodynamic phenomena around buildings and wind issues in pedestrian areas provide an opportunity for experimentation with the design of new mitigation systems through architectural explorations and digital technologies for visualisation.

This paper presents an additional approach to improve the control of protection in pedestrian areas: the aerodynamic features of windbreaks produce changes in the wind flow pattern that increase their region of protection. Likewise, these features can be used to improve the mitigation system designs of wind issues in outdoor environments.

The preliminary results of these experiments and simulations for a hypothetical tram stop design suggest that the aerodynamic features give a control of protection regions in a tram stop. They produce wind effects called wind thresholds and can be used as an effective passive method of mitigation of wind speed. This means to increase the protection region, avoid wind flow distortions and reduce the size of the physical barriers.

On the other hand, the visualisation and analysis of these aerodynamic phenomena and the effects of the aerodynamic features require technological

tools of simulation to improve the feedback between the designer and the comprehension of aerodynamic phenomena. CFD analysis is a tool with a relevant role in the analysis of cases and development of design strategies.

The next stage of this research will explore the adaptation of these aerodynamic features with other architectural alternatives, such as designs based on porous membranes (Figure 10).
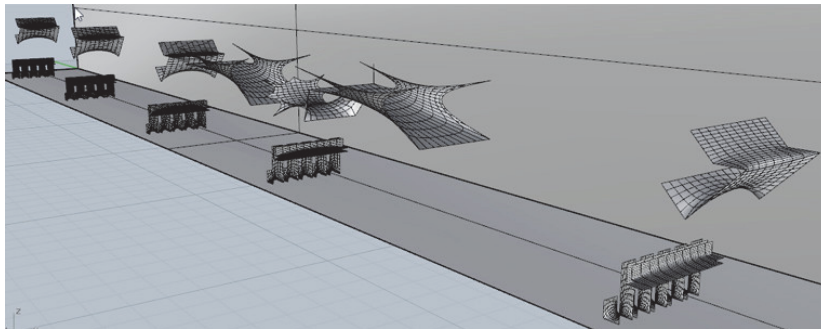
Figure 10. Propositions of membranes for screens and deflectors.

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Aerodynamic strategy applied in an urban shelter design

Simulation and analysis of aerodynamic phenomena in an urban context

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This paper presents an experimental study on strategies of utilizing wind as an architectural element, proposing the reconfiguration and projection of wind patterns to produce vaults of wind as regions of shelter in the outdoor environment. It shows an aerodynamic analysis and exploration of barriers, deflectors and porous screens in an existing urban wind canyon for a hypothetical urban shelter in a tram stop area. Computational Fluid Dynamics (CFD) software and physical tests in a wind tunnel using microelectronic hot-wire anemometry are the methods utilised. The experiments involve a comparison between screens with impermeable surfaces and porous membranes and their ability to project wind as architecture. The experiments showed that the use of porous membranes improves the mitigation level of wind speed and turbulence intensity in the wind vaults regions.

Keywords: *Urban aerodynamics, CFD simulation, wind discomfort, wind tunnel*

BACKGROUND

In many cases, urban configuration changes the pattern of wind flow, generating stream flows at the ground level and accelerating the wind; thus public spaces may require mitigation methods for local wind issues at the ground level (Stathopoulos, 2009). Even though, existing strategies to change or ameliorate pedestrian wind conditions near buildings are documented in the literature (Cochran, 2004), in some cases, the excessive use of canopies and trees difficult a normal incidence of sunlight or pollution dispersion in the outdoor environment. In general, it is necessary to elaborate new analysis consider-

ing local conditions of the urban configuration, wind speed, intensity and direction. For this reason, technologies for visualisation and wind analysis have become crucial to gain comprehensive knowledge of wind dynamics in an urban context to elaborate new strategies of design (Kim et al., 2011).

The field of numerical simulations (CFD) is under an intense process of change and improvement while wind tunnels are a reliable technology. In general, for architects there is a complementary of both technologies in the professional field with their advantages and disadvantages (Salim and Castro, 2012). However, in the more specific area of the early design
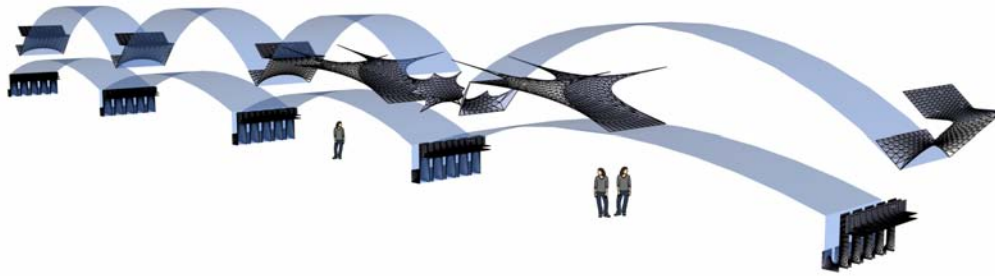
stage, CFD has become a useful tool for architects; especially, with new generations of CFD programs, such as Vasari, developed to be used by designers in the design process [1].

Moreover, porous membranes and permeable structures are being explored with new morphological approaches for designers to provide conditions of comfort. The current challenge is the adaptation and optimisation of these designs to be used in an urban context. In this sense, the studies of Jacques Gandemer about aerodynamic features of artificial windbreaks (Gandemer, 1979) provided a group of design rules to elaborate strategies of wind pattern manipulation that can be applied for the designer's explorations. These aerodynamic features might be fins, gaps, slots, or a graduation of porosity. A combination of these features can be strategically integrated into a flat porous screen. This can change the wind flow dynamics around the screen, increasing the protection area behind, while reducing the blockage factor of the wind mitigation feature. By reducing the geometrical domain of the element, opportunities arise in exploring wind as an architectural element.

RESEARCH AIM
The research aim is to analyse the differences in performance of impermeable surfaces and porous membranes to create architecture with wind and wind as architecture.

This research involves the analysis of windbreak aerodynamic features: fins as deflectors, porous screens, and slot systems. The approach is to use a passive strategy to manipulate wind patterns in an outdoor environment, to generate vaults of wind as protection regions for pedestrians (Figure1). This means the exploration is mainly about the wind aerodynamic patterns rather than to build complex screen designs. For the visualisation and analysis of the wind around the configuration of screens, experiments with CFD simulations and a physical wind tunnel were performed. In the case of the wind tunnel experiments, the goal was to verify the architecture of the wind projected by porous membranes that are too complex to analyse using Vasari.

EXPERIMENTAL METHOD
The context
Because of the complexity of the conditions involved with aerodynamic urban phenomena and the limitation of wind measurement instruments, it is necessary to simplify the simulation and to use standard conditions as parameters for this analysis. Thus, typical wind phenomena and context are used as the case for this research: an aerodynamic phenomenon called Channel Effect (Gandemer et al., 1978) which produces pedestrian discomfort due to high wind speed along a narrow street (Erell, Pearlmutter, et al. 2011). This kind of phenomena is very common in the city and can be viewed as a representation of the case observed in a tram stop area in the business district of Melbourne, Australia. For instance, figure 2 shows the wind measurement in this typical tram stop area
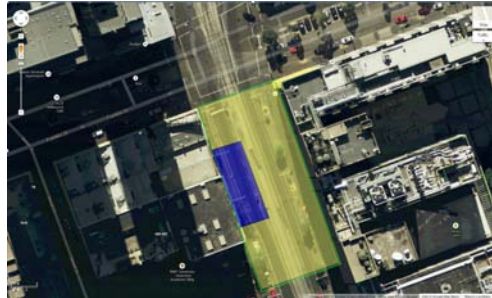
in Swanston Street in the CBD of Melbourne (Figure 2). The wind fluctuation in this place is over 5 m/s, which is considered as beyond the discomfort threshold for wind speed in this context (Figure 3).
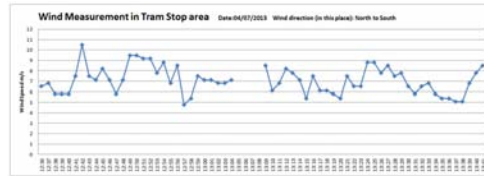
Thus, because of the street configuration, which produces this kind of phenomenon, the area analysed must be defined considering this two spaces: the street space and a tram stop site. Swanston Street is orientated from South to North and has 30m width including a tram track of the Public transport system. The area is surrounded by tall buildings that shape a closed channel. In this street a tram stop was built near the intersection between Swanston St. and Franklin St. The tram stop has an area of 4.5m width and 69m length on the west sidewalk of the street. The site has urban furniture and shelter of two glass roofs to protect pedestrians. The problem of discomfort is produced due to strong wind speeds running from the north to the south, along the street and near the corners.

The localised wind phenomena are difficult to attribute to the influence of tall buildings surrounding the site. But some statistics show a trend of prevalent winds from North to South during the second

half of the year (Bureau of M, 2013)[2]. This is coincident with the personal experience of the authors: recognition that this problem is more frequent in the winter season. Here, there is no protection from natural foliage of trees and the wind flows at ground level with high velocity.

The tram stop configuration
The installations are physical aerodynamic features based on windbreak designs to generate wind thresholds. This can be understood as upward deflections of the wind that produce a chain of bubbles of low wind speed (protection regions). Therefore, the wind mitigation elements must create a layer of low pressure above the tram stop area. These elements are gathered in five groups along the tram stop, including a structure of the roof for the shelter. With the association of three essential elements: a porous screen with 20% porosity, a horizontal curved fin as a deflector with a double slot system and a convex deflector above the barrier, the main requirement is to keep a low porous barrier (1.5m height). The area of protection is associated with the wind deflection (wind vault) created by the porous barrier.

The tram stop configuration has five parts, four vertical deflector components and a roof (Figure 4). These elements are organised strategically to define four regions within the tram stop area.
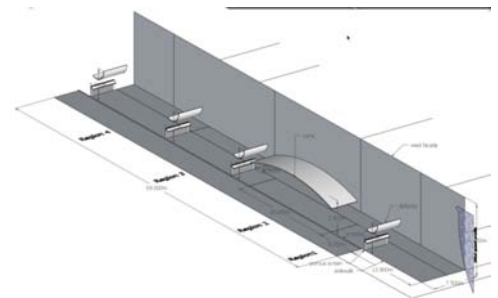
Above each screen, there is a curved surface of 2m height. This surface is a deflector that creates a wake region and low pressure layer at the top of the protec-

tion area. The idea is to produce a vertical lift effect of deflected wind to increase the height of this region. The total height of this screen is 5m (Figure 5).
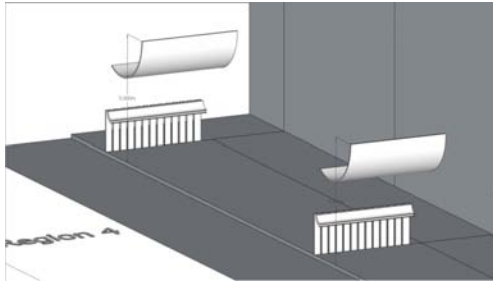
EXPERIMENTAL PROCEDURE PART 1
Numerical simulation using CFD software
The initial design concept was evaluated using CFD to verify the most relevant phenomena and introduce modifications for further tests. The use of the engineering CFD software can be difficult for architects because it requires expertise in numerical analysis and knowledge in wind engineering. Alternative easy-to-use programs, such as Vasari, can be used, but they have limitations in wind parameters such as the simulation of the atmospheric boundary layer (ABL) effect. This parameter can produce strong changes in the CFD analysis outcomes. The software used in these simulations was ANSYS to take advantage of its extended capabilities to represent wind phenomena in an urban context i.e. ABL simulation. But the complexity of the context and aerodynamic phenomena can be an additional challenge for an architect to realise this kind of simulation. Thus, simplification and standardisation of many factors facilitates the simulations and the feedback with these initial experiments. For the numerical simulation, the urban context was represented as a simple and regular geometry of a channel. This geometry is a fluid domain where the channel effect was recreated as a digital mesh. This volume was 30m wide (similar to the distance between opposite facades), 16m high and 69m long. Four faces of the geometry represent

the ground, sky and street facades, while two end faces represent the fluid inlet and outlet zones. A low grade of roughness is given to these surfaces to simulate the friction of facades and ground.

The wind profile at the inlet was setup as flow with a boundary layer effect, considering the power boundary layer equation and using a reference velocity relevant to the discomfort threshold - a speed of 5m/s at 1.5m height (Wisse, 1988). Also, in this case, wind flows only in one direction and the corner wind effect is omitted. The turbulence intensity was assumed to be 5%, and other objects were not considered in the area of the tram stop. Inside the Fluid Domain, a refined digital mesh is built achieving a more accurate solution of the wind phenomena such as the wake regions, the chain of aerodynamic bubbles and the level of wind deflection around the tram-stop. This refined domain has 10m high, 15m wide and 46m in length.

CFD Simulation Results
The engineering CFD simulation of these aerodynamic features showed several strong upward deflections (wind vaults) and protection regions behind each porous barrier, and along the area of the tram stop. This analysis and clear visualisation informs the designer of the patterns of wind flows for further experiments in the physical wind tunnel. One of the findings is that the aerodynamic bubble produced at the leeward side of the screen is higher than a similar screen without deflectors. This effect is coincident with the findings of Gandemer's studies, where he mentioned the use of fins integrated with the barriers as a method to increase the protection area behind a screen (Gandemer, 1979). The initial CFD simulation results confirmed the design concept of fins and slots at the top to produce a effect of vertical deflection. based on the initial finding, a new design strategy with an additional deflector above the screen is formulated. The effect of vertical deflection is more significant with this deflector and another of the effects observed is the regular form of the bubbles in the last three vertical screens. These screens installed in par-

Figure 5
Porous screen of 20% of density. Horizontal deflectors with double slot as accelerator. Convex deflector above of the barrier

allel define a more regular and continuous protection area (Figure 6). In fact, the first vertical screen after the group of roofs helps to reorder the wind flow that passes through the shelter zone and increase the protection region behind the group of roofs.
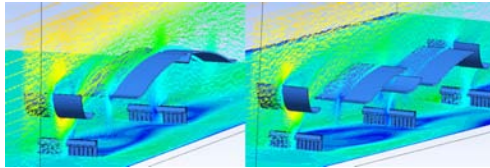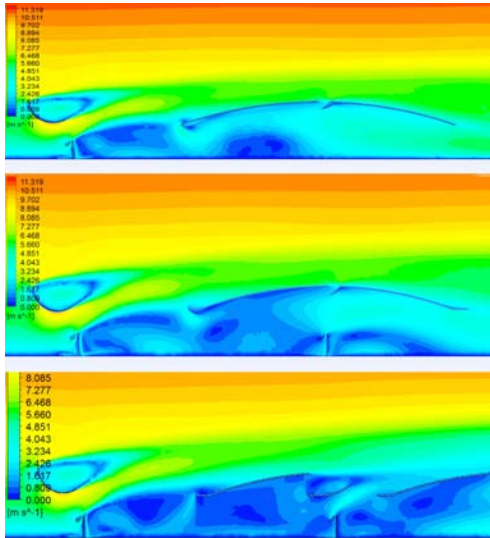
The most interesting observation of this visualisation was the fact that a roof with continuous surface produces an acceleration of wind speed in the region below. In contrast, if the roof is split in three parts with gaps, the wind speed is lower below these roofs (Figure 7). Based on the engineering CFD simulation results, for the experiments in the wind tunnel, the configuration of the roof was changed to three roofs.

EXPERIMENTAL PROCEDURE PART 2
Physical simulation using a wind tunnel
After the CFD simulations, physical tests were conducted in an atmospheric boundary layer condition within a wind tunnel simulating wind around the screens and deflectors. The scale models (1:30) of the screens with modifications were installed along a panel representing the footpath and west face of the street. The second group of experiments were conducted, changing the roofs composed of surfaces with porous membranes to analyse their performance as deflectors and wind mitigation devices (Figure 8).

The use of a wind tunnel can be a complicated task, but the main problem is the difficulty of obtaining accurate and rapid feedback of the simulation outcomes. To facilitate the visualisation and comprehension of the phenomena observed in these experiments several micro wind sensors were installed, after a process of calibration, to collect and visualise quantitative data in real time. In addition, a graphic interface was composed to read the data from the sensors. This platform was developed using a system of low-cost components, including micro wind sensors, an Arduino board, Grasshopper, Firefly and Rhino3D. To know more technical details about this sensor platform, see the work "wind sensing with real-time visualisations for designers" (Prohasky, 2014).

The aim of these physical experiments was to verify (with simple geometries and porous meshes) the level of vertical deflection of the wind behind the first screen configuration and to measure the wind speed above the area of roofs. Thus, the tests were separated into two stages: the first group of experiments with simple geometries of surfaces and a second group of experiments with porous membranes.

The condition in the wind tunnel considered a

wind velocity profile of atmospheric boundary layer at 1:30. Reference velocity at 50mm measured by petot static tube (3.95m/s). The equivalent reference velocity at 1:1 scale is located at an elevation of 1.5m. The boundary layer was estimated based on the power law equation (Aynsley, Melbourne, et al. 1977) (Figure 9).

Atmospheric Boundary Layer
Wind Velcity Profile - Scale 1:30

the changes in the wind flow pattern three tests were conducted: no screen and deflector, first screen and deflector (simple geometries), first screen and deflector (porous meshes), and a fourth - no screen and deflector (second post reference).

The results show that the velocity profiles behind both screens are quite similar. Only the sensor at 125mm height detected lower velocity in the wake region behind the porous canopy than the impermeable surface canopy. But this difference does not change the velocity at the other levels (Figure 10). Therefore, this shows that the vertical upward deflection of wind produced by the screen, it is not affected if the canopy is a porous membrane.

Experiment with a vertical screen

The first region tested with the group of micro wind sensors in the ABL wind tunnel experiment was behind the first porous screen and deflector canopy. In this place, the sensors measured the velocity intensity at 50mm, 75mm, 100mm, 125mm, eight (scale model 1:30 / 50mm=1.5m). To have a clear idea of

Experiment with a lateral deflector

A second experiment involves the evaluation of the first screen configuration and the effect produced by a lateral deflector with a shorter screen. Two experiments were set up to compare the effect: a first ex-

Figure 11
Three tests for a
lateral deflector and
results

periment of a lateral deflection of the wind in a standard screen and a second test with a shorter screen with a lateral fin. The distances are taken from the vertical wall of the model. The results showed that the lateral deflector extended the boundary of the protection region. A smaller screen with the lateral deflector provided very similar conditions of wind mitigation in the whole area of the sensors (Figure 11).

Analysis shelter area

Two sensors were placed in three positions below the roofs in the shelter area, for the last group of experiments. They were installed to measure the wind speed at head level to capture the effects of wind relevant to pedestrians and the effects of split roofs and roofs made with porous meshes.

The results of these experiments showed that the level of wind velocity in the area of the shelter (pos 2, 3) decreased using porous membranes. Besides, in the position 3, the turbulence intensity is lower below the membranes, but it did not change at the head level (Figure 12).

Results wind tunnel

The graphs generated were standardised into non-dimensional wind velocities relative to the reference velocities at relative pedestrian level measured from ABL conditions. Two reference wind velocity profiles were used to account for reference wind velocity drift during the experiments. The turbulence intensity plots are provided in addition to the average wind velocity since the data was available to do so. In subsequent papers, the wind sensors will be analysed for their responsiveness and reliability in measuring turbulence intensities. Though, the nature of the results seem quite satisfactory after deconstructing the evidence. In general, the wind velocities are reduced further with the porous deflectors with respect to the solid deflectors. And turbulence intensities are also decreased in the same fashion due to the graduated distribution of pressure differences by filtration through the porous elements.

Figure 12
Six tests for opaque
and porous surfaces
in the shelter area
and results
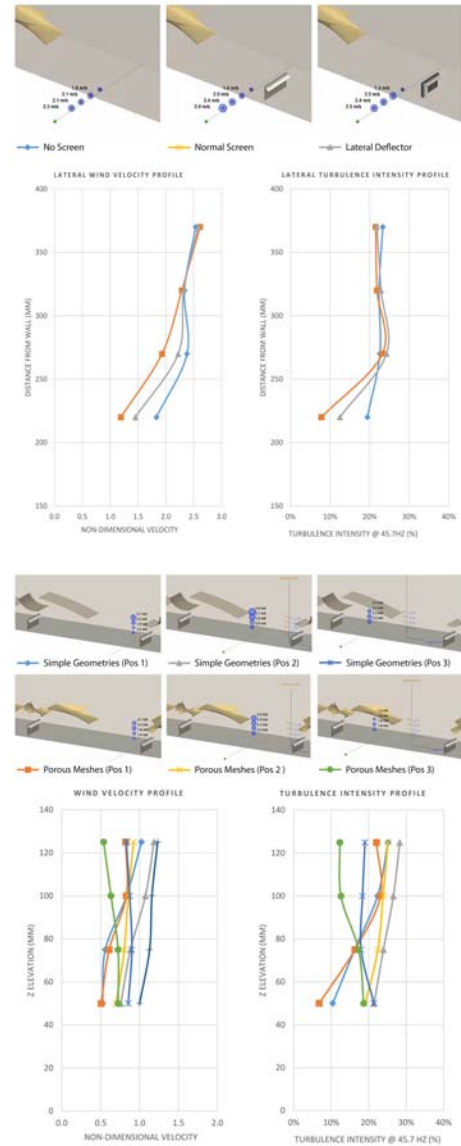
CONCLUSION

The aerodynamic phenomena around buildings and wind issues in pedestrian areas are an opportunity for experimentation with new mitigation strategies involving explorations of wind dynamics and digital and physical technologies of simulation and visualisation (CFD and wind tunnel). Consequently, the visualisation and analysis of screen configurations using CFD allow us to plan a better strategy of analysis in the physical wind tunnel. This strategy was focused on specific regions and effects of wind to evaluate their behaviour, but at the same time, the questions generated from two methods of simulation (empirical testing with digital sensing and CFD) were verified through comparison across these two technologies.

OUTLOOK

The parallel use of numerical simulation and physical simulation produces a complementary approach to improve comprehension of complex wind phenomena. For instance, to design the experiments in a wind tunnel required a general prediction of results. The position of the sensors must consider the most significant points to measure reliable data to derive relevant conclusions. In this sense, the visualisation provided by the CFD software can be useful to define the areas to test in physical experiments. Thus, both technologies provide not only data, but rather, support the facilitation of the design process in the discoveries and manifestation of the architecture of wind.

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EMPIRICAL EVALUATION OF THREE WIND ANALYSIS TOOLS FOR CONCEPT DESIGN OF AN URBAN WIND SHELTER

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Abstract. The aim of this investigation was to evaluate the performance of three wind analysis programs used in the early design stage (EDS) of a passive windbreak shelter concept for an urban context. This study compared the different workflows of these programs and the respective visualized results, identifying the differences and limitations of these tools, for design exploration. The programs tested were Autodesk Vasari, ODS-Studio, and ANSYS CFX. The results of this investigation indicate that basic computational fluid dynamics (CFD) programs such as Vasari was found to be more suitable for the observation of large-scale wind phenomena through the whole area of the shelter. Moreover, intermediate CFD tools (functions, usability) such as ODS-Studio can be used more efficiently in detailed visualization of wind interacting with design features. Finally, a more sophisticated CFD program like ANSYS CFX can be incorporated in the early design stage workflow for final verification of results.

Keywords. CFD; visualisation; wind; pedestrian comfort.

1. Introduction

Wind analysis in outdoor environments has become relevant in the design process of buildings and public spaces. This is because wind phenomena that are produced by buildings geometrical configurations can affect the level of comfort in pedestrian areas (Stahopoulos, 2011). As a result, architects have incorporated wind expert consulting and simulations with tools for wind visualisation into the design process (Naboni, 2013). However, because of the high cost and complexity of these technologies, experts generally use these tools for validation of final designs rather than form exploration in the

early design stage (Kirkegaard, 2008). The use of wind analysis during the exploration of conceptual designs, for pedestrian wind shelters, is a field of study for architects to develop more sophisticated strategies for wind mitigation. This was the case of the prototype of a canopy developed as part of the initiative CFD-ARCH (2012), in the SUTD-MIT International Design Centre. That project states: "the objective of this research initiative was not to extend knowledge in the field of CFD but to find ways of utilising CFD to support early stages of the architectural design process, where many critical decisions, including those pertaining to the building performance are made" (Kaijima, 2013).

Currently, a new generation of CFD programs is available to be used by architects for wind analysis of concept designs. Tools such as Vasari, and ODS-studio are technologies that are easy to operate and provide rapid feedback for the analysis of wind behaviour in spaces near buildings (Naboni, 2013). However, the performance of these programs to analyse wind on conceptual designs of windbreak screens for pedestrian areas have not been compared.

1.1 AIM AND METHODOLOGY

This investigation was an empirical and qualitative study of the performance of three CFD programs, used for visualizing wind through windbreak screen concepts. The aim was to identify the limitations of these tools for their use by architects to study an outdoor artificial windbreak concept for pedestrian areas. To achieve the research goal, several tests of wind visualisation were conducted with three CFD programs. Two of these programs (Autodesk Vasari, ODS-Studio) have been recently developed for the analysis of wind in the early design stage and a third program (ANSYS CFX) is a sophisticated numerical simulation program used in wind engineering.

2. Case study

The tools were used for an analysis of the wind in a windbreak screen concept for a tram stop. These windbreaks were designed to generate upward deflections of the wind flow at ground level. Thus, each screen produces a wake region as a chain of aerodynamic bubbles that works as protection regions for high speed winds. These screens are organised in five installations along the tram stop, including canopies for a shelter zone. The whole area occupied by the screens had a height of 5m, width of 4m and a length of 80m. The screens consist of four essential elements: (1) a low porous screen with 20% porosity (1.5m height), (2) a double horizontal curved fin as a small deflector, (3) a convex canopy deflector above the

barrier, (4) a roof of canopies. The area of protection is a wind deflection that produces a "wind vault" effect for each bubble of protection created by the screens. These elements are organised strategically so that they define four regions of mitigation within the area of the tram stop and other pedestrian zones (Moya, 2014). Digital models of these screens were elaborated to be imported in the CFD programs (Figure 1).
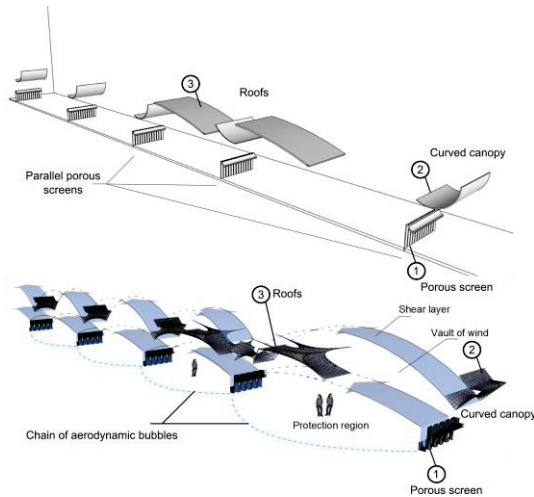
Figure1. Windbreak screen shelter concept. Top: screens and canopies with regular geometries. Bottom: screens and canopies with membrane morphology.

2.1 OBSERVATIONS

The use of three different programs for wind analysis allows a comparison for difficulties for their operation and performance, which are explained in the next sections. These comparisons are gathered in two categories: the observations related with the pre-process of wind visualisation (user, workflow and wind parameters) and the results in the post-process stage.

2.1.1 Vasari pre-process:

Vasari is a simulation tool that has CFD functions for preliminary wind analysis of conceptual designs. Following a short tutorial provided enough information to set up the main parameters for an acceptable visualisation of these experiments. The program allows the import of the digital models generated with Rhino3D plus Grasshopper: both screens, with regular geometries and membrane morphology. However, the configuration of the domain of the site for the simulation required to sacrifice resolution of the grid that program uses, to facilitate the simulation for the full tram stop

domain area. As a result, some aerodynamic effects from the screen features are missing; the low definition of the domain grid makes slower and unstable the simulation. Furthermore, it is necessary to consider that Vasari does not simulate the atmospheric boundary layer (ABL) as wind condition and it is not possible to make an adaptation to produce a similar effect (Autodesk 2013). Therefore, the experiments were set up with a flat wind velocity profile; the velocity was 5 m/s and the direction was constant. Finally, the model included a surface as wall to represent the street façade, making more similar the model to the spatial context of the street footpath.

2.1.2 Vasari results

The analysis of the screen group with regular geometries in Vasari showed effects of vertical wind deflection with some clarity. However, it is seen that the screens did not produce the significant change of wind direction that was expected. In fact, the wind flow is deflected below the group of horizontal canopies of the shelter and not above them. Furthermore, below the roofs the second screen did not produce a vertical airflow deflection passing through the gap between the canopies, and the wind flowed horizontally along the shelter zone, where the pedestrians are waiting. In addition, a 3D visualisation of the whole protection region (using isosurfaces) showed the space of aerodynamic protection bubbles with a low wind speed (around 1.5 m/s) and the differences of sizes of these bubbles. On the other hand, the visualisation of screens with membrane morphology looks very similar to the previous Vasari test with regular geometries. Again, the main observation is that the vertical wind deflection from these screens is not enough to produce protection regions between them. The visualisation with a colour pattern slice showed that the area of shelter roofs presents the smallest protection region (Figure 2).
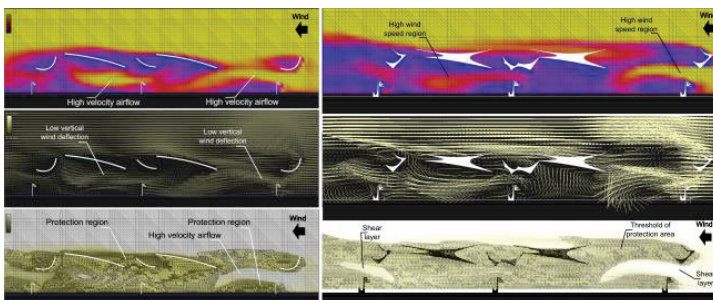

Figure 2. Vasari visualisation of high wind speed region behind and below screens. Left column: wind visualisation (contour, vector field, isosurfaces) of screens with regular geometries. Right column: wind visualisation (contour, vector field, isosurfaces) of screens with membrane morphology.

With a structure of screens with small details, and the area of the whole installation being too large, the resolution of the visualisation is low. Therefore, it was not possible to visualise other adaptations of the small fins, on the screens, that produce changes in the wind flow.

2.1.3 ODS-Studio pre-process

ODS-Studio is a recent tool aimed at rapid design and analysis of commercial and residential building design (Pitman, 2013). This is a script, which works as a link between three open source programs: the 3D modeller Blender (software to manipulate the digital meshes), OpenFOAM (CFD software to run wind simulations), and Paraview (an application for data analysis and visualisation). The software is more complex to use than Vasari (intermediate level). Thus, for these experiments ODS-Studio was used after a short period of training with a tutorial. The digital models of screens with membrane morphology were easily imported and manipulated with Blender; and at the same time it was possible to generate refined digital meshes as domain for the simulation with a high tolerance to the curvatures of these geometries. Therefore, the experiments only addressed this membrane configuration of windbreak screens. From the perspective of wind parameters, ODS-Studio simulates airflow as a simple and constant laminar flow without an ABL effect. However, it was possible to set up a screen and roughness in the domain to produce a minimal atmospheric boundary layer condition with a near wind velocity of 5m/s at a height of 2m. The idea was to increase the ground friction and turbulence, following similar methods used by real boundary layer wind tunnels (Cermak, 2003).

2.1.4 ODS-Studio results

The outcomes of the experiments with ODS-Studio demonstrated that behind each group of screen with canopy (installation with a height of 3m to 5m), a region of low air pressure is generated. These structures increase the upward deflection of the wind generated from the windbreak screens. However, in contrast of what was observed in the previous Vasari visualisation, the acceleration of wind flow produced a gap between screen and canopy, with a significant vertical airflow deflection above the roofs. The effect keeps the wind velocity at a low level in the pedestrian zone. Thus, an aerodynamic bubble effect is extended along the shelter zone, increasing the wind protection in a whole area, behind the screens and under the roofs. On the other hand, with a refined digital mesh in the domain, it was possible to see how, behind each curved canopy, the wake regions had no significant variations, when small modifications were applied in the canopy design.

Even though these screens have membrane forms, they are symmetrical and the surfaces follow the same profile. Then, the effect of vertical wind deflection was achieved and positively evaluated (Figure 3).
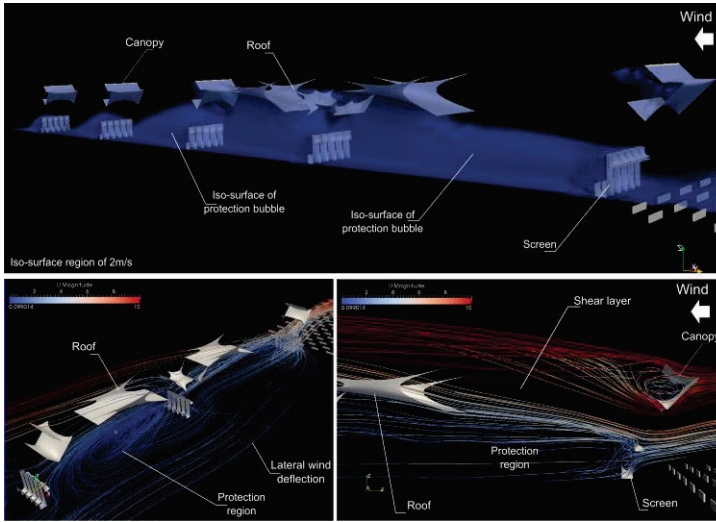
Figure 3. Top: ODS-Studio wind visualisation of windbreak screens with membrane morphology. Top: visualisation of an efficient protection region with iso-surfaces. Wind velocity mitigation of 1.5 to 2.5 m/s. Left bottom: visualisation of lateral deflection and vortex of airflow in shelter zone. Right bottom: visualisation of an efficient vertical wind deflection from first screen.

2.1.5 ANSYS CFX pre-process

For these experiments, the operation of ANSYS CFX required expert consulting about how to set up the basic conditions for these simulations, because there were no tutorials available with similar analysis cases to facilitate the preparation. This proved to be the more difficult part of the simulation process. Even though the program allows the import of the digital models, the experiments were only focused for concept designs using regular geometries, because the exploration and development of more complex membrane shapes with porosity requires a more accurate pre-process of elaboration that was not possible to resolve in the time of this investigation (the geometries created with Grasshopper were not useful to generate digital meshes in ANSYS CFX). On the other hand, the Design Modeller module of ANSYS has parametric functions; therefore, it was easier to build the digital models in the program and testing different screen positions (Figure 4).
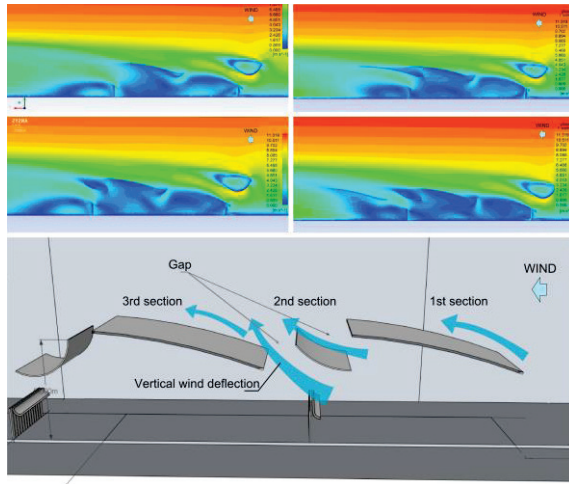
Figure 4. Different arrangements of roofs to produce a more wide protection region in the shelter area. Top: four wind visualisations with parametric model of roofs. Bottom: Better arrangement of roofs for the shelter zone.

As pre-process stage, two domains were elaborated for the experiments: the street space and the tram stop site. The first one defines the aerodynamic phenomenon that produces discomfort levels in the site (channel effect). This domain has a width of 30 m (similar to the distance between opposite façades in Swanston St.), a height of 16m and a length of 101.5 m. The second one is the area of the tram stop, where a hypothetical wind shelter was installed with a height of 10m, a width of 15 m and length of 80 m. In addition, this smaller domain has a more refined digital grid-mesh. For wind parameters the simulation considers a wind velocity profile with an atmospheric boundary layer effect. This had an intensity of 5 m/s at a height of 2 m.

2.1.6 ANSYS results

After the preliminary simulations, the CFD tests with ANSYS CFX verified that the combination of a porous screen with a horizontal deflector, and a convex deflector over the screen, can generate a significant upward wind flow. This accelerated airflow increases the height of the protection region at the leeward side of the barrier. For these experiments, the protection region reached a height of 3.5m. This means more than twice the height of the flat screen (1.5m). Furthermore, a second porous screen below the roofs extended the protection area of the first porous screen increasing the protection region. For the total area of the tram stop, the wind analysis showed that screens with deflectors, in a parallel order, produce a continuous

region of wind low velocity, extending their boundaries along of tram stop site. This area is protected by a succession of "vaults of wind or aerodynamic bubbles", deflecting the high speed of the wind above the screens and the pedestrian's level (Figure 5).
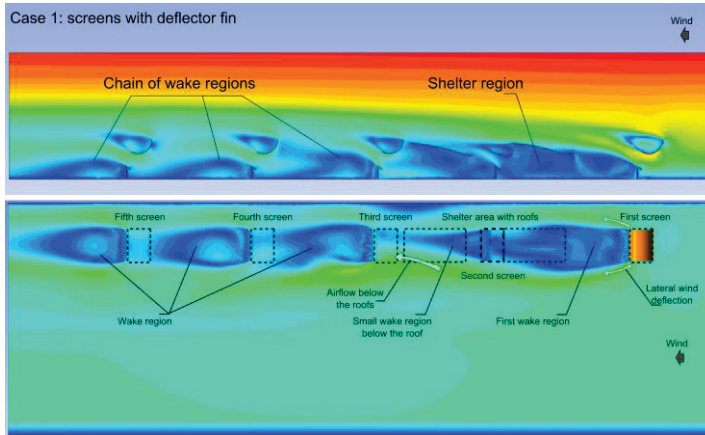

Figure 5. Wind visualisation of screens with regular geometries, using ANSYS CFX. Top: lateral wind visualisation of the aerodynamic bubbles produced by the screens. Bottom: top visualisation of protection regions with a small protection area after the second screen.

3. Conclusion:

In general, the observations of each wind analysis program, used in a context of early design exploration, can be summarised in the following table (Table 1).

Table 1. Summary of the main observation about performance of three CFD programs used for wind analysis of conceptual windbreak shelter.

		PRE-PROCESS			RESULTS		
VASARI	OPERATION	**EASY**	NORMAL	DIFFICULT	**REGULAR**	IRREGULAR	GEOMETRY EASILY TESTED
	MODELLING AND IMPORT	**YES**	NO		**LARGE**	SMALL	VISUALISATION DETAIL
	GRID RESOLUTION AND CONTROL	**LOW**	MEDIUM	HIGH	**LOW**	HIGH	VERTICAL WIND DEFLECTION
	ATMOSPHERIC BOUNDARY LAYER	YES	**NO**		**LOW**	HIGH	PROTECTION LEVEL VISUALISED
ODS-STUDIO	OPERATION	EASY	**NORMAL**	DIFFICULT	**REGULAR**	IRREGULAR	GEOMETRY EASILY TESTED
	MODELLING AND IMPORT	**YES**	NO		**LARGE**	SMALL	VISUALISATION DETAIL
	GRID RESOLUTION AND CONTROL	LOW	**MEDIUM**	HIGH	LOW	**HIGH**	VERTICAL WIND DEFLECTION
	ATMOSPHERIC BOUNDARY LAYER	**YES**	NO		LOW	**HIGH**	PROTECTION LEVEL VISUALISED
ANSYS CFX	OPERATION	EASY	NORMAL	**DIFFICULT**	**REGULAR**	IRREGULAR	GEOMETRY EASILY TESTED
	MODELLING AND IMPORT	**YES**	NO		**LARGE**	SMALL	VISUALISATION DETAIL
	GRID RESOLUTION AND CONTROL	LOW	MEDIUM	**HIGH**	LOW	**HIGH**	VERTICAL WIND DEFLECTION
	ATMOSPHERIC BOUNDARY LAYER	**YES**	NO		LOW	**HIGH**	PROTECTION LEVEL VISUALISED

Vasari is an easy tool to conduct wind simulation for early design stage, but presents limitations to visualise small details of a large model because of its low grid resolution (flow domain). Furthermore, the visualisation with Vasari performed well to observe the global region of protection with isosurface representation (protection bubble), but showed low vertical deflection of the wind through the group of screens. From this perspective, the analysis invalidates the configuration of screens and canopies. In contrast, ODS-Studio is a tool relatively easy to operate that can be used for a better visualisation of airflow through aerodynamic features of screens, because it has a better control to work with the flow domain grid. The visualisation conducted with this program demonstrated clearly, the effect of protected regions behind each screen and along the tram stop area (chain of protection bubbles). However, the phenomenon appears with a more strong and significant vertical wind deflection from each screen that keeps a low level of wind speed in the shelter zone. In this sense, ODS-Studio validates the conceptual windbreak screen configuration for the tram stop. Finally, ANSYS CFX is a more complex tool to be used in the early design stage. However, the visualisation of wind patterns movements from the windbreak screens demonstrates the significant deflections of the airflow from screens and the effective generation of a protection region along the tram stop. Thus, the analysis conducted with ANSYS CFX validates the configuration of screens and canopies as pedestrian shelter.

In summary, when the analysis involves airflows moving through large configuration of porous screens and canopies, tools for wind analysis in the early design stage, such as Vasari can be less reliable due to the low resolution of its grid domain, as omission of the screen aerodynamic feature effects. In contrast, ODS-studio can be used for this kind of analysis, for a more detailed visualisation of wind interaction with windbreak screens and as validation method for Vasari's results. Only if the results between them are quite different, a third wind analysis can be incorporated in the workflow with a program like ANSYS CFX to verify results, but its use requires a more complete knowledge and possibly consultation from an expert. These conclusions must be considered by architects if they want to incorporate these tools for design exploration, in the early stage of the design process, with a dynamic feedback level.

Acknowledgements

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Parallel Analysis of Urban Aerodynamic Phenomena Using High and Low-Tech Tools

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Abstract. *The study of wind conditions in cities is a significant factor in urban design in order to deal with issues related with pollution, wind pressures on buildings, and comfort on public spaces. This paper presents some results of a four-day workshop where some of the different techniques for simulating and visualising aerodynamic phenomena were explored. These technologies, classified as high-tech and low-tech tools, were used to investigate urban aerodynamic phenomena through parallel experiments, analysis, and eye observations. The experiments demonstrated that getting live feedbacks while interacting with the simulated aerodynamic phenomena is essential to improve the observers' general comprehension of the phenomena. Our proposed method for studying aerodynamic phenomena, which integrates both low-tech and high-tech tools, facilitates designers to explore multiple options and configurations in the early stage of a design process.*
Keywords. *Urban aerodynamic; wind tunnel; Computational Fluid Dynamics (CFD); wind simulation; urban design.*

BACKGROUND

Understanding the fluid dynamics of the urban airflow is crucial in architectural and urban design since the phenomena of wind flow and dispersion through a city determine environmental air quality, wind pressures on buildings, urban heat islands, pedestrian comfort, and ambient noise level in the surrounding environment (Boris 2005; Zaki et al. 2010). The main challenge in performing urban studies related with the wind and its aerodynamic impact on buildings is to simulate and understand the problem at the full scale. The limitations are mainly due to the technical difficulties of setting up full scale simulations and the high cost to gather data in real conditions. Therefore, complementary tools are required to support this kind of study. Technologies to reproduce or simulate the extra-large scale phenomena

of the wind interacting with dense groups of buildings are available. However, generating final datasets involves different approaches, different levels of operational complexity, and various ways to render the information. Analysing urban wind conditions is particularly crucial in the early design stage, when it is necessary to test many possible design options for a project and to get a live feedback on the performance of the designed buildings.

The first question that researchers face is how to visualise the aerodynamic phenomena of urban wind. Visualising aerodynamic phenomena in the urban environment can help architects to make the right design decisions and alternatives that can positively influence wind pressure, speed, and turbulence on site. Different techniques have been

developed for visualising wind flow, such as using numerical methods to predict the behaviour of the flow or using particle simulation or smoke to "draw" the movement of the wind. In both cases, there is an intention to simulate this physical phenomenon in a smaller scale. However, simulating urban wind phenomena is a complex task, due to the wind's invisible nature, its large scale fluid environment that produce chaotic effects when in contact with bodies of buildings, and the constant dynamic and real-time changes.

The most sophisticated Computer Fluid Dynamics (CFD) tools are limited in their abilities to reproduce the behaviour of complex and chaotic turbulence with a high Reynolds number (Boris 2005), a measurement for quantifying the viscosity and forces of fluids. The important phenomena of the urban wind conditions such as turbulence cannot be simulated in standard CFD tools which employ Reynolds Averaged Navier-Stokes (RANS) approach, which simulate the mean flow using approximation of the effects of turbulent scales (Boris 2005). The opposite of RANS is Direct Numerical Simulation (DNS), the resource hungry and time-dependent solution of the full Navier-stokes equations, the fundamental CFD algorithm. DNS can be used for small scale turbulent modelling, thus the most numerical studies are focused on general flow around a single building, where the simulation of the interaction between gases with surfaces gets better values of predictions. The development of the model k–ε (k–epsilon) with the Large Eddy Simulation (LES), implemented as a standard of a viscous turbulence model to predict turbulence around buildings, is a reliable technique for computational wind engineering (Stathopoulos and Zhou 1997), which has been used for analysing building envelopes, natural ventilation, wind pressure or snow accumulation around buildings (Bang et al, 1994). Currently, there are attempts to set up a more complex configuration to simulate wind passing between multiple buildings (Baskaran and Kashef 1996). Although the development of DNS is anticipated to improve in the next decades, the use of DNS for simulating urban aerodynamics is strongly limited with today's computing power and technology (Boris 2005). The requirements for high computing power and adequate time to run CFD simulations and input of experts with the right skills to set up the simulation correctly cause CFD tools to be really expensive and less accessible by architects and urban designers. Besides, the outcomes of the analysis require further validation in a wind tunnel.

On the other hand, techniques like industrial wind tunnels work with real aerodynamic phenomena and can be used to simulate and provide a depiction of wind turbulence in an urban context that is close to real-world. However, they are also expensive and could be difficult to access in some places.

The challenges addressed in this paper are stated in the following research questions:

- How to visualise urban aerodynamic phenomena such as vortices, directions, velocity?
- How to collect and process real-time data of the dynamic phenomena generated from changes in the design of the physical building blocks?
- How to create an interactive work-flow that enables designers to experience real-time feedback while designing with the urban aerodynamic phenomena?

This paper aims to present some results of the four-days Designing the Dynamic workshop where the potentials of using different tools to capture and visualise urban wind conditions in the early design stage were explored.

In the conceptual design stage, when design alternatives are generated and need to be iteratively evaluated, it is essential to get rapid feedback from such a simulation. This is an observation using a more qualitative approach, where the use of CFD simulations at the early stage of design need to involve very simplified urban models and high limiting assumptions or input data. Although the accuracy of the simulation is compromised for the sake of speed, the analytical process and results can be adequately intuitive for the purpose of supporting iterative decision making processes. The need to simulate urban aerodynamic phenomena in the

early design stage can benefit from simplifying the large scale industrial wind tunnel. These two approaches are investigated in this four-day workshop, where high-tech tools and low-tech tools were used and tested for visualising urban aerodynamic phenomena. Parallel analysis of urban conditions were conducted, evaluated, and compared in order to understand the potentials, strength, and limitations of each tool and how the tools can work in a complementary way.

TOOLS AND EXPERIMENTS

During the workshop, basic topological models were designed and fabricated at different scale. Two different CFD tools, Ecotect Wind Tunnel simulation (which is hosted inside Autodesk Project Vasari) and Ansys CFX, were used to visualise the aerodynamic effects of the airflow around the models in a virtual wind tunnel. Another experiment was conducted in parallel: the models were tested in two different wind tunnels, a small scale wind tunnel, custom made during the workshop, and a large scale industrial wind tunnel. The parallel experiments conducted in the workshop are depicted in Figure 1.

The tools used in this workshop could be cat-

egorised into two groups: high-tech and low-tech tools. High-tech tools refer to those with high level of complexity and industry support, and require high initial investment and running cost. In contrast, we refer to custom-made or Do-It-Yourself (DIY) tools and technologies as low-tech, as these tools can be fabricated at low cost or require only a minimum capital investment.

The high-tech tools

The high-tech tools used in our experiment include the two CFD software, Vasari and Ansys CFX, and the industrial wind tunnel in RMIT University Bundoora Campus. Autodesk Project Vasari is a free technology preview (beta) of an easy-to-use design tool for creating building concepts. Ansys CFD is a well-know and powerful software package for fluid simulation made by Ansys. It offers a high-end CFD solution package for fluid simulation that provides powerful analysis and better accuracy, but entails a high licence fee and requires expert input and translation. Therefore, Ansys is not an affordable option for academic research (Chung and Malone-Lee 2010). The involvement from local architecture and engineering practices in the workshop enable the

Figure 1
Process diagram.
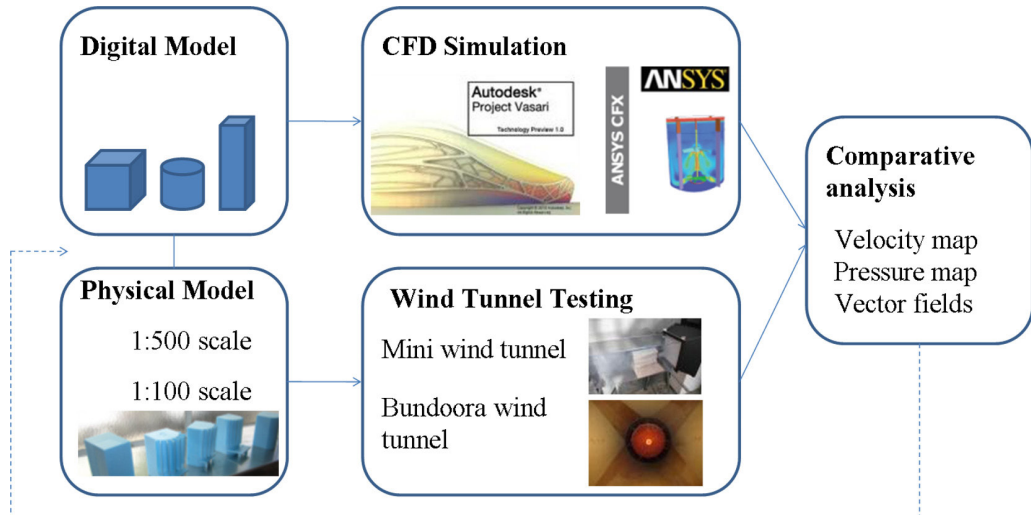
use of Ansys for simple 2D simulations, given the time required to run Ansys could take a few hours to a few days. On the other hand, Vasari is free and is intended only for conceptual design stage. Although Vasari is designed for architects and assumed to provide intuitive interface for users who are never trained in fluid dynamics, expert training is still required for designers to use the Ecotect wind tunnel simulation in Vasari properly.

The industrial wind tunnel is also considered a high-tech tool as it requires a complex set up, especially if some probes or monitoring sensors are to be placed on and around the fabricated 3D models. The wind tunnel that was used in our workshop has a test section that is 3m wide, 2 m high and 9m long, and has been used for research and commercial testing of new cars and airplane wings. In terms of cost, the industrial wind tunnel can be more cost effective and efficient in comparison to the use of CFD in simulating urban aerodynamics. This is because the wind tunnel could be used to simulate turbulence phenomena in a more complex urban setting and visualise wind pressure on the edges of, corners of, and between buildings.

The low-tech tools

The low-tech tools used in the workshop include our own custom-made mini subsonic wind tunnel and the Particle Image Velocimetry (PIV) technique to analyse the video and image recordings from the wind tunnel simulation.

The subsonic condition refers to a model of wind tunnel of low wind speed and an open–return type design (i.e. air intake and exhaust are not connected to each other) with a reduced size closes to the first wind tunnel used by Wright brothers' for their first experiments in 1901. It was a low-cost tool that requires simple fabrication for hands-on wind simulation. Mini subsonic wind tunnels are a well-known technology with practical applications in various education and scientific fields. The advantages are the low cost and its portability. It is a technology capable of producing real aerodynamic phenomena. It has been known since 1930 that there are different results in pressure distributions from testing the models in uniform flow wind tunnels and from full scale tests (Aynsley, Melbourne et al. 1977). With the understanding of the differences between dif-
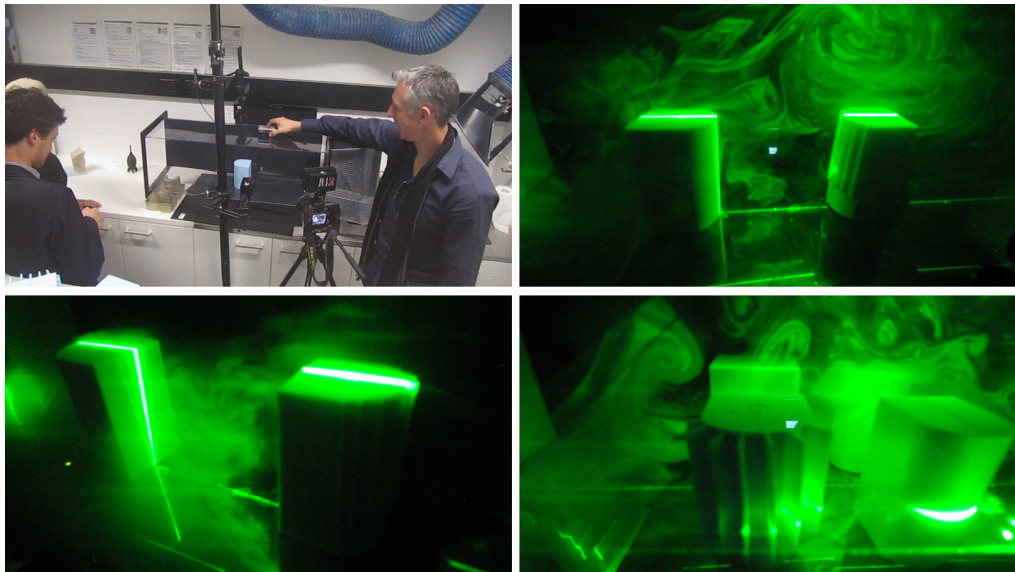

Figure 2
Mini wind tunnel.

ferent tools and their limitations and by calibrating a group of basic parameters in the first stage of the design process, some wind conditions can be visualized and studied.

Existing architectural projects that used "low-tech subsonic wind tunnels" in the design process include the project for a new Navy School in Valparaiso City in 1952-1957 (Pérez de Arce and Pérez Oyarzún 2003) and Errant's lodge (Casanueva Carrasco 1996). In both cases several tests were performed in mini low-tech wind tunnels to design different architectural elements to control the seawinds that blow against the buildings. Both cases demonstrate that it is possible to use these low-tech tools to visualize the physical phenomena of the wind, develop an empirical process of experimentation with models of various scales, and collect sample data for further processing.

Finally, in order to capture and post process the information from the wind tunnel experiment, the Particle Image Velocimetry (PIV) technique was chosen. PIV is an optical method of flow visualization that it is used to obtain instantaneous velocity measurements and related properties in fluids [1]. This technique is increasingly used in aerodynamic experiments (Baker 2007). Among the existing open source and commercial PIV tools, the open-source JPIV software was chosen [2].

The experiments

The mini wind tunnel (Figure 2) built for the workshop consists of a test chamber, contraction section (cardboard extractor hood in black color to avoid laser reflections), anti-turbulence screen, fans, smoke/fog machines, 2D slicer laser device, and digital cameras.

The smoke machine was used to draw the flow of the wind inside the test chamber. It was necessary to work in a dark room for the experiments to work with laser devices, which are used to visualize the wind behaviour on 2D planes. Two green laser lights were used to visualize the fog in front and plan view. The speed of wind was around 1 to 2 meters per second.

We tested 3D models with different profiles:
- Single volumes: regular boxes, boxes with cylindrical faces, irregular faces.
- Group of volumes: two volumes, four volumes in different configurations.
- Different wind speed: to visualize vortices, low pressure areas, etc.

Using the mini wind tunnel, it was possible to draw the motion of the wind and visualize the wind behaviours, such as acceleration, direction, while interacting with physical objects. The workshop participants gained an understanding of the physical effect behind a wind flow, because they saw the movement of the air, and at the same time, they could interact with small scale models to visualize the impact of different configurations. This fast feedback in the experiment was the most valuable experience from working with our low-tech wind tunnel.

A second type of experiments was performed in the industrial wind tunnel in RMIT Bundoora Campus. In this instance, we used 1:100 scale models of volumes with different profiles (similar to the experiment in the low-tech wind tunnel) and two façade models that have different texture configurations. The wind tunnel was set up to reproduce a wind flow profile similar to the ground level. The visualization was using bubbles. The models were tested to visualize the following aerodynamic phenomena:
- Deflection of wind and turbulence on the top of the models.
- Turbulent zones in the ground level of the models.
- Turbulent zones of wind in the corners of the models.

We used Vasari and Ansys CFX to perform a numerical simulation of the physical experiments in the mini subsonic wind tunnel and analyse the effects of different façade treatments on a volume. We performed a digital wind tunnel simulation to firstly visualize turbulent zones on a regular model from the top view and lateral view. After applying different façade textures on the model, the wind simulation was repeated to produce a visualization and com-

parison of turbulent zones on models with different textures on the faces (Figure 3). The building and façade models were also fabricated for a parallel test in the industrial wind tunnel (Figure 4 and Figure 5).

After a series of experiments in four days, we gathered initial data and analysis results from different tools in order to compare the results and investigate the clarity and intuitiveness of the visualization of the aerodynamic phenomena produced from using these tools.

COMPARATIVE ANALYSIS BETWEEN PERFORMANCES OF TECHNOLOGIES

Digital simulation tools (Vasari, Ansys, JPIV)

The first comparison was between the CFD simulation software used in the workshop, which are Vasari and Ansys. The digital tools were used to replicate and visualize the aerodynamic phenomena that were simulated in the mini wind tunnel. Both tools are useful for performing wind tunnel simulations with digital models. When Vasari, which is a free technology preview released by Autodesk for a limited time, is compared with Ansys CFX, a full-fledged CFD commercial product with a high license cost, Vasari performed quite well and produced similar results (as seen in Figure 6). Although the wind simulation in Vasari could work faster than Ansys due to the simpler algorithm used in Vasari, the urban model used in the simulation must be a very simplified massing model that has only a limited number of buildings without any detailing; otherwise Vasari would crash or the simulation would not run at all. Ansys CFX is a complex tool, unsuitable for a simple and quick analysis in the earlier stages of a design process. Both software allow clear visualization of wind separation zones around the model. The digital tools could work with simplified models and models with textured faces. Vasari, particularly, was able to provide a quick indicative result useful for comparing multiple design options. However, such digital simulation software have limitations in simulating turbulent wind conditions and are unable to clearly visualize vortexes.

Another digital tool employed in our experiments was the JPIV software, which was used to post-process the information gathered from physical models tests in the industrial wind tunnel. The PIV technique has been used for analysing images captured from wind simulations in industrial wind tunnels (Kompenhans et al., 1999). The advantages of JPIV as a post-processing tool are the ease-of-use and the negligible cost with the open source version. Using JPIV, we were able to visualize the wind direction, measure wind speed, and convert wind movement into vector data from images captured in the industrial wind tunnel (Figure 7). Unfortunately, JPIV could not be effectively used to post-process images taken from our mini wind tunnel, since the photographs are not very clear due to the dark room where the experiment was performed.

Physical simulation tools (large scale industrial wind tunnel, mini wind tunnel)

The large scale industrial wind tunnel is able to reproduce real aerodynamic phenomena and has calibrated instruments for measuring and collecting wind data digitally. However, the infrastructure was offsite and the access was limited. Furthermore, it required more human resources to operate the wind tunnel and higher amount of time to set up the simulation conditions and calibrate the measurement devices. Given the limitations of time during the workshop, we were unable to utilise the sensor probes and measurement devices in the wind
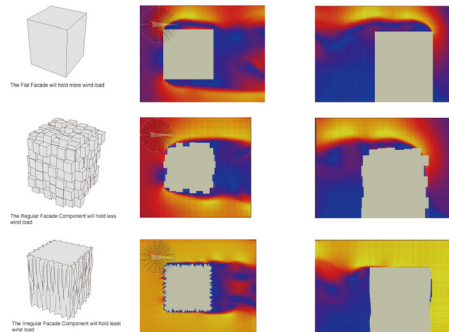

Figure 3
Analysis of different façade treatments.

Figure 4
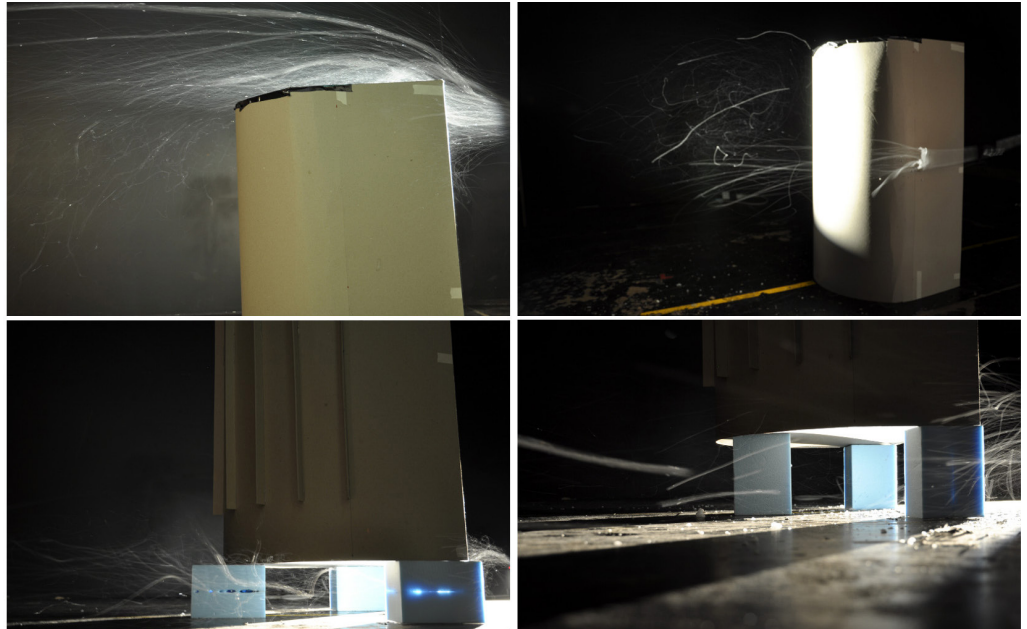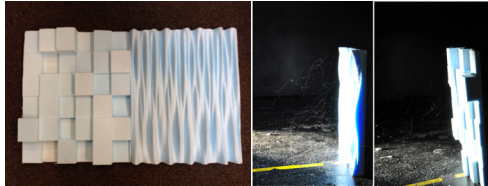Wind tunnel simulations with
the physical models.

Figure 5
Wind tunnel simulations of
different façade treatments.

tunnel since the set up time of those probes might require up to a week. However, during the experiment, it was possible to see the movements of the wind, vortex and Eddy areas clearly on some parts of each model. Without the probes, we were unable to see the aerodynamic phenomena around multiple physical models. On the other hand, using the low-tech mini wind tunnel, we were able to quickly set up simulations that were capable of showing changes in wind behaviour with different configuration of volumes. The time to set up each experiment was short, and the visualization of different ranges of vortices and Eddy areas is possible

even with different wind speed. With the laser devices, it was possible to clearly see two-dimensional layers of movements of wind on planar sections of each volume and the movement of the wind passing through of a group of models. Data collection was quite straightforward using cameras to capture videos and images for post processing with the JPIV software. In a nutshell, the mini wind tunnel tool enables designers to interact with physical models in a wind simulation that provides an instantaneous visual feedback of the aerodynamic phenomena. This makes such a tool to be particularly useful for the early design stage.

CONCLUSION
Decisions made in the first stage of a design process are very critical in influencing the direction of the project. Therefore, a good understanding of the dynamics of the space, such as urban aerodynamic phenomena, is needed. A clear visualization helps

designers to understand how the wind flow affects a site and how different design options and configurations may affect the wind conditions of the site. To facilitate basic comprehension of the phenomena, designers need visual feedback in performing hands-on aerodynamic experiments, such as wind tunnel simulations. This is the premise of our experiments in a four-day workshop.

Parallel analysis and evaluation of the high- and low-tech tools resulted in useful findings. CFD analysis could provide an intuitive feedback for visualising urban aerodynamics phenomena but requires high computing cost and highly limiting assumptions to be taken into account in setting up the models and help from experts to translate the results. The industrial wind tunnel also requires high initial and ongoing investment cost to run, but is more effective in simulating more facets of urban aerodynamic phenomena using a more complex urban model that cannot be hosted inside a CFD simulation.

A novel discovery in our experience is that the analysis results from observing the aerodynamic phenomena simulated in the low-tech wind tunnel made and used in the workshop are comparable with the results from high-tech tools. The simplicity of setting up basic models for the simulation makes the low-tech mini wind tunnel suitable for performing aerodynamic experiments in the early stage architectural design. Additionally, the low-tech subsonic wind tunnel is useful for pedagogical airflow analysis, given its capability to visualise the physical properties of the airflow and allow hands-on experiment with instantaneous feedback. These kinds of tools have been displaced by the current CFD techniques and computational methods, however they are very easy to set up and implement, and their usefulness for early stage design explorations are evidenced by the workshop.

In places where high-tech tools like industrial wind tunnels and expensive digital tools are not available, the mini wind tunnel proposed in this paper is a good alternative for promoting comprehension of basic aerodynamic phenomena in the conceptual design stage. Digital simulations with the high-tech tools can complement the low-tech tools to improve an inquiry of the urban aerodynamic phenomena on a specific site.
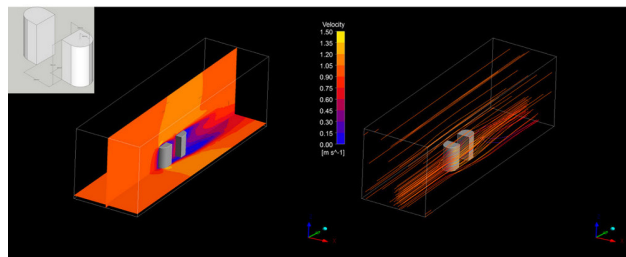
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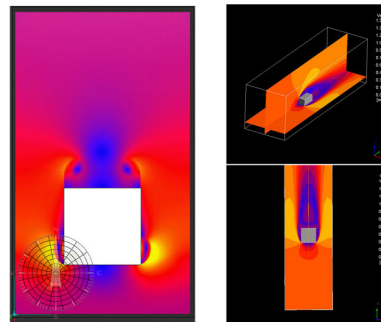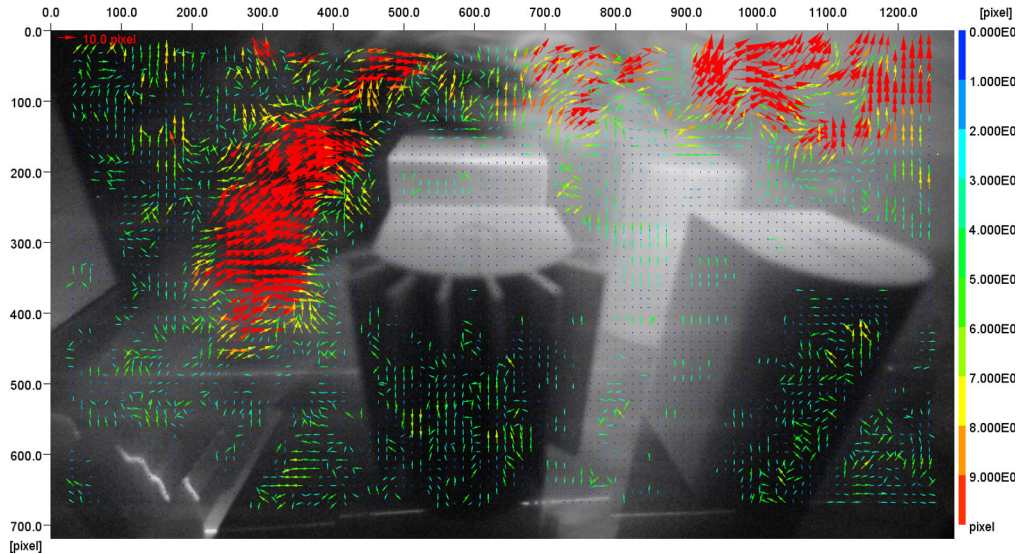Figure 6
Vasari vs. Ansys CFX.

Figure 7
Post-processing of an image
from the mini wind tunnel
simulation using JPIV.

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Wind sensing with real-time visualisations for Designers

An approach to understanding wind phenomena for pedestrian comfort using low cost wind sensors

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The evaluation of a low-tech wind sensing platform for urban aerodynamic simulations relevant to pedestrian comfort. In this paper, the wind canyon effect is simulated with two different building morphologies. The platform provides conceptual knowledge of the dynamics in wind relevant for designers, architectural practitioners and students of design. Low-cost hot wire anemometry is utilised for the design of an Experimental Fluid Dynamic (EFD) wind sensing network interface. This paper explores the validity of the sensing platform for a new approach for non-wind engineers to gain a better understanding of the dynamics of wind. The influence of real-time feedback from quantified wind on the understanding of wind phenomena for non-wind engineers is discussed and compared with post analysis data. It was found that real-time quantified feedback from wind intrigues and stimulates the intuitive notion of wind dynamics through discussion, however post analysis remains critical to evaluate building design performance.

Keywords: Wind Sensing, Real-time feedback, Experimental Fluid Dynamics, Hot-wire Anemometry, Atmospheric Boundary Layer

INTRODUCTION

The study and knowledge of urban aerodynamic phenomena is very important in the fields of sustainability, environmental design and human comfort (Boris, 2007). The aerodynamic phenomena produced by wind in the built environment and its effects on the level of pedestrian comfort usually require complex and expensive technologies to quantify the wind condition and visualise the effects in the built environment. Tools such as: Computational Fluid Dynamics (CFD) or the use of various high cost and complex wind sensing techniques i.e. multi-hole pressure probes coupled with Experimental Fluid Dynamics (EFD) can be overly complex (Watkins, 2002). The nature of wind is beautiful and majestic, though chaotic which creates difficulties when attempting

to introduce the topics of observation and analysis of complex wind flow phenomena in built environments to architects and designers. Architects and designers should have a broader knowledge about the more important and fundamental concepts involved in wind around buildings so they may understand the parameters involved at the conceptual design stage. Wind phenomena around buildings has strong relevance in urban planning and architectural design and is imperative for an architect's ability to share common knowledge with disciplines such as wind engineering in their professional careers in design (Wisse, 1988).

The Wind Sensing Platform

The wind sensing platform proposes an improved method of phenomenological exploration and observation of the dynamics of wind by quantifying empirical experiments in real-time. The platform provides real-time feedback of the changes in wind speed in understandable units (metres per second) at strategic points around a scaled building design with a direct digital interface to visualise data. The sensing platform was tested with two scaled buildings in two different wind flow scenarios to show the capabilities of the sensing technology to identify the predicted wind phenomena surrounding the buildings.

Empirical observations of wind dynamics are the most informative and stimulative way to understand the dynamics in wind, which is suggested as a good introduction method for architects (without a wide theoretical background in fluid mechanics) to understand aerodynamic phenomena in built environments. The sensing platform presents an opportunity to add value to and actually quantify the empirical experiment in real-time for on-the-fly discussions and decision making. Rapid feedback about the dynamics of wind improves a designer's ability to choose the most effective design based on the wind speeds around a building (a good indicator of pedestrian comfort levels) (Gandemer, 1978). It has been found that using empirical explorations and digital sensing technology is much faster when iter-

ating through multiple design concepts in comparison with virtual simulations (Williams, 2013). This is just as evident in the specific realm of fluid dynamics where CFD is notoriously enigmatic.

The sensing platform integrates three main technological approaches: physical simulations of wind with a wind tunnel, micro anemometer sensors connected to an Arduino board and a digital interface to visualise data using Grasshopper3d (0.09.0056) with the Firefly plugin and Rhino5.0 software.
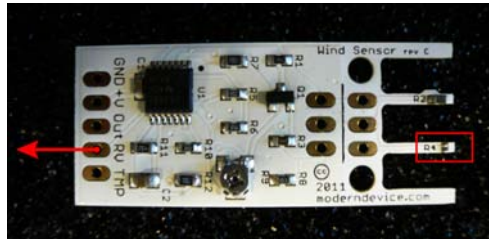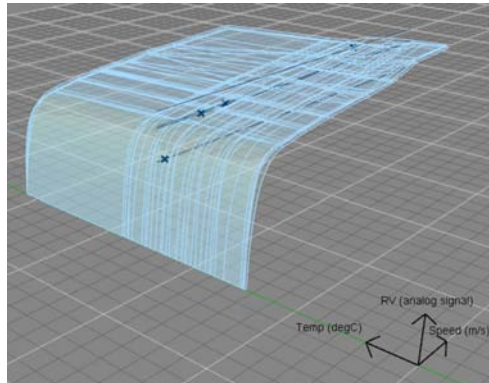

Figure 1
Hot-wire anemometer ModernDevice (revC)

Figure 2
Hot-wire anemometer calibration surface in Rhino 5 using Grasshopper3d

The adaptation of the wind sensors

The wind sensors were acquired from ModernDevice (see URL in references). These particular sensors were originally designed for the purpose of recognising if someone was breathing. Five wind sensors went through a calibration process within the low-turbulence aerospace wind tunnel at RMIT University. The anemometers are dependent on temper-

ature changes in the ambient conditions as well as the temperature difference created by the change in wind speed (figure 1). The dependency on the orientation of the sensor with respect to the wind direction was also tested. A surface was created in 3D space to relate ambient temperature, analogue signal and wind speed (figure 2).

EXPERIMENTATION IN THE WIND TUNNEL
The low-cost anemometers were utilised in two main scenarios within the industrial wind tunnel at RMIT University, Bundoora. Firstly, the sensors were used to measure the Atmospheric Boundary Layer (ABL) wind velocity profile at a 1:100 scale. The second set of experiments involved two different building forms that would display interesting wind phenomena. A second building was placed windward to the building in question to simulate a canyon wind effect in subsequent experiments.

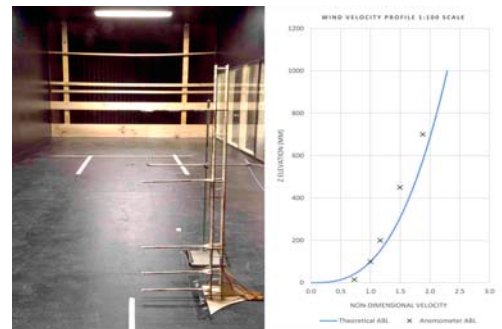### Wind Velocity Profile Measurement and Calibration
The first task was to set up a group of sensors to measure the wind velocity profile of the 1:100 ABL condition (Aynsley, et al. 1977). An existing rig to create the 1:100 ABL condition in the industrial wind tunnel was used (figure 3). The wind velocity profile was measured with the anemometers and plotted against the ABL power function. The wind velocity profile and turbulence intensity profiles are documented from previous experiments with a cobra probe. These results were used as a reference for the hot-wire anemometers, though detailed analysis of the hot-wire anemometer performance for turbulence intensities will be well documented in further research. The scope of this paper covers an exploration into techniques to calibrate the wind tunnel boundary layer condition for wind speeds in real-time (figure 4).

The ABL calibration process is usually an arduous and time consuming task. The hot-wire anemometers used in this wind sensing platform show promise in this area of wind measurement. Basically, a the-

oretical boundary layer condition should be calculated and plotted on an elevation verses wind velocity graph. A reference velocity should be chosen relative to the height which is of some significance - commonly taken as 10m above ground level for urban conditions. However, these experiments are focused on the effect of pedestrian comfort around buildings, so a reference velocity is taken at 1.5m above ground level (head height). The sensor positions are then chosen and values along the theoretical ABL power curve equivalent to their elevation are noted for reference during the real-time calibration process.

Timber of various sections were used as wind barriers to configure the wind dynamic to achieve the ABL. Each effect of each additional timber element was measured in real-time. The aim was to achieve the reference wind speed at each elevation. Though when one wind barrier is added, the effect on the wind measurements were dispersed amongst surrounding measurement points. A major advantage of multiple sensor measurement creates the opportunity to observe these de-localised effects and immediately take action to balance the distributed effect. The resultant configuration for the 1:30 profile included one additional slat and a series of 90x45mm timber sections to alter the 1:100 ABL profile into a 1:30 ABL (figure 4).


The red curve in the Rhino 5 screen capture moves with the wind along the wind speed axis (figure 5). It was possible to observe the dynamic fluctuating ef-

Figure 3
Wind velocity profile anemometer measurements (Scale 1:100) Vertical slats were used to create the ABL condition

fects of the wind as the curve snaked around its theoretical counterpart, the blue curve, which describes the theoretical ABL wind velocity profile. The values represented virtually at the location of the sensors were a display of the target speed and real-time speed measured by the anemometers. It was difficult to understand the nature of the velocity profile curvature with these measures alone, but proved to be useful when trying to reach the target velocities during the calibration process (while adding or altering timber elements).
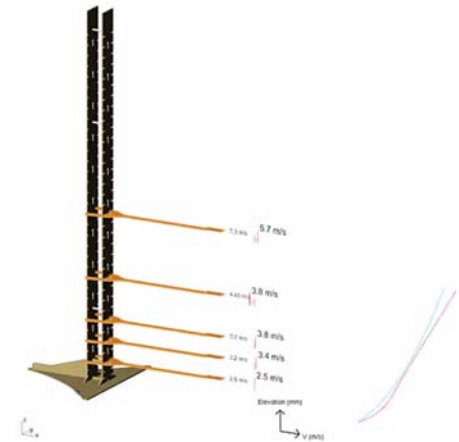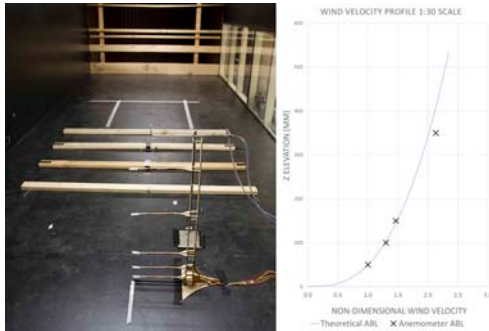
The methods of visualisation had a strong impact on how one may understand or interpret the quantified wind data. For measurement of wind at various chainages along a vector, a continuous curve has shown to be the most useful. ABL measurement requires the measurement of a reference velocity and should match the ABL power law (Walshe, 1972). Relative wind velocities or turbulence intensities need to be quickly compared with respect to one another - the curvature of the velocity profile is critical since the results are represented non-dimensionally and in non-compressible fluid flows the geometry of the wind flow should not change with respect to the magnitude of the wind velocity.

The instantaneous ABL curve representing the anemometer measurements appeared to move too and fro about the theoretical ABL curve. During observation, discussion and manipulation of the timber elements it was possible to see the change in the wind velocity profile using this curve, however, as a time dependant visualisation (45.7Hz sample rate with 20 point weighted smoothing applied). This removes the abstraction of the static depiction of post analysis velocity profile plots. The decrease in abstraction of the reality is proportionate to the increase in understanding of the reality. In this sense the process is valuable to the non-wind engineers whom are interested in observing and understanding wind dynamics.

It was possible to estimate the wind velocity profile of the ABL through real-time observations of the hot-wire anemometer measurements. The observed data was strategically logged and quite readily averaged over a one minute sample to plot the wind velocity profile. It only took one attempt to achieve a very reasonable resultant ABL condition. The entire process of calibrating the wind tunnel from a 1:100 profile to a 1:30 profile was achieved in approximately an hour.

Measuring Wind Speeds around Buildings
The following building examples were chosen to create some interesting, but clear wind effects and in some cases quite well known in the wind engineering literature. Effects, such as: the canyon effect

Figure 4
Wind velocity profile anemometer measurements (Scale 1:30) A combination of vertical slats and horizontal wind barriers were used to create the ABL

Figure 5
An example ABL wind velocity profile measurement real-time visualisation (calibration of the 1:30 velocity profile (Castro et al., 2014))

and channel effect were created with the two building morphologies (Penwarden, 1975). It was possible to check the wind speed at various locations around each building model and project the quantified wind values in real-time to the observers. Some interesting discussions about the wind phenomena displayed began to change how we approached the experiment, but also allowed us to reflect directly on the data which we saw in real-time on the digital interface.

Figure 6
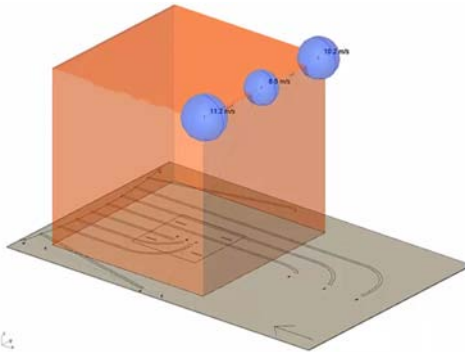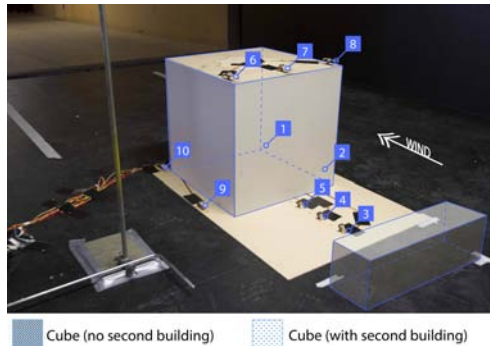Virtual visualisation of quantified wind: Cube building example

Figure 7
Cube building example 45(W)x45(L)x45(H)cm Two scenarios depicted: 1. without smaller building 2. with the smaller building

Cube (no second building)   Cube (with second building)

The experiment to test the sensor platform was designed to simulate of the canyon effect, an accelerated vortex of wind in the space between both a high building and lower building. The phenomenon is produced by a downward wind flow deflected by the high building facade to the ground level. The wind effect around a building could have a strong impact on the pedestrian comfort level. For this reason, it is relevant to study the relationship between geometry of a windward facade and the wind speed deflected from the facade to the ground.

The aim of the experiment was to detect the differences of the wind flow produced with respect to the two buildings, one of a regular shape and another with a twisted hyperbolic form. The sensors were installed in specific points in front of the building facade, at the corners and on the top of the building to detect the main variations of the wind flow (Penwarden, 1975).

Digital Interface and Real-Time Feedback

Using Grasshopper3d with firefly and Rhino 5 it was possible to develop a digital interface to directly receive the analogue signals from the sensors, calibrate them through a surface in 3D space and translate this data into graphical information. This allowed an easy comparison between physical and virtual realities. Additionally, this information can be overlapped on a 3D digital model of the building shape (figures 6 and 8) or urban configuration to help define zones of turbulence and wind speed variations.

The anemometers were placed in regions chosen with reference to ratios of the building geometry (Penwarden, 1978). These configurations were matched with theoretical wind patterns which are well known in the field of wind engineering. These were very relevant in the case of the cube building example, in contrast to the hyperbolic building morphology. So, a smoke machine was used for direct observation of the turbulent characteristics around the hyperbolic building (video footage is available). It was evident that the wind was channelled and accelerated along the facade down towards sensor 10. Diagonally skewed eddy vortices were also observed on the leeward hyperbole surface. A similar and slightly more intense effect was observed in the region of sensor position 2. Though, this was a combination of wind channelling and wind shedding about the acute building edge condition.
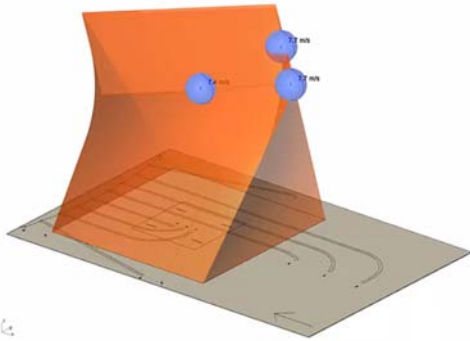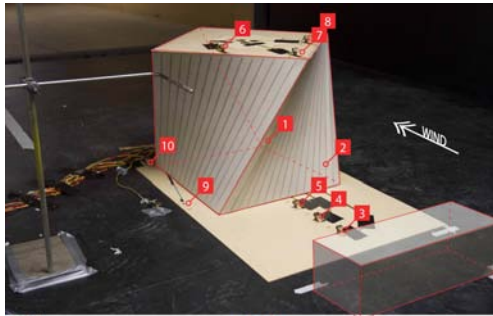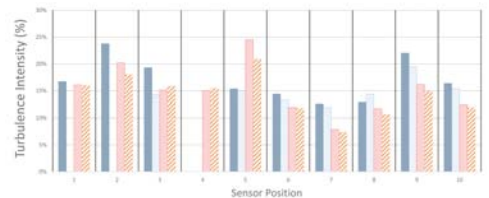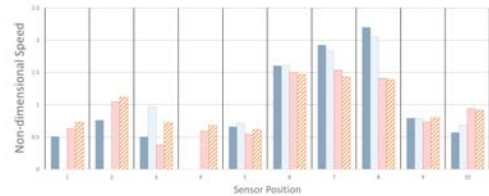
Hyperbole (no second building) Hyperbole (with second building)

The sensors were strategically placed around each scale model building. During on-the-fly discussions it was possible to identify the accelerations in wind due to wind shedding on the windward corners of the buildings, the amplified effects of the wind within the region between the smaller building and the larger (canyon effect) and the differential effects of the wind on the leading edge of the rooftop. It was also possible to identify that there are asymmetries in the wind flow within the wind tunnel. The observation of the asymmetries in the wind flow became very useful knowledge for the post analysis process - something which would not have been readily concluded during post analysis. These observations were recorded through video and audio recording during the experiment. A selection of these recordings will be presented at the conference.

Post Analysis Results

An interesting example of the canyon effect has been observed in the above results. The canyon effect is created by the differential wind speeds simulated by the ABL condition in the wind tunnel. One would assume that when one *blocks* the wind with another building the wind speed should decrease at sensor position 3. However, we observe the contrary. The effect of the ABL and low pressure systems in-between the two buildings creates an accelerating effect (Penwarden, 1975).

It is evident that after post processing the collected data, the average speeds surrounding the two building morphologies expressed very similar patterns to those inferred from the real-time observations.

This is the first application for the measurement of turbulence intensities for these particular wind sensors. So, it is not possible, at this early stage to verify the measurements' accuracy. Though it may be within reason to speculate that the measurements observed are in-fact quite relevant - as is observed in "Aerodynamic strategy applied in an urban shelter design"(also presented in this conference) (Moya Castro, 2014). These observations are merely self-

reinforcing evidence at this stage, however further tests will be conducted prior to the conference proceedings to clarify the accuracy of turbulence intensities and wind speeds measured with the low-cost anemometers.

The application of the sensor platform for rapid visualisation and comprehension of physical simulations can improve the observation and analysis of wind dynamics in the built environment for architects and designers, potentiating the communication with other specialists. This tool has the potential to be used in the study and design of microclimatic conditions for pedestrian areas near buildings.

CONCLUSION

This research presented a technological platform which integrated different techniques of simulation and visualisation of wind phenomena and analysis of aerodynamic simulations of wind flow around built environments. This technology has the potential to help non-engineers to better understand the dynamics of wind around buildings. It is a practical tool to analyse problems of discomfort produced by wind in areas near buildings, but also, it is a tool that can assist architectural practitioners and designers to explore aerodynamics through quantifiable empirical observations. It is a cheap, relatively low tech, reliable and quick method of measuring wind effects around buildings. This approach to wind visualisation is relevant because architects and designers should share (at least) a basic knowledge of wind with engineers to have a discussion about the problems related with the factor of wind in design.

OUTLOOK

This wind sensing platform is very relevant for use in the design industry and wind engineering. The fact that this sensing platform is a low-cost, reliable and quick feedback tool for the measurement of wind speeds within reasonable accuracies promotes this research as an option to adapt the sensors to any conceptual design challenge where the effects of wind are relevant.

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A Physical and Numerical Simulation Strategy to Understand the Impact of the Dynamics in Air for the Design of Porous Screens

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ABSTRACT

This paper describes a virtual and physical design and prototyping strategy intended to aid designers to understand the relational dynamic between airflow and porous screens for building facades at the conceptual design stage. The strategy consists of three main components: 1) A prototyping phase involving a combination of computer aided modeling (CAM), physical additive and subtractive fabrication; 2) A virtual simulation phase using computational fluid dynamics (CFD) software; 3) A physical simulation phase of experimental fluid dynamics (EFD) using a miniature wind tunnel (MWT) and microelectronic measurement systems (MEMS) that measure: wind speed, air temperature and relative humidity. The design strategy supports the designer to make design decisions based on relevant feedback from both CFD and EFD methods – covering a vast design solution space. The tools utilized within this design strategy are presented as a kit containing parts that are relatively inexpensive, easy to assemble, and have been successfully user-tested at an international design workshop. The paper includes the description of the application of the strategy combining CFD, MWT, MEMs and real time visualization to the design and study of various porous screens produced during the design workshop.

Author Keywords

Physical prototyping; aerodynamics; façade design; computational fluid dynamics (CFD); experimental fluid dynamics (EFD).

INTRODUCTION

Wind flow in the built environment produces aerodynamic phenomena that affect comfort of building inhabitants and people in public spaces. For this reason, the study of the interaction between aerodynamic phenomena and architectural phenomena has become very important in many fields such as sustainability, environmental design and the area of human comfort [1]. To address the effects of interaction between wind dynamics and architectural forms, designers have started to incorporate wind analysis as an input within the design process by incorporating performance simulations developed with wind experts [2]. Wind engineers consider wind tunnels a reliable technology for wind analysis, but because of the expensive facilities required, this technology has not been fully incorporated into the design process or the education of architecture students [3]. Moreover, technologies such as CFD have facilitated the analysis and quantification of wind pressures and approximations of average wind velocities and turbulence intensities for wind engineering and structural engineering applications. The expertise required to operate advanced CFD tools such as ANSYS is rarely accessible to architects for such architectural design tasks as the design of porous screens for wind mitigation and filtration into the interior environment.

Our proposed technical platform is a miniature wind tunnel (MWT) incorporating microelectronic sensors and real time sensor data visualization for testing physical prototypes. Low fidelity CFD simulation with the digital models used to build the prototypes is considered in parallel. It integrates the capabilities of both physical and virtual simulations of wind flow. It is targeted for use in the early design stages,

as a preliminary design exploration suite for small-scale models or architectural details. The relative short feedback time between simulations allows designer to explore multiple conceptual ideas in quick succession. The aim of the simulation tests is less on the performance validation, but to offer opportunities for the designers to grasp the general behavior of wind in the context of their architectural design, assist designers in ranking the aerodynamic performance of designs, and understand how, in general to alter design parameters to improve the wind performance.

This paper includes the details of the wind simulation and sensing systems (both virtual and physical) chosen to support early stage conceptual design. We conclude this paper with a set of porous screen designs to illustrate how our proposed simulation platform contributed to design decisions that were developed during an intensive design workshop.

CFD METHODS FOR DESIGN STRATEGIES
Simulations using CFD principles have been incorporated progressively into the architectural design process for Building Performance Simulations (BPS) [4]. The BPS simulates hypothetical environmental scenarios for building design and makes it possible to visualize the results. In the past few years a large set of computer applications for simulating wind speed and turbulence around buildings have been developed for architects. These range from simple smooth flow CFD programs to more specialize and involved simulation, which, whilst very computationally expensive, have been validated against benchmark flows [5]. However in general the CFD tools for architects are somewhat incomplete and require further development [6].

The incorporation of CFD wind visualization into the architects' design process has presented difficulties because CFD based tools require specialist knowledge for both modeling and the interpretation of results [3]. Moreover, high fidelity simulations are very time consuming and need very fine mesh spacing and are therefore rarely integrated into the workflows of most practicing architects. Also, CFD modeling is challenged to provide a sufficiently accurate solution due to the complex nature of the turbulent atmospheric boundary layer. Thus, in the architectural design process, CFD tools have been used to evaluate the effects of wind on the final building form rather than as a tool used to inform early design decisions [3]. To deal with these difficulties, new versions of CFD programs have been developed to be used by architects from the early design stage. This new generation of programs such as: Autodesk Vasari or Flow Design facilitates the setup of simulation, visualization and analysis by architects without a strong theoretical background in fluid dynamics. However, these are focused on the general visualization of outdoor wind flow around buildings and they do not include other parameters such as temperature or humidity. For these cases, more sophisticated programs are required such as ANSYS.

CFD for architects and those inexpert in fluid dynamics
The programs Flow Design and Vasari were chosen for the case study design workshop because they represent a new generation of CFD tools developed for architects and designers. They are easy to setup for smooth uniform wind conditions. The capabilities of these CFD programs can provide quick and accessible information by presenting wind analyses during the conceptual design phase. These programs focus mainly on providing graphical representations for the qualitative analysis of wind flow, a user-friendly interface and the integration with other architectural CAM programs such as Autodesk Revit. Thus, one aim of this research was to understand the limits of the performance of these programs for visualizing and feeding back wind effects in various architectural design contexts for particular design typological problems (see Figure 1). To this end they were used in parallel with testing physical models using electronic sensing to gather data for analysis. The models tested both in the CFD and Miniature Wind Tunnel and sensing environments were of complex porous screens for microclimatic control of an indoor environment in an apartment building.

	Pros	Cons
CFD: Vasari/Flow Design	More accessible than traditional CFD software or wind tunnel facilities; suitable for users without a strong theoretical background in fluid dynamics; rapid visualization and feedback; relatively easy to setup and operate; integrated workflow between 3D model, CFD simulation and visualization; useful for the early design stage for low resolution designs.	Mainly for simulation of outdoor wind flow; low level of accuracy in results; cannot simulate/measure temperature or humidity; Methods of visualization with 2D and 3D flow produce different air flow movement patterns which can be confusing; not reliable for detailed analysis of final design
EFD: MWT with MEMS	Portable structure more accessible than a real wind tunnel; relatively cheap; D.I.Y construction; focused on the early design stage; flexible to incorporate platform of multiple sensors	Provides a continuous and relatively homogeneous airflow across the test domain section, not necessarily a replication of real wind conditions

Table 1: Summary of the technology used
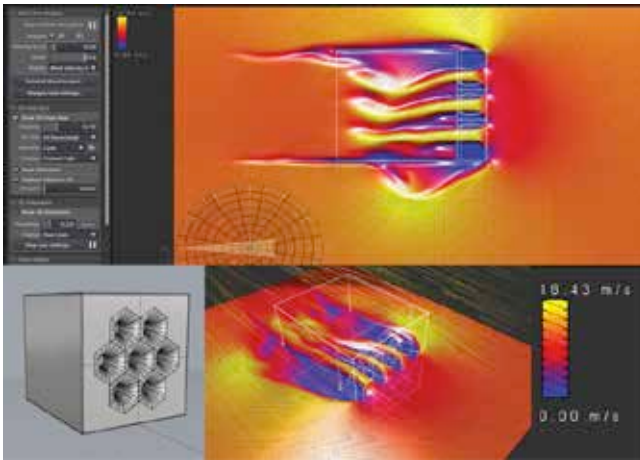
Figure 1. Example CFD visualizations from Vasari

WIND TUNNELS AND VISUALIZATION TECHNIQUES

Wind tunnel tests have existed since 1871 [7] and wind tunnel tests have been conducted for architectural purposes since the early 1890s [8]. Yet simulating the wind for architectural design is challenging - the dynamics in wind around buildings involves the turbulent nature of the atmospheric boundary layer [9]. The first wind tunnel studies focused on reproducing real wind flows in 12m long tunnels. Subsequent wind tunnels were designed to reproduce the atmospheric boundary layer with a section 2.4m wide, 2.15m height and 33m long [10]. Industrial scale wind tunnels are large and expensive facilities, may require advanced data acquisition systems and processing systems that require specialist training to operate [11-13].

Techniques of visualization used in wind tunnels include tracer methods of the airflow such as fog/smoke emission, the use of floating particles or gas bubbles. Other methods trace air movement patterns on model surfaces using dye or oils to draw wind patterns [14] i.e. the erosion technique [15]. In general they provide a qualitative approach to visualizing the pattern of wind vortices, separation flows, turbulence and changes of wind direction. Quantitative techniques typically involve the analysis of results after the experiment has taken place. Hot-wire anemometry, pressure transduced anemometry (such as a pitot static tube) or tracer methods (such as the particle image velocimetry (PIV) technique) require post analysis for the evaluation of the physical design [16]. It is feasible to note that these techniques could be used to provide near real-time visualizations of the wind. The physical wind sensing system using a MWT and MEMS provides near real-time digital visualizations of the wind, using transduced signals from hot-element anemometers [17,18].

Digital visualizations of scientific data can augment the real world with 'real-time' qualitative representations that enhance communication within groups. For example, animations that depict wind flows around physical models of architectural form can help communicate the behaviors of complex wind phenomena across design teams where not all members have an extensive knowledge of wind dynamics. This holds true even when the representations are not as accurate as traditional methods of simulating wind flows, as demonstrated in the Tangible Teamwork Table (TTTHub) project [19]. Digital and physical representations were combined to communicate the complexity of wind flow dynamics for a team undertaking an exercise in urban planning [19]. In a similar manner, the augmentation of physical wind through the quantification of wind at strategic points in space around physical building models or building details can provoke productive design discussions.

EFD: The Miniature Wind Tunnel

The use of physical models to test wind dynamics allows architects to experiment with complex designs and environmental patterns without needing to use advanced numerical simulation tools to verify their experiments. The use of miniature wind tunnels can allow designers to observe how the wind may interact with a complex screen configuration. The use of a MWT can inform the designer through various visualization techniques to aid the design process towards more desirable interior microclimatic conditions. The particular wind tunnel used in this study incorporated a microelectronic wind sensing system which allowed the users to observe how the screen may affect environmental parameters such as: the dynamics in air movement, temperature and relative humidity that may be produced by the simulation of rain. These kinds of experiments are much more feasible to conduct using physical means, such as the MWT, even if the simulated airflow does not match the full scale in situ conditions. The idea is to conduct these experiments with a platform of low cost technology that can gather digitally airflow data and visualize it with a graphical interface to provide real-time feedback for architects. The design and improvement of the MWT is a work-in-progress, experiments are being conducted to evaluate the performance of the MWT to an industrial scale wind tunnel.

### The Portable Miniature Wind Tunnel

The MWT is designed to be portable and is constructed by hand (see Figure 2). All of its parts are provided as templates that can be cut using a laser cutter and quickly assembled without the need for any tools. It consists of a test chamber containing four modules. Each module has a dimension of 0.9m wide, 0.9m high and 0.6m long The tunnel walls consist of 8 sheets of 0.6m x 0.9m x 6mm MDF, 8 sheets of 0.6m x 0.9m x 3mm Acrylic. Laser cut 6mm MDF sheets were used for the structural frame. The vertical bracings were designed with two sections, which are then replicated — one corner section and one spanning section (8 of each are required per module). The lateral bracing requires one section type (16 are required per module). Connectors for the frame elements and between the modules are also required.

In addition, four fans are installed in the inlet zone to produce a continuous airflow of approximately 4m/s. In general, the wind tunnel is not designed to reproduce full-scale wind flow conditions such as atmospheric boundary layer or turbulence intensity profiles. However, it presents a controlled and stable wind flow environment for reasonable observations of the dynamics in environmental parameters that, in situ, exist in a similar manner.

The Physical Test Domain for Porous Screens

The test domain and sensor configuration utilized for observing the effects of porous screens within the miniature wind tunnel had the following attributes (Figure 3):

· 0.3m wide, 0.3m high and 0.6m long Acrylic square sectioned tube

· Centrally suspended within the MWT test section

· 0.3m wide by 0.3m high prototype screen to be placed at inlet

· Outlet configured for three scenarios: open, closed and doorway-sized opening to simulate variations in cross ventilation

· Test domain is an abstract representation of an apartment not dissimilar to one that may be located in Hong Kong

· 9 sensor positions within the test chamber arranged in a 3 x 3 grid with 10cm spacing
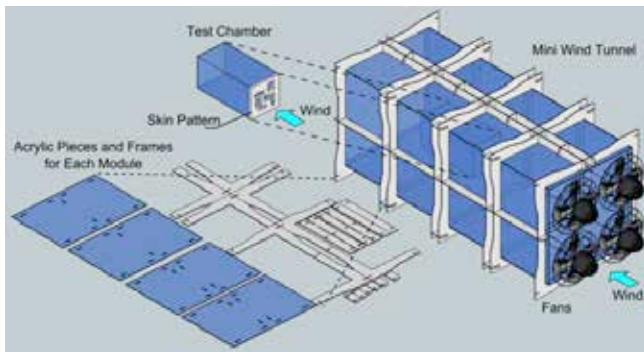
Figure 2. The exploded axonometric of the MWT.
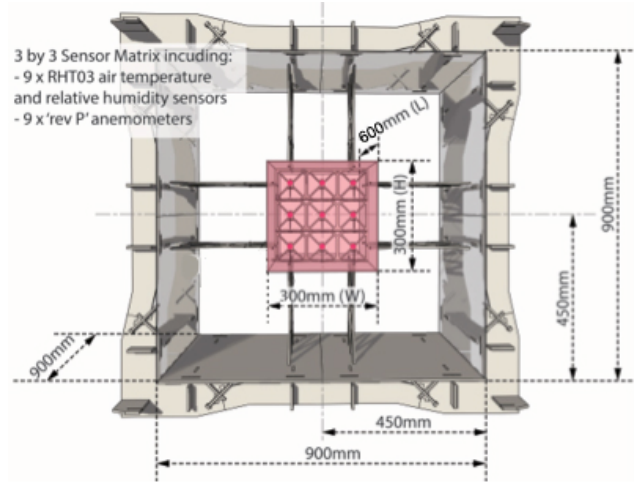
Figure 3. MWT porous screen test domain details

Figure 4. The assembled MWT in operation. The large screen in the background displayed the real time visualization of the sensor outputs. Several porous screen prototypes were also on display.

Microelectronic Measurement

Microelectronic measurement systems (MEMS) have been utilized for the quantification of environmental parameters i.e. airflow, relative humidity and air temperature within industrial wind tunnels in the past. However, they are typically used for high precision measurements at a single point, which is then traversed within the fluid flow (more commonly for airflow velocity measurements), rather than using multiple sensors (due to the cost of the measurement systems). Temperature measurement is taken at a single reference location within the fluid flow and relative humidity is taken from the nearest weather station (along with barometric pressure for the determination of air density when using pitot static tubes for wind speed measurements).

The environmental sensing system and visual interface that is presented here is an integrated low cost system relative to traditional systems that allows the user to measure and observe fluctuations in wind, relative humidity and air temperature, see Figure 5. The system can be repurposed

for use in industrial scale wind tunnels [17,18], in-situ en-mass measurement of atmospheric boundary layers or post occupancy evaluation of buildings for thermal comfort. This particular application is specified for use in the MWT for architectural based assessments of porous screens.

Figure 5. MEMS Dataflow

Figure 6. MEMS Processing Setup

The microelectronic wind-sensing platform (Figure 6, Figure 7) uses multiple electronic wind, temperature and humidity sensors to quantify the relative environmental parameters within the MWT. It is integrated with two microprocessors (i.e. Teensy 3.1 and an Arduino Uno) (Figure 6) using 18 x 13 bit A/D channels reading from 9 revP wind sensors [20] and 9 digital pins reading 9 x RHT03 relative humidity and air temperature sensors.
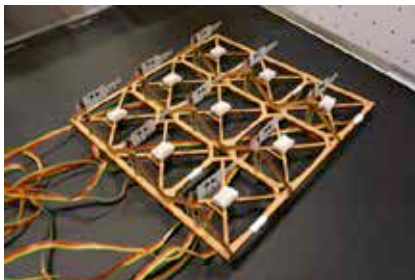

Figure 7. Sensor Matrix

Two separate serial communication ports were used to transfer data from the microprocessors. The high-speed connection (a direct USB serial connection) was used to collect relatively high frequency data (300Hz) for detailed post analysis. A pair of XBee modules was used to collect data at a relatively slower rate (20Hz) required for near real-time visualization.

Visual Interface
The acquired data can be visualized in many conceivable forms within the constraints of the software used (Grasshopper3D, Firefly and Rhino3D) (see Figure 5). In this case a virtual geometric representation of the physical apparatus was preferable with a mesh enabled to morph colors and magnitude of peaks which represented the relative values of temperature and relative humidity. A 3 by

3 grid of spheres represented the magnitude of wind speed. The calibrated numerical outputs in relative units were overlaid with the graphical display to allow the users to compare with other simulations (see Figure 8).

The ability to visualize and discuss the sensor data during physical simulations creates opportunities to adapt during experimentation. This is a constructive environment for designers that are creating conceptual designs. The rapid feedback offers designers a tangible grasp of the performance of designs, complementing and enhancing design workflows that may rely solely on commercially available digital simulation packages. However, to actually evaluate the performance of the porous screen designs the post-analysis of gathered environmental data (e.g. average interior wind speeds, dynamic interior wind patterns or wind pressure on the façade) is also necessary. An example of the data output for post-analysis is shown (Figure 11), however the detailed analysis of results is not within the scope of this paper.
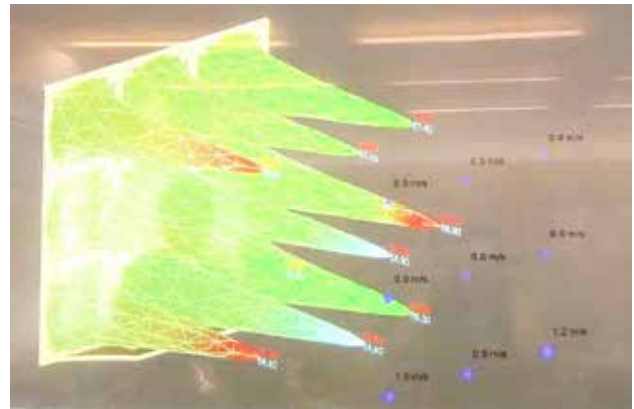

Figure 8. Example real-time visualization of environmental parameters

CASE STUDIES: POROUS FAÇADE DESIGN
There is a long tradition of moderating the breeze and bringing it into internal or semi enclosed spaces without mechanical aid, just through the design and placement of perforated or porous screens. The initial stages of the design process were performed using porous screen designs from the collaborators involved in a recent design workshop. The porous screens were designed to be tested in either the virtual or physical wind analysis platforms and, in some cases, within both. This generated reasonable results from the two methods of wind analysis.

The aim of this case study was twofold: 1. Testing the system to demonstrate its feasibility for early stages in the design process of porous screens to facilitate informed decision-making; 2. Discussing the interactions of the workshop collaborators with respect to three main topics including: form discovery; fabrication and analyses. This approach allowed the designer to receive prompt information about the environmental parameters, which is an integral part of this design process. We explored

multiple forms of porosity, the initial design began with exploring a Venturi-based design. The architectural interventions were designed to accelerate and decelerate wind flows.

A series of porous screen prototypes (Figure 13) have been designed using the proposed design strategy and tested with the wind simulation tools i.e. CFD and the MWT. One set of simulation results can be seen in Figure 9 to Figure 12. Various fabrication techniques including: computer numerical control (CNC) milling, 3D printing and laser cutting were used to fabricate numerous porous forms for wind filtration within the wind tunnel. The observable effects measured by the wind, temperature and humidity sensors were discussed within the team. Parametric patterns were changed to influence the surface characteristics that associate different dynamics in the wind, which could then be observed in near real-time. Recurring patterns within the porous screen designs created the opportunity to further understand how the basic elements or cells change the air movement or air patterns. This was the necessary link for observations of the dynamics within the wind to the geometric characteristics of the physical prototypes. Multiple configurations were defined by varying parameters such as surface roughness, size of apertures, density of porosity and shape of the inlet and outlet openings on the screens.

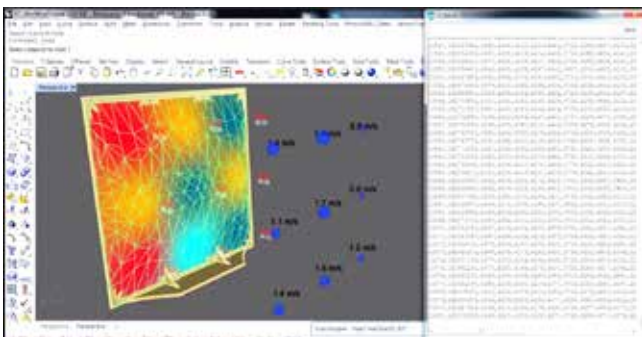**Figure 9. An example physical prototype tested in the MWT**

Figure 10. A screenshot of the real-time visualization of MWT environmental parameters, the sensor outputs can been seen on the right.
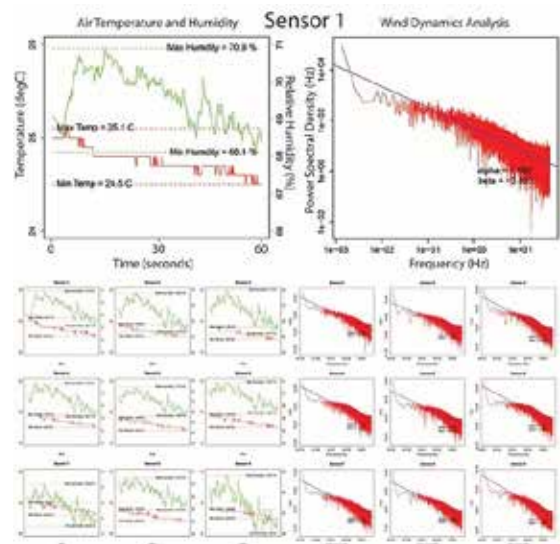

Figure 11. MWT sensor data output was captured for post-analysis
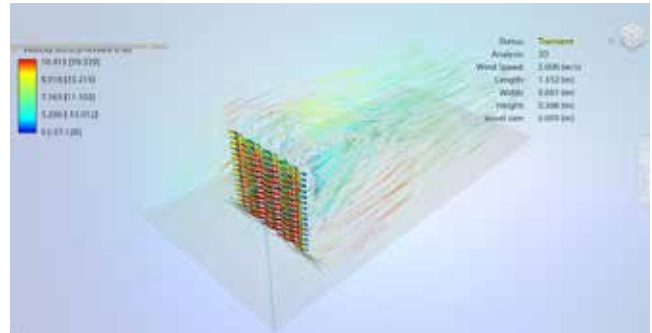

Figure 12. The design was modeled digitally and simulated with Flow Design

We observed that virtual prototypes, digitally modeled using parametric software packages such as Autodesk Dynamo and Rhino Grasshopper, were best suited to explore the full functionality of our system. When software packages are compatible, the CFD simulation can be directly applied to the parametric models, allowing more direct feedback between the model parameters and the simulation results. In other cases the parametric model had to be exported into a generics static 3D digital model to prepare it for digital simulation. Without the interactivity, this still allowed relative quick design iterations to occur. For physical simulations, physical models can be constructed using a combination of laser cutting, 3D printing and CNC milling. These rapid automated physical fabrication techniques allowed designers to have precise control over the physical models, implementing design updates to be available for the next iteration of EFD simulation with relative little delay.

Figure 13. A selection of the physical prototypes produced during the design workshop

DISCUSSION

The mini airflow tunnel is a tool to facilitate the exploration and learning process aerodynamic phenomena interacting with designs. And it is an empirical 'hands-on' experience, 10here users can have a better and closer feeling with the airflow. This tool works as a first step prior to applying CFD techniques that appear more "abstract" to designers without a strong theoretical background.

We are working on the evaluation of a rapid and flexible visualization interface for the proposed EFD. We acknowledge the limitations of this MWT EFD for simulating real wind environments (technical and theoretical), although a precise and accurate quantitative wind simulation is not the intention of this experiment. For this reason, the atmospheric boundary layer effect, turbulence intensity, nor calibration with Reynolds number (Re) were considered.

Some CDF programs used by architects for rapid feedback (such as Vasari) are also limited because they are focused on visualization of outdoor airflow with limited control of the grid domain dimensions and density which does not allow the visualization of small details and airflow phenomena. In addition, other data (temperature, humidity, sound) are not possible to incorporate in the analysis with those programs.

CONCLUSION

This paper presented a design simulation and prototyping strategy to aid designers to understand the relational dynamics between airflow and porous screens within conceptual design processes for building facades. The platform allowed designer users to make design decisions based on relevant feedback from both CFD and EFD simulations, covering a vast design solution space. Near real-time observations of numerical and qualitative environmental data provoked productive design discussions supported by both CFD and EFD visualizations.

The CFD software used was found to be very effective in achieving fast simulation results for multiple virtual design iterations; however limitations on obtaining satisfactory results were discovered for the finer resolution porous screens. The EFD method of wind flow measurement was not restricted by resolution or flexibilities in material.

The rigorous evaluation of effects of variable environmental parameters is still under investigation. However, the tests presented here demonstrate the potential and limitations of combining CFD and EFD wind simulations for the virtual and physical construction of prototypes relevant to the conceptual design process of architects.

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