

# **Parametric Design Optimization in Sustainable Urban Design: In Hot Climate**

كفاءة التصميم البارامتري في التصميم الحضري المستدام  
في مناخ حار

**By  
Mousa A. M. Musleh**

Dissertation submitted in partial fulfilment of the requirements for  
the degree of MSc Sustainable Design of the Built Environment

Faculty of Engineering & IT

Dissertation Supervisor  
Dr. Hanan M. Taleb

November-2012

**Abstract:**

The aim of this research is to investigate the potentials of applying parametric design optimizations processes over the conventional urban design processes in achieving a more sustainable urban design, and incorporating the computer and computational design methodologies in the design process and to give the computer a more active role in the design process and not just a drafting or visualizing tool. The benefits that could come to architects and urban designer from adopting such methodologies in enhancing the process of design to cope with the more demanding global energy and resources crisis that we are facing nowadays .

This research employs Genetic algorithms as the computational design methodology to achieve parametric design optimization to design for a more sustainable cities and urban. The research investigate and study The viability of computational design and the current-state of the-art computer tools in achieving an optimized parametric design like, Grasshopper, Radiance, Energy plus and ANSYS CFX.

The suggested methodology is applied to real life urban scale to investigate the applicability of parametric design optimization tools on urban scale and their potentials. The application of suggested methodologies on real life case put it under test to evaluate its viability, precise of prediction and the outcome benefits to the practical current urban design processes.

This research aims also to investigate the applicability and integration of the proposed methodologies within the current conventional urban design methodologies by investigating parameters and urban morphologies which are available and common in the conventional urban design which makes these methodologies less burden on the design team when applied.

## خلاصة:

ويهدف هذا البحث التحقيق في إمكانات تطبيق تصميم بارامترية على العمليات التقليدية في التصميم الحضري من أجل تحقيق تصميم حضري أكثر استدامة، ودمج الكمبيوتر ومنهجيات التصميم الحسابي في عملية التصميم وإعطاء الكمبيوتر دور أكثر نشاطا في عملية التصميم وليس مجرد صياغة أو أداة تصور. الفوائد التي يمكن أن تأتي إلى المهندسين المعماريين والمصمم الحضري من اعتماد مثل هذه المنهجيات في تعزيز عملية التصميم التعامل مع أزمة الطاقة والموارد العالمية التي نواجهها في الوقت الحاضر.

يستخدم هذا البحث الخوارزميات الجينية كمنهجية التصميم الحسابي لتحقيق تصميم بارامترية لتصميم مدن أكثر استدامة. البحث يدرس جدوى التصميم الحسابي وأحدث خوارزميات و أدوات الكمبيوتر في تحقيق تصميم بارامترية أمثل من أجل تحقيق تصميم حضري أكثر استدامة مثل: (Grasshopper, Radiance, Energy plus ) ANSYS (CFX).

تم تطبيق المنهجية المقترحة علي مثال من واقع الحياة الحضرية لتحقيق في مدى قابلية تطبيق أدوات التصميم البارامترية الأمثل على نطاق المدن وإمكانياتها. تطبيق المنهجيات المقترحة علي مثال من واقع الحياة الحضرية تضعها تحت الاختبار لتقييم قدرتها على التحسينو قدرتها في دقة التنبؤ وانعكاساتها على عمليات التصميم الحضري التقليدية.

ويهدف هذا البحث أيضا التحقيق في مدى انطباق وإندماج هذه المنهجيات المقترحة ضمن منهجيات تصميم المناطق الحضرية التقليدية الحالية بالتحقيق في مدخلات ومورفولوجيس متاحة وشائعة في تصميم المناطق الحضرية التقليدية مما يجعل هذه المنهجيات أقل عبئا على فريق التصميم عند التطبيق.

**Acknowledgment:**

Special thanks and appreciation to my supervisor, Dr. Hanan Taleb for here supportive patience, continuous encouragement and Guidance

Special thanks to my tutor, Prof. Bassam Abu-Hijleh for his useful information, guidance and helpful comments



# Contents

Abstract.....	2
Acknowledgment.....	3
Contents.....	4
<b>1 CHAPTER 1: Introduction.....</b>	<b>6</b>
1.1 General Overview .....	7
1.2 Research Objectives and Aims .....	8
1.3 Research Layout .....	9
<b>2 CHAPTER 2: Literature Review .....</b>	<b>11</b>
2.1 Design Strategies .....	12
2.2 Complexity Theories and Urban Design .....	15
2.2.1 City as Complex System .....	15
2.2.2 Complexity and Urban Design .....	17
2.3 Parametric Design.....	20
2.4 Sustainable Urban Design Elements.....	23
2.4.1 Microclimate and Urban Ventilation.....	23
2.4.2 Solar Radiation .....	31
2.4.3 Urban Morphology and Energy Consumption .....	34
<b>3 CHAPTER 3: Methodology .....</b>	<b>39</b>
3.1 Computer in the Design Process.....	40
3.2 Design Optimization Methods .....	42
3.3 Parametric Design Optimization .....	46
3.3.1 Stochastic Optimization.....	46
3.3.2 Evolutionary Algorithms .....	46
3.3.3 Comparison between GAs and SA .....	57
3.4 Computer Simulation Tools.....	59
3.4.1 Grasshopper and Galapagos GAs.....	60
3.4.2 Diva for Rhino and Grasshopper.....	64
3.4.3 ANSYS CFX .....	65

<b>4</b>	<b>CHAPTER 4: Parametric Design Optimization Experiments .....</b>	<b>67</b>
4.1	Case Study Location .....	68
4.2	Climate and Weather Data .....	71
4.3	Optimization Set up .....	74
4.3.1	Energy and Solar Optimization Experiment Modelling and Setup .....	75
4.3.2	CFD Optimization Experiment Modelling and Setup .....	81
<b>5</b>	<b>CHAPTER 5: Discussion and Analysis.....</b>	<b>87</b>
5.1	Base Case Study Analysis .....	88
5.2	Simulation results and Optimization.....	93
<b>6</b>	<b>CHAPTER 6: Conclusion and Recommendation .....</b>	<b>107</b>
6.1	Conclusions.....	108
6.2	Recommendations and future Studies.....	110
<b>7</b>	<b>REFERENCES.....</b>	<b>111</b>
<b>8</b>	<b>APPENDICES .....</b>	<b>117</b>



## CHAPTER 1: Introduction

## 1.1 General Overview

The conventional architectural and urban design process had always depended on the visual and intuitive analysis of the designer, by visualizing, collecting and analyzing the data around the site location, and the environmental and climatic conditions. All of that intuition in the design process and the total investment budget doomed the final performance of the development. This instinctive design process has led to a poorer urban and architectural performance and put the project under the mercy of the designer expertise and the project budget without achieving the optimal balanced design. The latest sustainable wake-up and the need for performance optimized buildings have put these instinctive design processes under difficult tests which they fail to cope with. With the break-through of sustainability and lack of advancements in the design process, urban and architectural designers stepped aside for the other parties to refine and make their design more sustainable and green.

Parametric and algorithmic design researches gave the light at the end of the tunnel, once again urban and architectural designers gain control over their design process and give them the right tool to produce an original sustainable design that interact with the project environment, climatic and sustainable constraints. The parametric urban design researches showed that parametric design may give a good tool to achieve sustainable and healthy communities by minimum form and high performance spaces particularly in a hot humid climate where outdoor life is absent, high solar radiations and local materials and resources are rare or limited.

The recent years showed a strong trend toward urbanisation and according to 2010 statistics and researches done by United Nations more than half of the globe's population is residing in urban towns and cities, Figure (1.1). Population of the cities and urban towns changed from 729 million in the year 1950 to 3.5 billion in 2010 and the total earth population changed from 2.5 billion to 6.9 billion within the same time duration this growth expected to go on the same. Figure (1.1) shows that within the past decades urbanisation was centred in Europe and United States and this fast urbanisation shifted to Asia due to the changing economic factors and fast expansion.

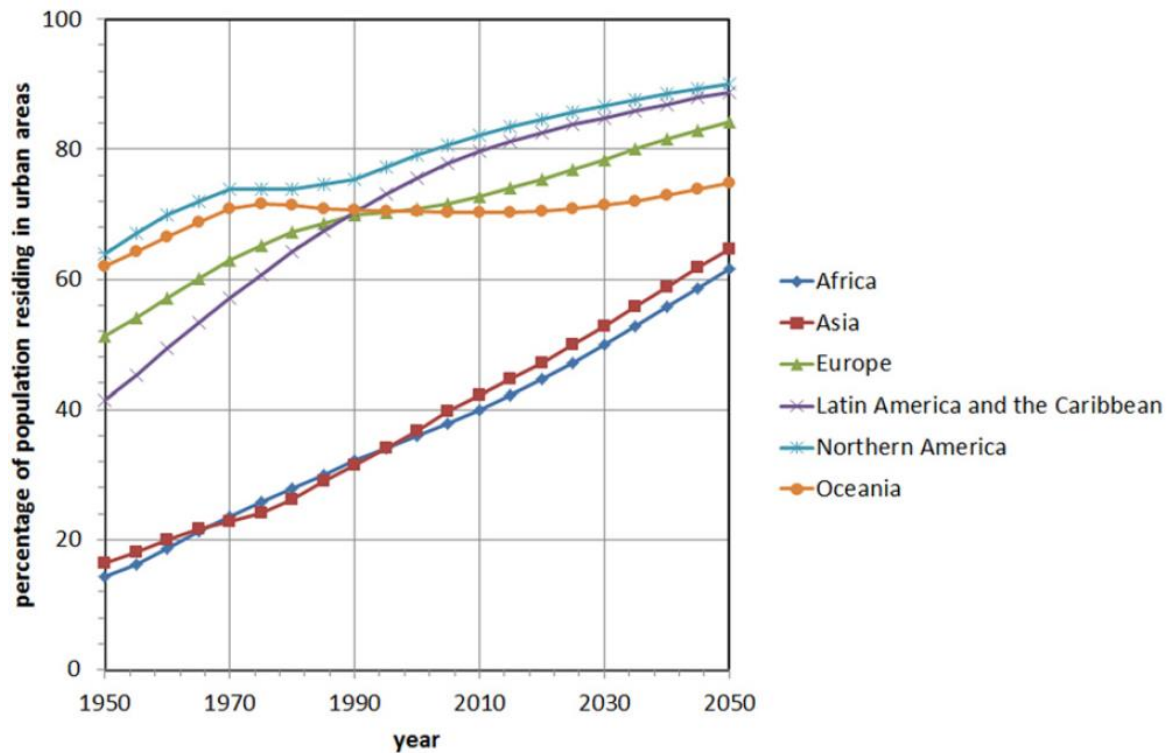


Figure 1.1: Population in urban by continent 1950–2050, United Nations, 2010.

## 1.2 Research Objectives and Aims

The main objectives and aims of this research can be summarized as follows:

- The potentials of parametric design optimizations processes over the conventional urban design processes in a achieving a more sustainable urban design and cities.
- The potentials of Genetic algorithms in achieving optimized parametric urban design to design for sustainability.
- The viability of computational design and the current-state of the-art computer tools in achieving an optimized parametric design like, Grasshopper, Radiance, Energy plus and ANSYS CFX.
- The applicability and integration of the proposed methodologies within the current conventional urban design methodologies by investigating parameters and urban morphologies which are available and common in the conventional urban design which makes these methodologies less burden on the design team when applied.

- The integration of the computer and computational design methodologies in the design process and to give the computer a more active role in the design process and not just a drafting or visualizing tool.
- Investigating the applicability of parametric design optimization tools on urban scale and their potentials.
- Investigating the interaction of parametric design with urban elements and environmental factors like solar irradiation, urban ventilation and building forms and orientation to generate the sustainable urban morphology.

### **1.3 Research Layout**

The research layout starts by the introduction chapter which introduce the main general current problems that are facing the city and urban design process in the quest for achieving a more sustainable cities and urban development's. The following chapters of this dissertation comes together to build a case for the research from literature review to selected methodologies and then the parametric experiments and their results. Then analysis and results chapter follows and finally the conclusion and recommendations chapter.

The general layout of the chapters is as follows:

## **2 CHAPTER 2: Literature Review**

This chapter reviews the body of literature of the most relevant work to this research and influential to the forming of ideas presented in this dissertation. Starting by tracking down the history and advancement in the design process in broad way and narrowing to the specific, design methodologies and the different argument and approaches which were made to tackle the problem, in favour of optimal design solutions.

## **3 CHAPTER 3: Methodology**

In this chapter the research methodology is discussed and a comprehensive review to the literature related to the selected methodology and its application in different case studies. A comparison between the different methodologies is made, finally a brief review of the

computer software and tools which are going to be used in this research. This section starts by looking at the changing role of the computer in the design process, then review to the optimization methods and examples on them and the computer tools for the research.

#### **4 CHAPTER 4: Parametric Design Optimization Experiments**

In this chapter the setup of the parametric design experiment and environmental inputs of the experiment are discussed. The first section is Introduction to the experiment location and its urban morphology and style. Then, the climate characteristics and weather data are analyzed to the experiment study. Modelling and optimization setups for the experiments are the last two sections in this chapter, where the input and output data parameters are discussed in more details which in this case represent the initial steps in building the simulation experiment.

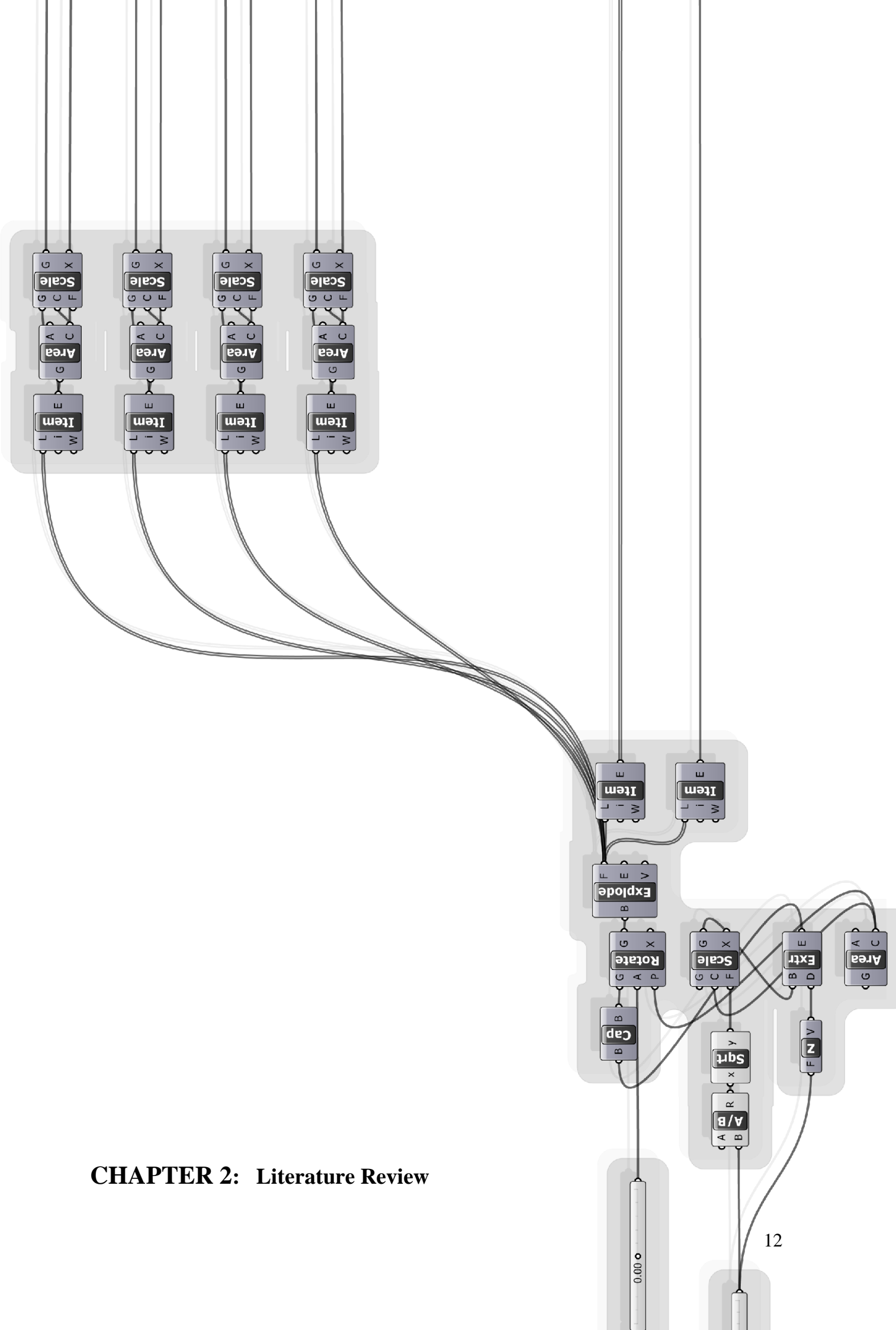
#### **5 CHAPTER 5: Discussion and Analysis**

This chapter is a discussion and analysis of the results of the two experiments of optimization energy/solar and CFD optimization. Based on the base case study and as built, a comparison between all the optimized points and the base case is concluded at the end of each experiment analysis. The first section looks at the base case from the point of view of each experiment and tries to highlight the conflicting factors affecting the optimization process. The second section is a detailed analysis of the optimized point and their generation with comparison with the base case to highlight the amount of optimization.

#### **6 CHAPTER 6: Conclusion and recommendation**

Chapter 6 concludes and complements the research results and findings and the applicability of the used research methodologies in benefiting the urban design process to achieve a more sustainable developments and cities. It also highlights recommendations and future studies to further more research in this domain.

CHAPTER 2: Literature Review





This chapter reviews the body of literature of the most relevant work to this research and influential to the forming of ideas presented in this dissertation. Starting by tracking down the history and advancement in the design process in broad way and narrowing to the specific, design methodologies and the different argument and approaches which were made to tackle the problem, in favour of optimal design solutions. It also reviews the complexity theories and urban design and the researches done in this field. Then design optimization methods as general is reviewed and the advancement in these methods. The use of computer and its roles in the design process is reviewed. Parametric design and parametric design optimization and its methods, application and practice is researched and reviewed. The most common optimization tools and stochastic optimization methods, Evolutionary algorithms and Simulated Annealing, are discussed through the body of literature and comparison is drawn between them. A review to the main sustainable urban design elements which are studied in this research is made and their importance in achieving sustainable urban design.

## **2.1 Design Strategies**

The word design has always been used as the solution to the problem or problems in hand within the satisfaction of the design requirements and needs and in consistent with the limitation or constraints. Constraints may be due to resources limitation or constraints enforced by the location or the entire surrounding environment and its elements. This characterization of design springs from the historically strong relation between science and architecture and clearly formed in the 60s with the Design Methods Movement and the work related to its appearance.

The relation between science and architecture can be traced back to the age of Renaissance, at that age architecture and science were connected together strongly Gomez (1983). In the modern and machine age when architecture was compared to machine and a connection is drawn between the function, design and behaviour of machine to architectural design Banham (1960). Finally, in the 60s the Design Methods movement appeared and many researches done in that field of Design methodologies and design rationalization.

By the end of the war of World War two and in the Sixties many approaches were made to reform the science of design, and to form design methods that depends on technologies from science and science validations. The design Methods Movement was one of the pioneers in this regards and many researchers spot the lights on them. They tried to construct a science for design and design methodologies Cross (2001).

The general feeling among the designers and thinkers of that era is to put design in a science frame, design as a solution to the problems and in the same time to cope with the constraints. Putting Design in that frame lead to divide the design problem to its partial parts and to be studied and approached as any scientific method by identifying its parts and the ingredients which form the whole scientific problem. These parts become known later on as input variables, output variables, parametric modelling, design optimization, constraints and optimization tools and algorithms. The Design Methods Movement had two schools of thoughts and passed into phases of followers and censures.

One of the pioneers of this movement is Christopher Alexander. Alexander designed an approach to solve the design problem using the computer and schematic diagrams. These diagrams consists of the partial parts of the problem and how these parts are interrelate with each other and this system leads to groups that connected directly to each other and form one entity. Then, the problems within the entities and the others are solved. Christopher made some advancements and improvement in these diagrams and then became what we now know them as The Atoms of Environmental Structure. The designers used these diagrams to solve the problems such as related to people behaviours and how they used the building or the design. So, the role of the designer is based on the physical situation and reality and does not spring from his judgment or the way he feels the design should be Broadbent (1981).

Many disapprovals and points were taken on these design methods and been described as none-human, uninteresting, systematic and kill the creativity in the designer or the design itself. These points put force on the people who pioneered these techniques and made them abandon their school of thoughts, like Christopher Alexander and John Christopher. The parties who believed in the design as a feeling in the designer and the design has human nature argued these points which led the abandon of that school of thoughts Broadbent (1981).

Due to the arguments raised against the first school of thoughts on design methods another school born with different ideas and application on the design methods. While this one was based on design optimization and the mechanical principle of thoughts to reach to the suitable design solutions, the other was built on design solution satisfactory and the participation of all the parties in the design process to reach a good solution to the problem of design. These parties form the users of the building, the owners, the investors and any part of the community that interact with the concerned design problem and solution Cross (1993).

The idea of professional designers who know how to design for the users had become none-realistic and there is no such designer. They now just became professional in the materials and their physics just enough to build the design form in consistent with the requirements and needs of the other parties like the building users, owners and the investors, as commented by Broadbent (1981) to describe this school of thoughts.

All the early schools of thought during the sixties were meant to make the design as bias as possible from the opinion of the designer and his imagination to the problem and its solution. If the study of the problem inputs and constraints and their analysis lead the design to a solution, then this is the right solution to the problem and away from any designer speculation or his design sensation. In the 70s the case has changed and the design was not only the resultant of the analysis, but also the inputs of the users' opinions and their needs and the designer has only to optimize that as a system Lawson (1972).

The period which followed that was either an oscillation between the two schools of thoughts or in some cases the designers combined their principles in order to form the design solutions. That era had many differences between the reason of the design and the intuition of the designer and how each can be applied to the design problem or to design solutions to the problem, big distance existed between the two parties.

Nowadays the belief that there is a system or a set of rules that can be applied to the design problem and could lead to the optimal design solution does not exist. So, the look at design methodologies nowadays as they are a part of vey vast methods that can be applied to the design solution, no such thing as appropriate method or a good method since it I based on reason or intuition of the designer. Some designers even went to use the design method of

randomness to come up with the design solution Cross (1999). The current state does not mean that these methods from the first school of thoughts or the second has been lost or been over looked by the current designers, rather than that the common sense is that these methods are a part of many other methods that can be adopted to the design problem.

## **2.2 Complexity Theories and Urban Design**

Complexity Theories has always been a specialized branch of science pioneered in the first place by physicists and mathematicians. Those scientist studied complexity and its application on physics, particles and chaos systems in order to understand or predict the behaviour of these systems, their growth, equilibrium and dynamics using mathematics. Nowadays Complexity theories are applied to cities and urban design, and not only physicists or mathematicians are invited to the study, but also city planners, urban designers and geographers.

### **2.2.1 City as Complex System**

From the first look at cities it is obvious that the city is consisting of systems and sub-systems and sub...sub-systems. These systems can be transportation, housing, commercials, educational, garbage or infrastructures. If we take a look at the transportation system we can see sub-systems under it like road networks, metro and even pedestrians or bicycles. The city systems and sub-systems and their sub all interact between each others on the micro and macro level and they depend or built on each others, housing system uses transportation system to reach commercial or educational system and so on. Other systems are political systems, business systems, human systems and environmental systems and others which interact with the other systems and their subs. These systems have fuzzy boundaries and it is very difficult to draw the boarders on the micro or macro levels. From these interactions, existing systems or sub-system could vanish and new systems come to existence and problems may come from the unpredictable relations between them. These systems and their subs are the real designer, manager and planner for the city and its dynamical growth and evolution, and as questioned by Jeffrey (2012), who could predict these systems, who could grasp these complex systems and who could forecast the future in order to design for these systems.

When we realize that complexity is one of the main ingredients that form the city and its sub-systems, three dominant results walk hand in hand with complexity. Firstly, it is impossible to know and understand the system as it is, same like the organs of the natural living things and their parts it unknown how they come to existing the way they are and the form they took in respect to each others. Secondly, it is also impossible to predict or grasp the results of intervention or interference with the complex system and what this will have results on the direction the system is taking or will be taking in the future. So, adding sub-system, modifying elements or interfering in any layer of the system could have unpredictable results. Thirdly, as we saw it is impossible to predict for the complex system its optimal future conditions, since all the systems and sub-systems are co-evolving Stephen (2012).

There are many examples from the history of urban planning and urban regulations that gives exactly the results and behaviour which would be expected in a complex system and the unpredictability of the results when designing to that system. One example by Juval (2012) is the Butterfly Effect of Tel Aviv balconies. Balconies in Tel Aviv has been used commonly for the ordinary daily habits and they were very common the architectural style. Roughly in 1950s one of the residents of Tel Aviv decided to close his open balcony and makes it half-room; neighbours liked the idea and did the same to their balcony and this started a Butterfly Effect that made the whole country balconies to be closed. At this point the municipality wanted to interfere and started to tax on these half-rooms. At this point investors and builders started to build buildings with closed balconies. Then the postmodern architecture with its balcony styles arrived and the designers of that era started to ask for approval on open balconies. So city planners granted the approval on open balconies, but in a way that can't be closed which led to the Jumping balconies which are very common nowadays in Israel.

The story of the jumping balconies not only shows us how the neighbourhood or the city and its systems or sub-systems is a very complicated and unpredictable complex system, but also that the single person of the city has much power of effect on the urban design, architectural design and city panning than the real designer himself. Another conclusion can be derived from this example, that the sub-systems at all the levels the micro or macro of the city are self-organised and the urban planning is the outer force on these systems. These conclusions and other enforce on us to shift our understanding of urban planning

and architecture in the future or the way the planning codes are made and applied to any city or neighbourhood.

Some look at the complexity of the city as benefit rather than unpredictability or a difficult thing to design or interfere in. Stephen (2012) thinks that city complexity gives us benefits over simplicity. Perceptual richness comes from the complexity of the city and its roads, main streets, alleys and its complex forms and it can be perceived as beauty and makes the idea of basophilic design. Another benefit is its functional capacity; this functional capacity comes from the diversity of the organs of complex system over the simple one and their specialized function, a street with different routes and parts can handle the requirements of a neighbourhood and its function better than just a simple street with simple routes. Other benefits come from its synergy, the synergy that may come from the addition of its specialized functions of its parts which may add up to greater result than the sum of these parts. The modern planning developments have always ignored these benefits of complexity and the consequences were less optimal systems, although it is designed to be optimal.

### **2.2.2 Complexity and Urban design**

When applying complexity theory to urban planning new important perspectives added to the theory of urban planning and the way urban planning could evolve in the future. These important perspectives include self-organizing systems, non-linear systems, social transition systems and others. With these new perspectives we could have the right tools of understanding how we can design and intervene and what is possible and impossible to manage or control by urban planning. So it is important for the planners to analyze the urban areas in context with these new complexity perspectives and which of them has the potentiality of success and to which trends they are going to be attracted. The non-linearity, transformation, uncertainty and evolution aspects which are governing principles of urban planning at the level of macro systems or locally within the micro systems indicate that the design of urban planning is not controlled by the blueprints manipulations or controlling a change in the whole system. So connecting these variables of non-linearity, social transition, evolving processes and the other aspects of complexity theory has promising future on spatial planning as argued by Gert et al (2012).

Many interpretations or modelling ideas were suggested to mimic or simulate the process of urban planning and the consequences or resultant of each process and how each process can lead to different urban configuration, in order to understand urban design in the context of complexity. One modelling case is particularly relevant to this research and the ideas that are discussed here; this case is the Urbanism as Computation proposed by Nikos A. Salingaros.

Nikos (2012) proposed computational approaches that depict the urban design processes and how the resultant configuration of urban elements behaves according to the selected approaches. He suggested four different classifications for the urban configuration, Interactive computations, None-interactive computations, Random and None-computational.

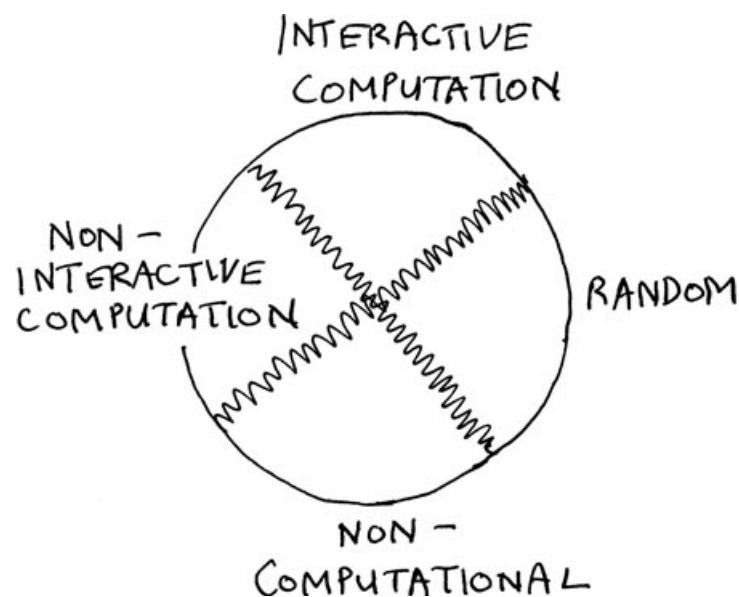


Figure 2.1: Four different classifications for the urban configuration. From (Nikos, 2012).

The interactive computations resemble the urban configurations that come from the active computations and which has loop of feedback that generate an adaptive urban configurations dictated by the attraction factors of environmental conditions of the system and the requirements of the human needs. Nikos believes that the traditional urban design configurations before the age of industry fall under this computations.

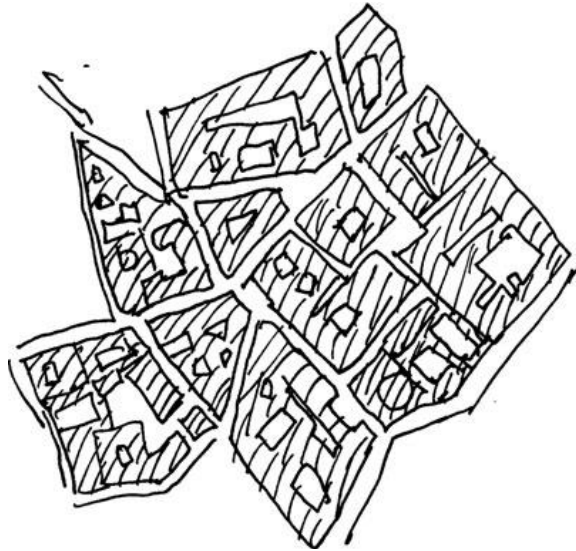


Figure 2.2: Traditional urban fabric, interactive computation. From (Nikos, 2012).

The none-interactive computations use predefined algorithms and no feedback happens during the computations and no adaptations for the partial parts that are being computed, so there is no progressing adaptation happening in the system.

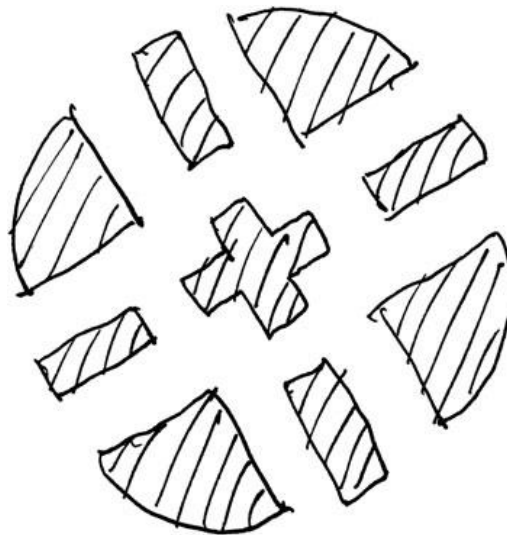


Figure 2.3: none-interactive, organized but irrelevant geometry. From (Nikos, 2012).

The random configuration in Nikos opinion may be the result of computations, but this category is irrelevant to urban adaptation which is the real fabric in the city.



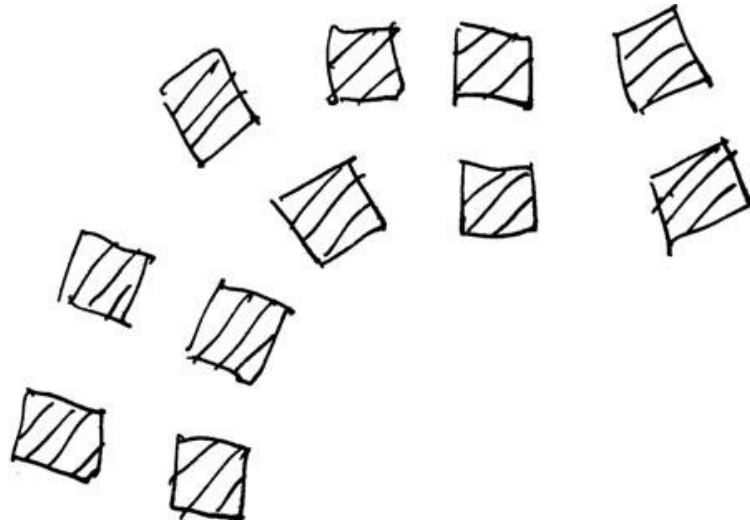


Figure 2.4: Buildings distributed along a randomly applied curve. From (Nikos, 2012).

He explains the non-computational configuration as the resultant of a constant output of a function or algorithms to any input with the same results. The morphologies that result from the none-computational forms are very simple and may not include any computations at all. These constant results of the none-computational category resemble the international urban style, industrial areas, warehouses and the very functional buildings or urban design like the military camps. The idea behind these computations and classification of urban fabric was to give a model that can be used to study the effectiveness of an urban fabric taking into consideration complexity theory and computations provided the means which allow the process of this analysis and formation.

### 2.3 Parametric Design

The parametric design method can be defined straight forward as a way of generating diverse forms and design configurations by changing the input parameters of that design model. Although this simple definition looks easy and straight forward, but parametric design can also be as complex and complicated depending on the parameters under study or the interactions of these parameters with the respect to the final form generated within the constraints. These constraints may be imposed on the design by the designer himself to study a specific range of cases, or constraints related to the environmental forces, factors and physics. The complexity of the parametric design does not stop here, the input parameters may extend to these constraints. The interaction of these parameters and the

way they are translated to form the form could be simple by altering the main dimensions of the main or sub elements in the design or they form an input to algorithms which then translated to the final form of the design Monedero (2000).

A good example of using the straight forward parametric design is the parameters of a circle or the bitmap-driven parametric façade. Where the inputs of a gray scaled gradient image control the dimensions of the openings in the Façade in a given criteria to achieve better lighting or views, Figure 2.1, Steffen (2008). The difference in the colours of each pixel of the image (right), controls the dimensions of the openings (left). So the generation is done automatically by the software and the designer may control the percentage of the effect.

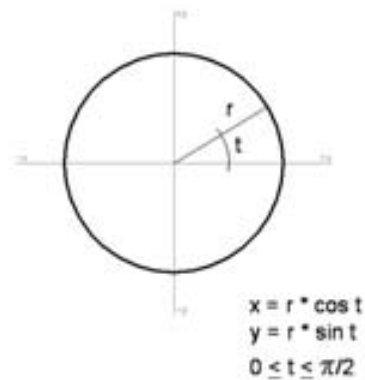


Figure 2.5: Parametric Definition of a circle. From Branko (2009).

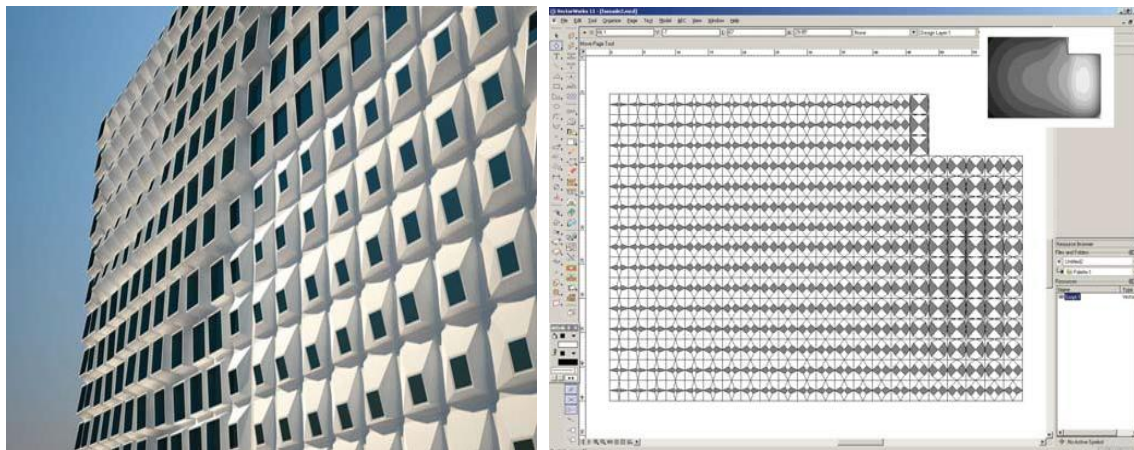


Figure 2.6: bitmap-driven parametric façade. From Steffen et al (2008).

Another good example of parametric design where not only the parameters is the dimensions or locations of these openings, but also the constraints of the environment like rain recycling, daylight, ventilation and the structural stress for the Clyde Lane House roof,

Dublin, Alan (2008). When comparing this example with previous one obvious difference appear, in the first direct translation of the image input to dimensions of fixed locations of openings, while in this example the locations and distribution of the openings is controlled by the constraints of the environment and the element physics become input parameters besides the other dimensions and the design is performance driven design in total.

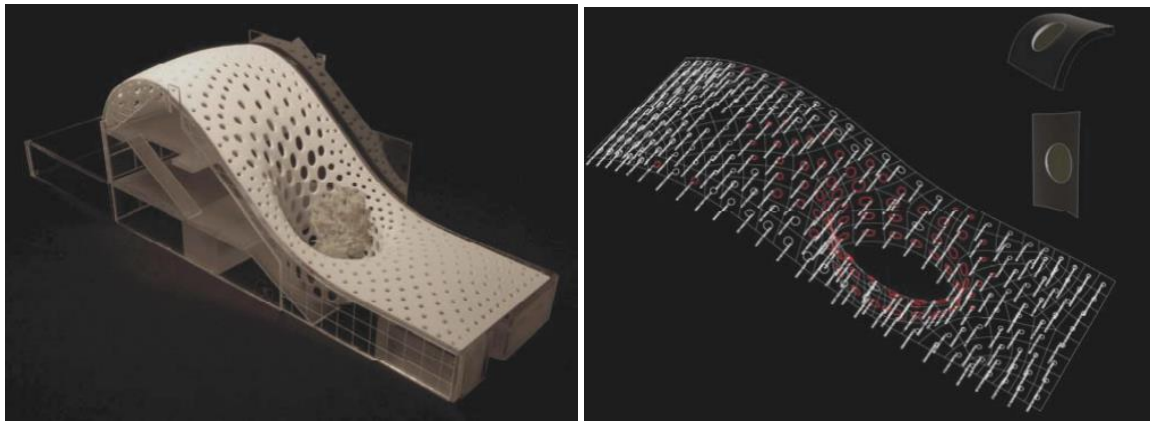


Figure 2.7: Clyde Lane House roof, Dublin. From Alan (2008).

Parametric design can be classified depending on the generation method of the model. Monedero (2000) described two ways: variation method and history based method. In the variation method the design configuration is predefined and the constraints are defined by algorithms and the whole model is then generated once according to these algorithms. While the history based method, as the name indicates, the generation of the design configuration is done as a series of steps that transform the shape to its final configuration. The main difference between them is that history based method generate the model by a sequence of operations and it track that progression, while variation method does not.

The parametric method for design generation and iteration has very good advantages by the power of controllability over the design by the designer and the generation tools. Another good advantage is the manufacturability of the final configuration, its parts and elements. Some drawbacks highlighted by researchers that parametric design does not give many diversity and variety to the design configuration, although this limitation can be realized as a limitation in the designer analysis to the problem and its constraints, or a limitation in considering all the possible space of domain when we studied the problem under modelling or generation.

## 2.4 Sustainable Urban Design Elements

In this section a brief review to the main urban element, constraints and physics which will be studied as parameters in the optimization and the reason for choosing them and their important effect on achieving sustainable urban design. All these elements and parameters suggest the holistic approach when we design for a sustainable urban. The sustainability of the building is depending on the sustainability of the street, and in the same the sustainability of the street is depending on the sustainability of the neighbourhood which also its sustainability interacts and can only be successful if the whole urban fabric is sustainable.

### 2.4.1 Microclimate and Urban Ventilation

The urban atmosphere is divided into layers depending on the energy and mass exchange in each layer which form the climatic conditions of the city. The layer from ground level to around 1000m is the urban boundary level. The urban boundary has another layer underneath it, an Urban Canopy layer (UCL), (Isaac, 2009), Figure (2.8). The urban canopy layer is typically considered at the mean roof height of the buildings in the city. Because of the characteristics of the urban fabric, taller buildings and higher volume the UCL has higher temperature and the air fields are weaker and more turbulent than the upper layer as described by (Edward, 2010).

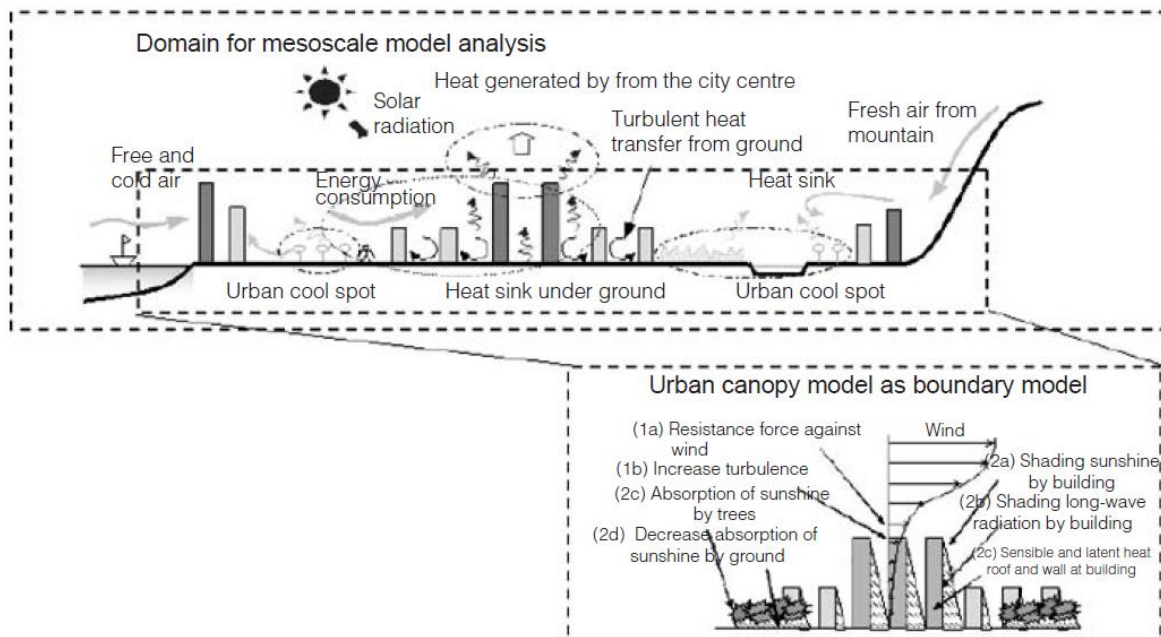


Figure 2.8: Urban canopy and urban boundary layers, From (Isaac, 2009).

Many previous studies, mostly done by engineers and civil designers, on the pedestrian wind and air flow around the buildings in the urban context were focused on the effect of strong wind on the pedestrians. These studies particularly were made on sites with high windy conditions and tall buildings (Bloeken et al, 2004). They concentrated on their study on the effect of building and urban configuration that induce and channel the wind flow to the pedestrian level which amplify it and can cause serious effect in terms of physical force; however this was not the case for studies on pollution dispersion which studied the effect of weak wind flow and the urban comfort at street levels.

In the recent studies, the effect of weak wind flow in the dense urban canopy and the benefits of a good ventilated urban design have been studied extensively. (Edward, 2010) highlighted the benefits and impotence of urban ventilation on health and human comfort within the city and open spaces. The indoor passive ventilation of buildings depends drastically on the availability and strength of air flow in the urban canopy which in term affect the energy consumption of buildings and their passive design. Another benefits come from the ability of good air flow and better urban ventilation to disperse pollution and pollutant particles which come either from cars and combustion operation or it may be natural like sandy and dusty weathers. These particles and pollutants not only affect the health of the human being, but also have strong effect on the urban heat island, acidic rain and visibility (Rajagopalan, 2009). The urban thermal comfort is another invaluable benefit of good urban ventilation. The outdoor thermal comfort is dictated by the following physical factors: air temperature, air speed, relative humidity, type human activity, clothing ratio and solar radiation (Littlefair, 2000), Figure (2.9).

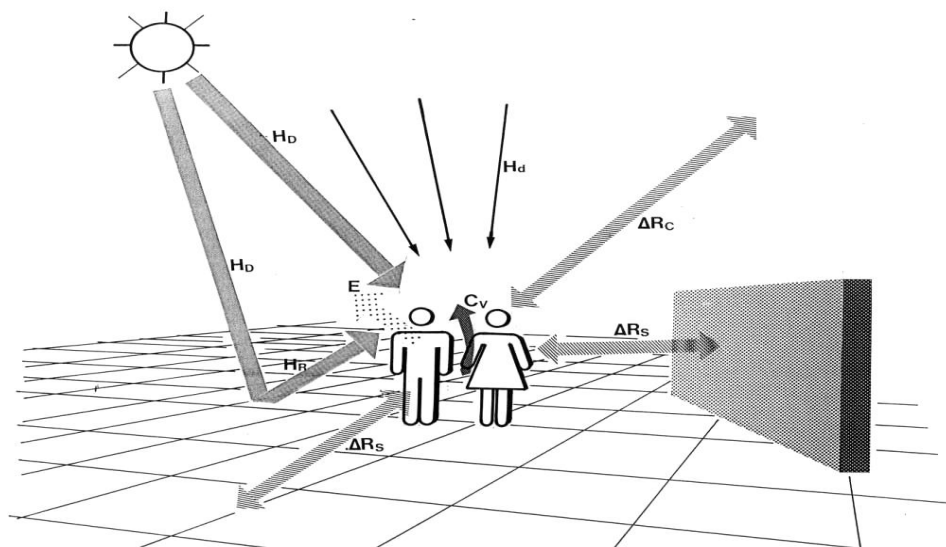


Figure 2.9: Outdoor thermal comfort factors, From (Littlefair, 2000).

Comfort in hot tropical cities may be achieved by designing for high wind speed if the pedestrian is partially shaded, in the same a lower wind speed is required if the ambient air temperature is lower Figure (2.10). If the pedestrian is shaded a stable average wind speed of 1.5m/s is preferable to give thermal comfort in the case study from the chart. Another indirect important beneficial that come from achieving better urban ventilation, besides healthy life people tend to stay indoor most of their time which and use air conditioning systems which increase energy consumptions.

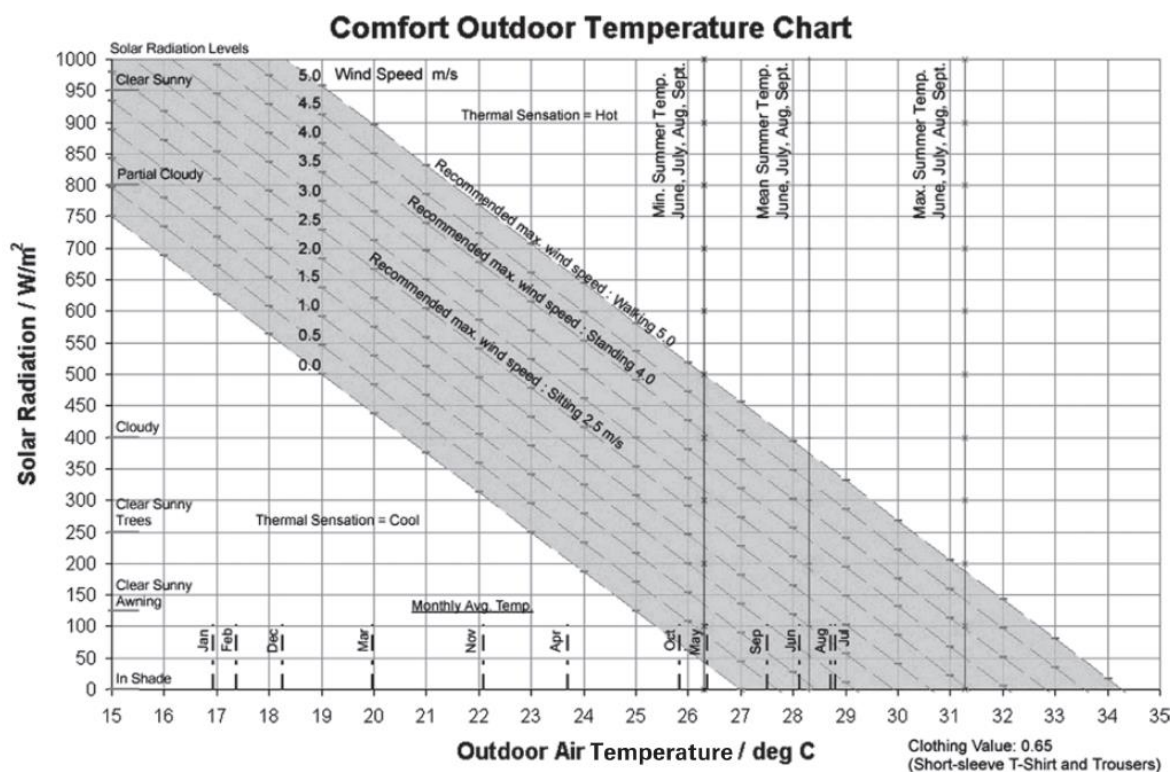


Figure 2.10: Comfort outdoor chart based on survey, tropical cities, From (Edward, 2010).

Evaporative cooling from the human body and plants are greatly affected by wind speed at the pedestrian level Figure (2.11). The amount of 0.68Wh of heat is removed with every gram of water that evaporates from the human body or plants and surroundings. In the human body there are two types of physiological cooling: continuous cooling due to evaporation in the lung and cooling from the evaporation of sweat over the body skin. The cooling in the lung is proportional to activity and metabolic rate and the breathing rate to provide more oxygen into the blood (Baruch, 2010).



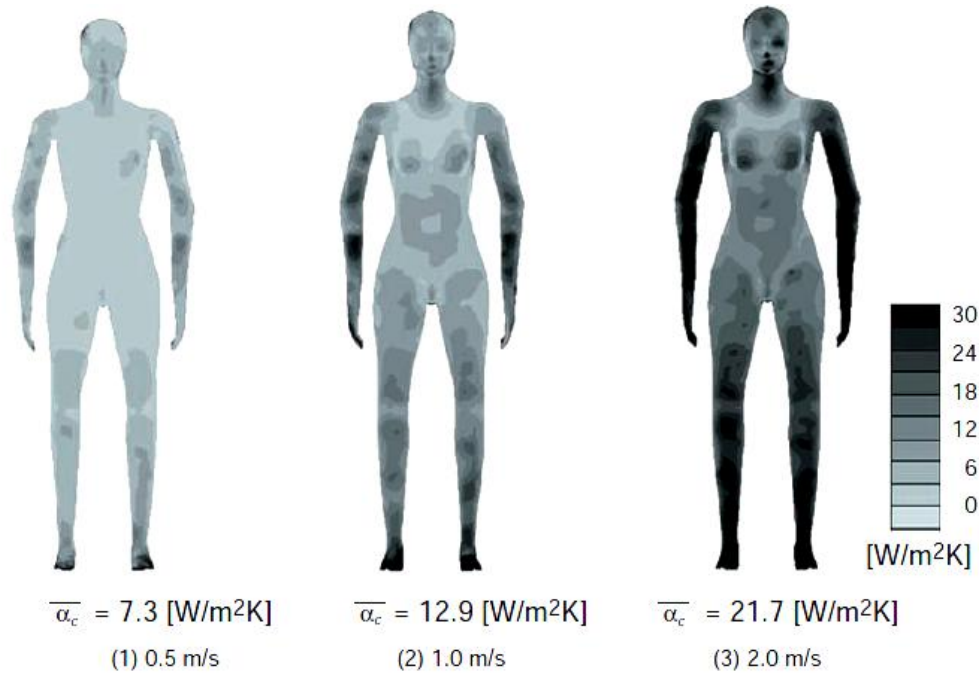


Figure 2.11: Convective heat transfer coefficients on human body surface under various wind speed conditions, From (Isaac, 2009).

Another study conducted on outdoor thermal response and comfort in four different universities: Chinese University of Hong Kong, China, City University of Hong Kong, China, National University of Singapore and King Mongkut University of Technology in Bangkok, Thailand. Figure (2.11) shows the four experiments setting with different types of exposures: setting 1, sun umbrella, exposed to wind, in setting 2, behind a vertical windbreak made of transparent polyethylene, which greatly reduced the wind speed, in setting 3, under a sun umbrella and behind a windbreak, in setting 4, under direct sun and exposed to the wind (Baruch, 2010).



Figure 2.12: The four experiment settings, From (Baruch, 2010).

Figure (2.12) shows the result of the study in respect to wind speed conditions and their effect on thermal response of the subject in the experiment. Average wind speed on the subject with the windbreak 0.3m/s while without the windbreak 1m/s.

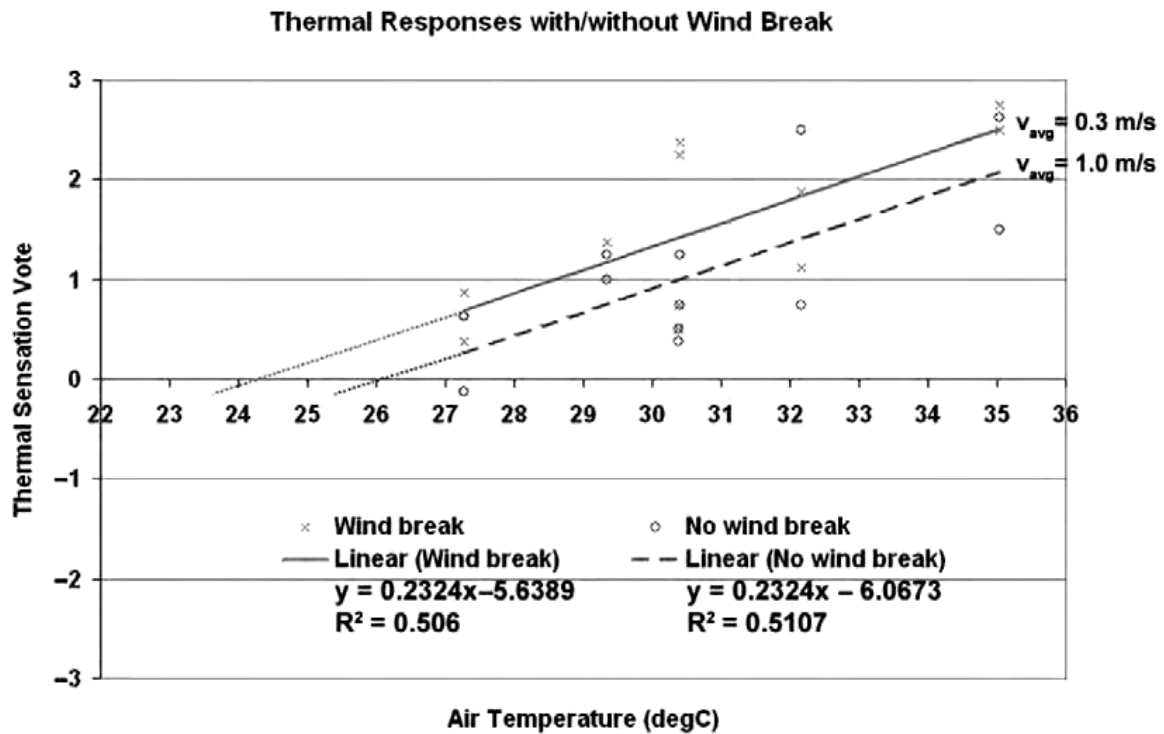


Figure 2.13: Effect of wind conditions on thermal responses, From (Baruch, 2010).

The difference in the average thermal response between using a windbreak and without windbreak was 0.43 unit which means that the increase in wind speed from 0.3m/s to 1m/s resulted in difference in the ambient air temperature around 1.9C drop without windbreak.

One of the main effects of urbanization and dense cities is the increase of roughness of the urban surface within the urban canopy and apply a drag on the pedestrian level and building level winds. So, the on the long term with the increasing urbanization wind speed on the building level is decreasing. Lam (2010) discussed this urbanization phenomena, Figure (2.13) shows wind speed at King's Park and Waglan Island from 1968 to 2005.

Waglan Island is an offshore and there is no effect on wind speed from urban surroundings and the reading show the natural fluctuation in wind, in the other hand King's Park which is surrounded by urban buildings reflects a steady decrease in the wind speed.



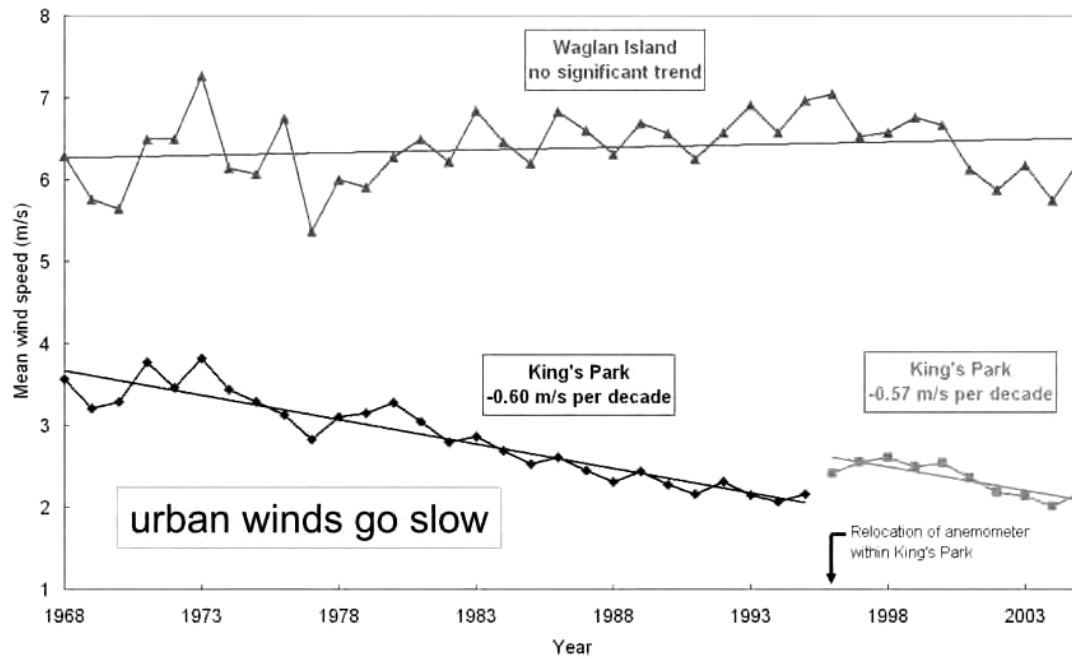


Figure 2.14: Annual average of mean wind speed of King's Park and Waglan Island (1968–2005), From (Lam, 2010)

Designing an urban design with better urban ventilation especially in hot summer and dense cities is very critical matter for urban designers. The city morphology and its design is very important to achieve urban ventilation, since it is impossible for the building architect to generate wind in the local building own site Edward (2010) Figure (2.14).

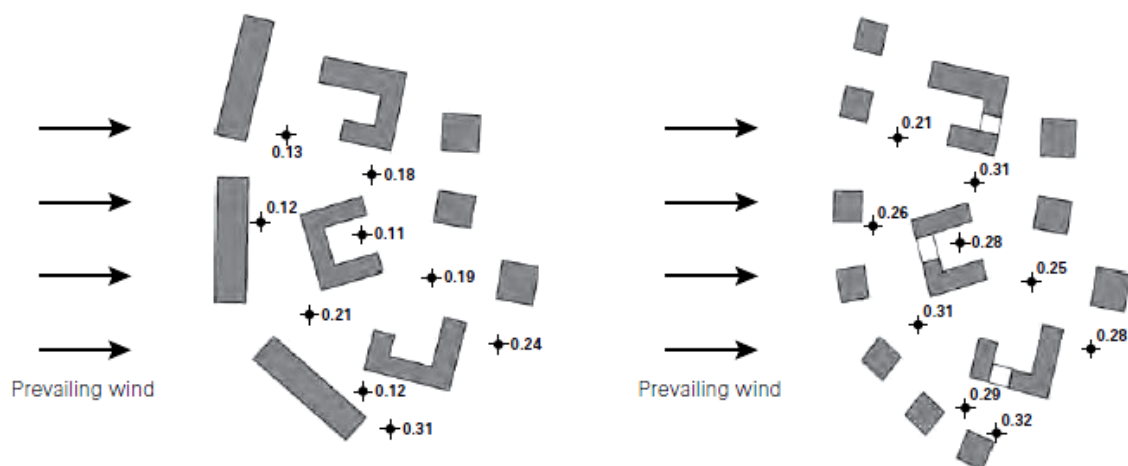


Figure 2.15: Urban morphologies and effect on wind speed, From (Edward, 2010).

Edward (2010) highlighted five important parameters to building and urban morphologies and characteristics that affect urban ventilation and wind speed at pedestrian and building level. These parameters are: air paths, deep street canyons, street orientations, ground cover ratio and differences in building heights.

Figure (2.15) shows the relation between buildings and air paths, dense cities with tall buildings impose on the urban designers to design the streets without enough width for the air to flow to the ground levels from top. The minimum building height to street width ratio must be less than 0.7 which means that the width of the street must be greater than the building height.

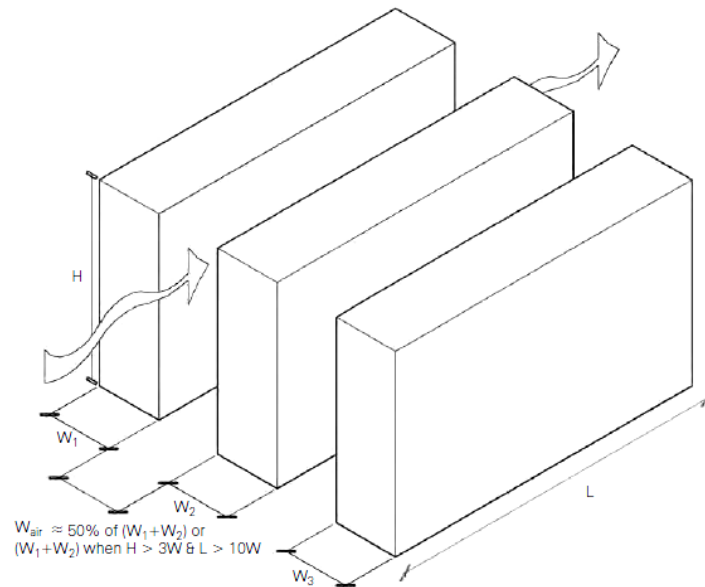


Figure 2.16: Air paths and buildings geometry, From (Edward, 2010).

Street canyons width and height can affect on the depth that the air circulation and vortex can reach in the urban areas of the dense cities. Most recommendation for a ratio of 2 and less between the height and width and other recommendation can be found in Figure (2.16), (Edward, 2010). From the combination of the street canyons and air path it is obvious that the orientation of the streets in according to the prevailing winds in summer is a crucial thing to promote urban ventilation. When considering the actual physical phenomena of air flow and its dynamics the street orientation also has to take in consideration topography and solar access.

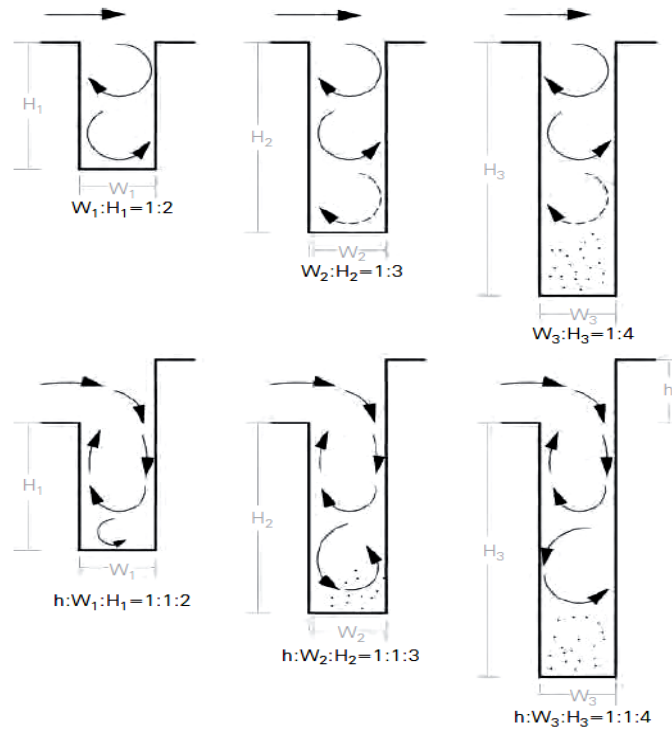


Figure 2.17: Various street canyons and air circulation vortices, From (Edward, 2010).

The difference in building heights of the city has very important aspects on the ventilation of the general urban configuration, this means that a city with the same volume but has variety in the building heights perform better than a city with less buildings height contrast Figure (2.17). These differences in heights allow the tall building to catch the wind and thrust it down to the street levels and this downwash of wind does not happen only on the facades that faces the wind but also on the back facades with wind vortex. The positive and negative pressures from the differences of the building heights induce wind movement parallel to the facades.

Height contrast	Height difference Max:Min	Air changes per hour
0	4:4	10.5
3	3:6	10.8
4	3:7	11.9
6	2:8	13.8
7	2:9	11.2
8	1:9	13.3
10	1:11	13.4
10	0:10	17.9
14	0:14	17.0

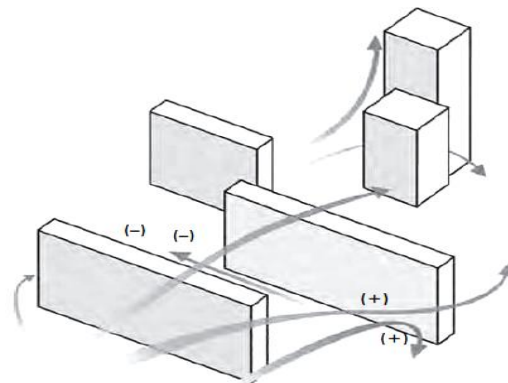


Figure 2.18: (left) buildings height and air change, (right) better building heights, From (Edward, 2010).

## 2.4.2 Solar Radiation

The sun radiation is the main energy source for all the thermal and physical phenomena that happen in the urban context Figure (2.19). The solar radiations reaching earth heat the urban boundary layer, urban canopy and the building within the urban context. The solar radiation is absorbed by the ground, buildings and other parts of the city. Some fractal of the rays are reflected back to sky or to other buildings or absorbed by the air as latent. This phenomenon is so complex and many create many other physical phenomena.

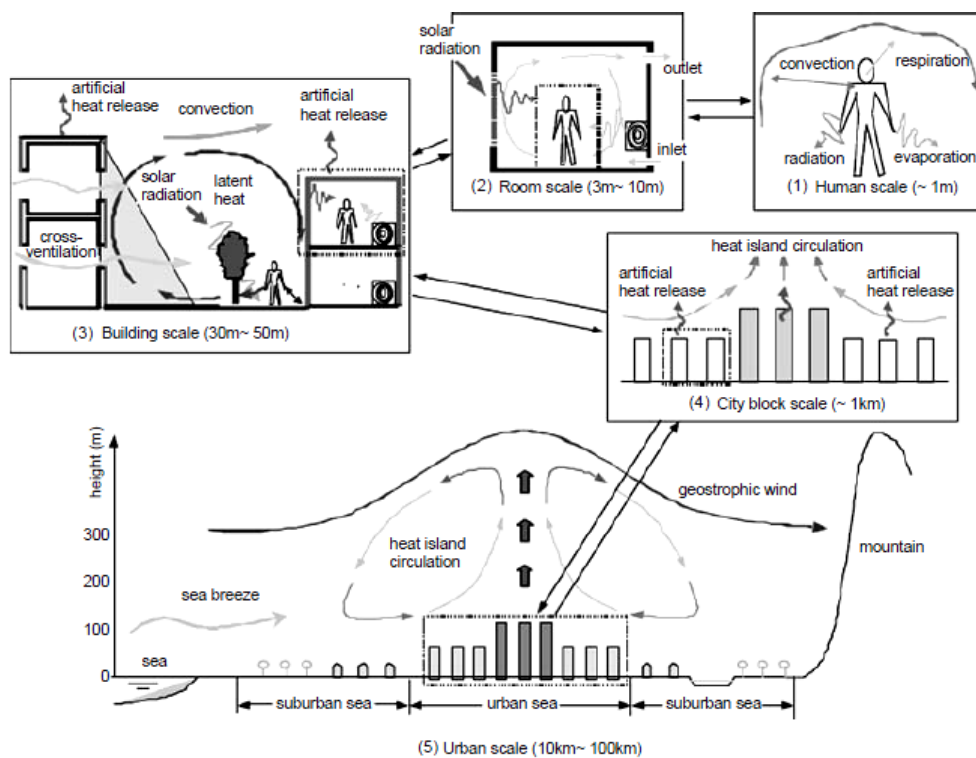


Figure 2.19: Various scales of phenomena within urban climate, From (Isaac, 2009).

In hot climate the amount of solar radiation on building façade have direct and great implication on the heat gain in buildings and energy consumption for indoor cooling. Many recent studies on the benefits of dense cities and their morphology have been done in term of solar insolation and mutual interaction. In the dense hot cities mutual shading is very important for the thermal behaviour of the street canyons and the spaces adjacent to it. Mutual shading can be achieved by the proper street canyon orientation and urban morphologies of building proper harmony of heights and size. With the good urban design morphology shaded areas in the streets and mutual shading between buildings can be achieve most of the time especially in hot summer (Littlefair, 2000), Figure (2.20).

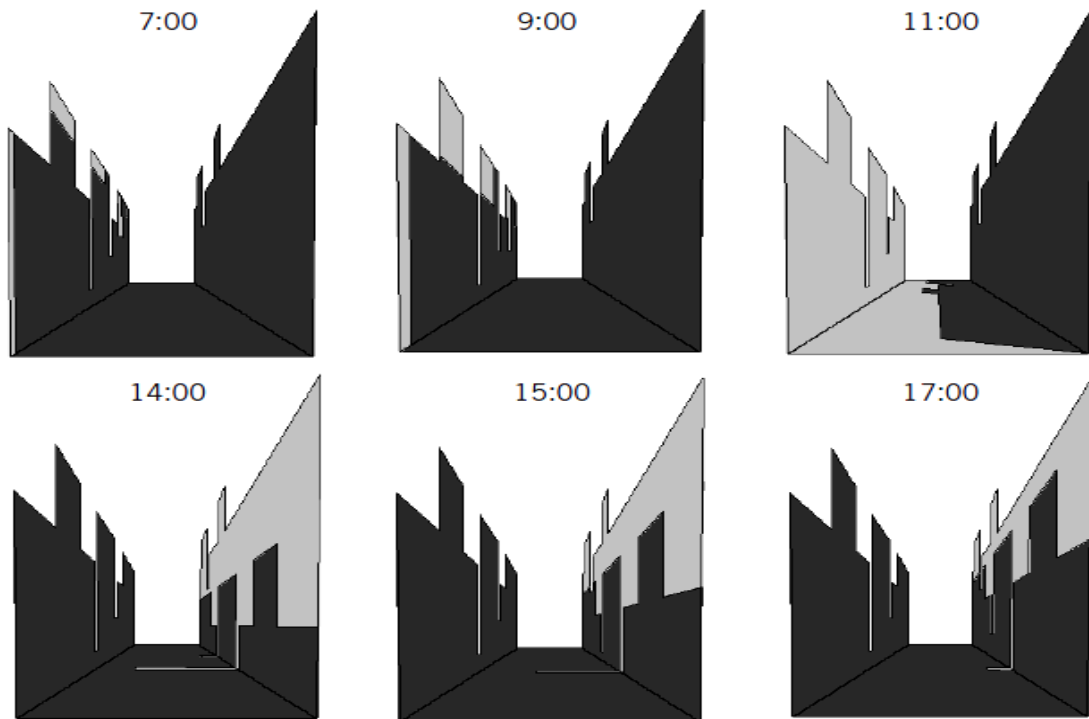


Figure 2.20: Mutual shading in a street canyon, From (Littlefair, 2000).

Although high dense city indicates good mutual shadings and good thermal behaviour, but the reflected radiations on the façades plays a conflicting factor to this configuration. Anderson et al (2011) studied the effect of the dense and close buildings on the total energy consumptions. In the results of the study energy consumption increase by decreasing the distances between buildings and this is due to the reflectivity of the façades which reflect light and heat to the adjacent buildings Figure (2.21).

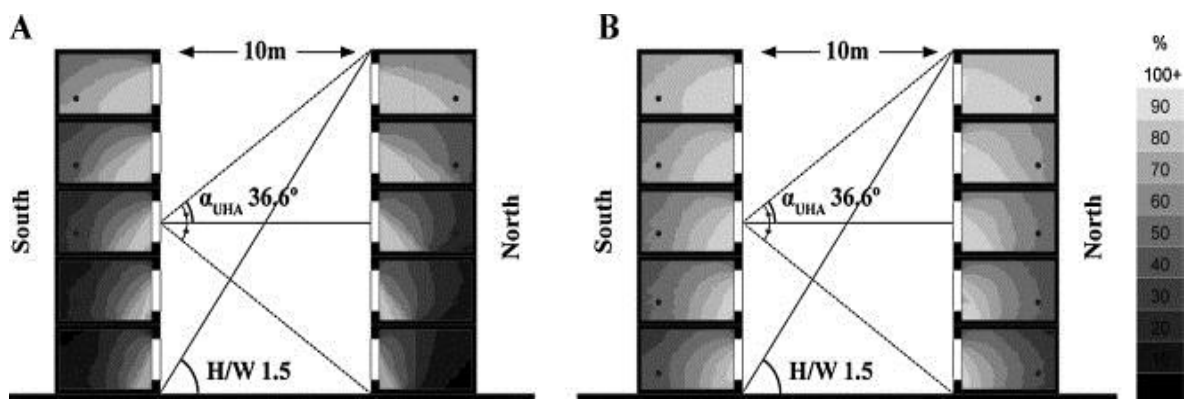


Figure 2.21: Reflectivity of the façades in a street canyon, From (Anderson et al, 2011).

Another study conducted by Maizia et al (2009) on the energy consumption for heating of a four type of urban morphologies: dissentious housing, continuous housing, dense individual housing and dispersed individual housing Figure (2.22). The study looked at the best urban morphology and the potential for solar gains in order to reduce energy consumptions. The result of the study concluded that dispersed individual housing type has received the most solar gain than the other types.

















	HABITAT COLLECTIF DISCONTINU					HABITAT COLLECTIF CONTINU (Ilot)							HABITAT INDIVIDUEL DENSE			HABITAT INDIVIDUEL EPARS		
TYPE URBAIN	6.1	6.3	6.5	6.2	6.4	4.4	5.3	5.1	4.3	5.2	4.2	5.4	2.4	4.1	2.3	1.1	2.2	2.1
DESCRIPTION	Habitat collectif discontinu à Cergy ville nouvelle	Habitat collectif discontinu à Suresnes	Habitat collectif discontinu à Beauregard (Poissy)	Habitat collectif discontinu à Cergy ville nouvelle	Habitat collectif discontinu à Le Chesnay	Habitat collectif continu bas à Poissy	Habitat collectif continu bas à Mantes-la-Jolie	Habitat collectif continu haut à Levallois	Habitat collectif continu bas à Le Vésinet	Habitat collectif continu haut à Boulogne-Billancourt	Habitat collectif continu bas à Paris, Porte de Champerret	Habitat collectif continu bas à Paris, Porte de Champerret	Habitat individuel continu bas à Cergy ville nouvelle	Habitat individuel continu bas à Cergy ville nouvelle	Habitat individuel continu bas à Cergy ville nouvelle	Habitat individuel continu bas à Cergy ville nouvelle	Habitat individuel continu bas à Cergy ville nouvelle	Habitat individuel continu bas à Cergy ville nouvelle
IND./COL.	COL	COL	COL	COL	COL	COL	COL	COL	COL	COL	COL	COL	IND	IND	IND	IND	IND	IND
PLAN MASSE																		
Date de construction	de 1949 à 1967	de 1915 à 1948	de 1968 à 1974	de 1975 à 1981	de 1975 à 1981	av. 1914	de 1949 à 1967	av. 1914	de 1915 à 1948	de 1915 à 1948	de 1915 à 1948	de 1915 à 1948	de 1968 à 1974	de 1975 à 1981	de 1975 à 1981	de 1915 à 1948	de 1968 à 1974	de 1968 à 1974
U bat W/m <sup>2</sup> /°C	2.356	2.188	2.01	2.25	2.25	2.088	2.356	2.088	2.188	2.188	2.188	2.188	1.789	1.475	1.075	2.04	1.789	1.789
Besoins chauds kWh/m <sup>2</sup> /SHON.an	76.76	73.61	67.99	55.23	51.59	102.31	80.12	86.29	85.75	75.86	75.65	69.39	120.46	59.23	52.07	128.35	139.43	98.66
CLASSEMENT	10	7	5	3	1	15	13	12	11	9	8	6	16	4	2	17	18	14
Besoins froids kWh/m <sup>2</sup> /SHON.an	16.37	23.22	30.34	20.34	22.4	17.97	18.28	18.12	21.96	25.85	21.35	32.53	14.79	23.58	33.8	18.59	17.42	16.48
CLASSEMENT	2	13	16	9	12	5	7	6	11	15	10	17	1	14	18	8	4	3
Apports solaires kWh/m <sup>2</sup> /SHON.an	69.52	98.18	134.78	88.23	80.67	89.25	87.31	75.7	99.34	96.25	86.64	82.36	111.87	93.53	106.48	117.08	139.03	99.87
CLASSEMENT	18	8	2	12	16	11	13	17	7	9	14	15	4	10	5	3	1	6

Figure 2.22: Heating and cooling of the four types with potential solar gains, From (Maizia et al, 2009).

Hii et al (2011) also studied the urban morphologies and high dense residential urban forms in tropical context and their performance in term of the total solar insolation on urban surfaces. The study also proposed a quantifying indicator for insolation performance for different urban forms and morphologies Figure (2.23).

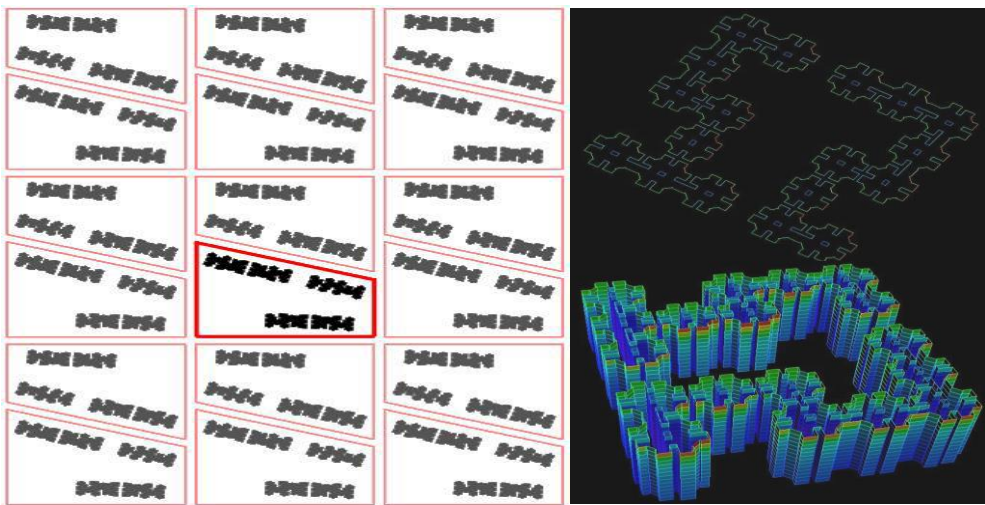


Figure 2.23: Urban morphologies and solar insolation performance, From (Hii et al, 2011).

Different geometrical and urban morphological parameters that can affect minimization of solar isolation were studied like: floor area ratio, site coverage, open space ratio, area to perimeter ratio, compacity: envelope area/building volume, Convolution Index: (Perimeter of the building footprint – Perimeter of the smallest convex shape of the building footprint) / Perimeter of the smallest convex shape of the building footprint and building heights. Figure (2.24) shows the result of the study by grouping the different morphologies into five sub-categories: open, perimeter, point, point slab and slab. The perimeter blocks receive the lowest and in other hand point blocks were among the highest solar insolation for every floor area ration.

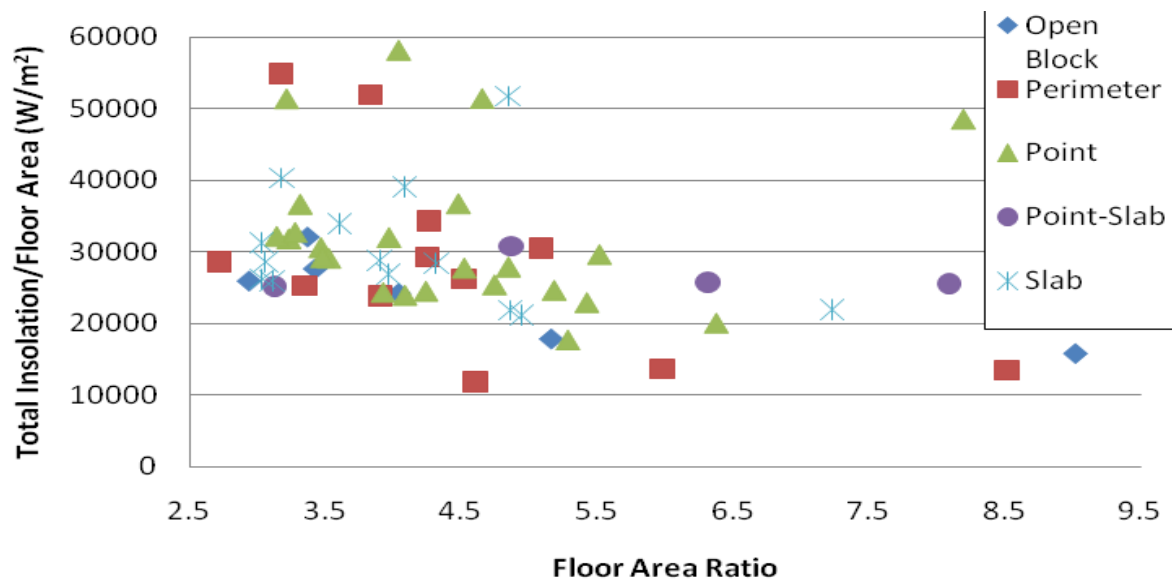


Figure 2.24: Average total solar insolation / floor area for different typologies, From (Hii et al, 2011).

### 2.4.3 Urban Morphology and Energy Consumption

The physical thermal phenomena of an isolated building are different than the same building within the urban context. As the studies in the previous section and the studies by (Rasheed, 2009) showed that the energy consumption of a building in an urban context is affected by the mutual interaction between buildings and buildings with the surrounding urban context. Another factor that affects building's energy consumption with the urban context is the effect of the urban heat island on the whole urban fabric is different than the effect on local scales of buildings.



Kolokotroni et al (2006) highlighted that the energy consumption of a building in an urban context is affected by:

- High air temperatures because of the effect of urban heat island
- The increased urban roughness in term of slowing wind speeds
- Reduction in the heat radiation losses during the night
- Mutual shadings and mutual reflections affect solar heat gain
- Different radiation and heat transfer balance between buildings (Second law of thermodynamics)

Although most of the previous studies done on the energy consumption and the effect of urban context and its complex thermal phenomena isolated two or three of these factors to simplify the simulation and evaluation. Some recent important studies tried to simulate the energy consumption of buildings within the urban context. Wong et al (2011) studied the energy consumption of a building in different urban morphologies and surroundings Figure (2.25).

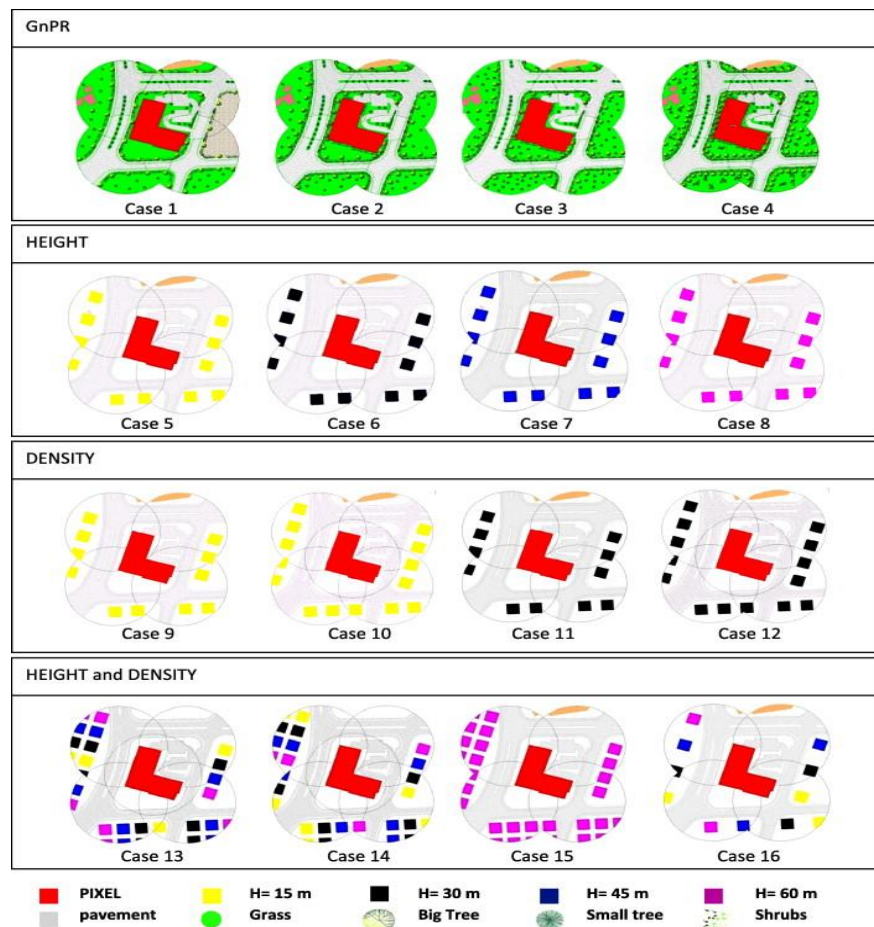


Figure 2.25: First 16 urban morphological cases, From Wong et al (2011).



The study by Wong et al (2011) used 32 experiments of different urban surroundings categorized by: greenery, height, density, height with density, greenery with height, greenery with density and greenery with height and density. The results of the study concluded that urban morphology has strong impact on the variations of temperatures in the urban micro climate. Greenery, height and density have important impact on the local and ambient temperature which can vary between 0.9 C and 1.2 C and the effect of the impact was the highest for greenery then height and density. By only altering the urban morphology of the surroundings there was 5-10% reduction in cooling loads.

Chan (2012) conducted a study on the effect of buildings self shadings and mutual shadings and their effect on the total Sensible cooling load Figure (2.26) in hot climate. The study concluded on the importance of buildings form and orientation and their impact on cooling loads in summer.

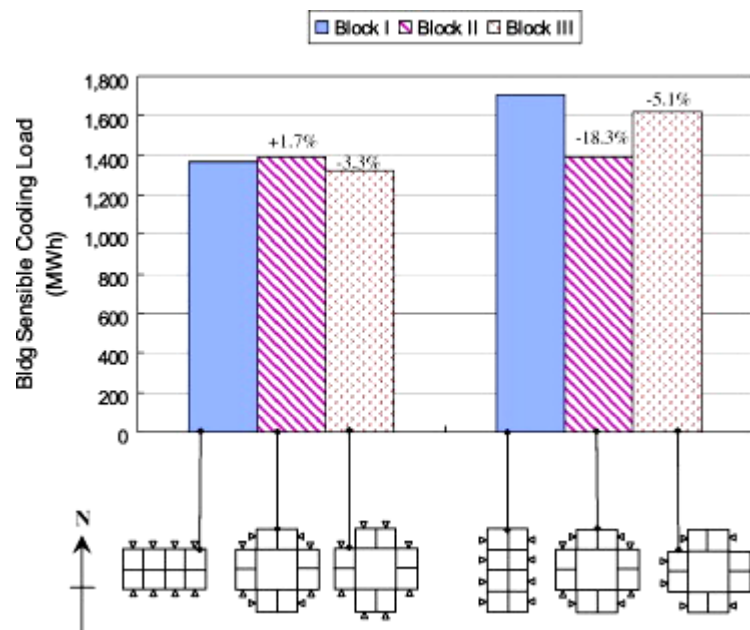


Figure 2.26: Sensible cooling load in all air-conditioned rooms, From (Chan, 2012).

The effect of surface to volume ratio and passive to none passive zones were studied by Ratti et al. (2005) and their effect on energy consumption Using the Digital Elevation Model (DEMs), Figure (2.27). The study results showed that non-passive zones consume roughly double the un-obstructed passive zones and the importance effect of urban morphology on the total energy consumption of buildings within the urban context.

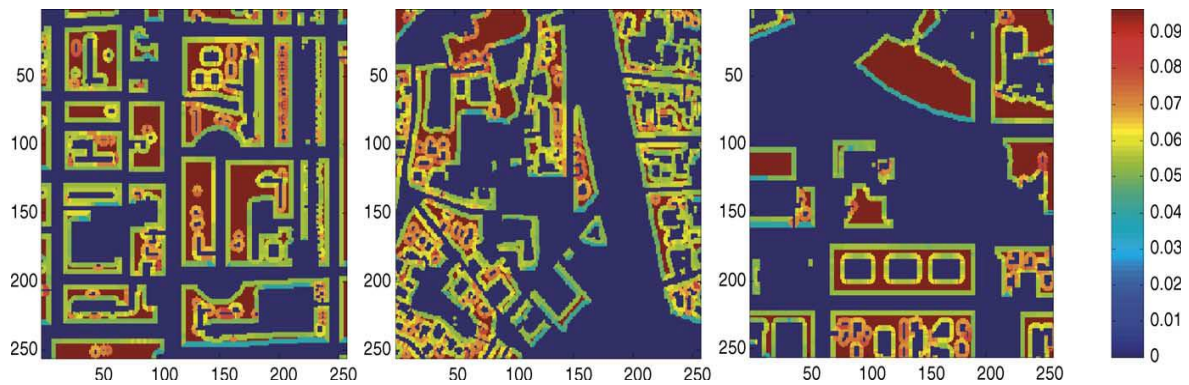


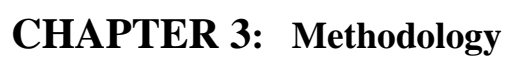
Figure 2.27: Energy consumption in London, Toulouse and Berlin on the second floor glazing ratio 50%; values in kWh/ m<sup>2</sup>/ y, From (Ratti et al, 2005)

### Summary:

From the previous brief literature review we can summarize the main following points:

- Different design strategies have been introduced to study and optimize the forms and shapes of buildings to achieve better overall performance. The relation between science and architecture was the main catalyst that moved the advancements in this area of design strategies.
- City is a very complex system in term of predicting the effect or result of any kind of intervention and it is governed by the characteristics of complex systems. Designing for such system needs a careful look and re-thinking of the concepts in urban design at meso-, macro- and micro-level.
- Parametric modelling gives the designers a powerful tool to study and experiment with the design options in real time which can enhance the design methodologies and strategies. It can parameterize the inputs and outputs from the geometry of the design and the constraints from the entire physical surrounding environment.

- Urban ventilation and microclimate have very important impact on the performance and liveability of an urban design. Urban ventilation affects the outdoor comfort, potential passive local building ventilation, buildings energy consumption, pollutant disperse and can help mitigate the urban heat island. Urban morphology affects the quality of urban ventilation and ambient wind speed at pedestrian levels.
- Solar Insolation in hot climates contributes the most on energy consumption in the cooling loads. Urban morphology, buildings orientation, street canyon characteristics and surface area to volume ratio all affect the solar Insolation and the potentials of the heat gain to a building façades.
- That the energy consumption of a building in an urban context is affected by:
  - High air temperatures because of the effect of urban heat island
  - The increased urban roughness in term of slowing wind speeds
  - Reduction in the heat radiation losses during the night
  - Mutual shadings and mutual reflections affect solar heat gain
  - Different radiation and heat transfer balance between buildings (Second law of thermodynamics)



In this chapter the research methodology is discussed and a comprehensive review to the literature related to the selected methodology and its application in different case studies. A comparison between the different methodologies is made, finally a brief review of the computer software and tools which are going to be used in this research. This section starts by looking at the changing role of the computer in the design process, then review to the optimization methods and examples on them and the computer tools for the research.

### **3.1 Computer in the Design Process**

The early use of computers in architectural design can be rooted back to the years before and during the era of the design methods movement. In 1959 Chermayeff, S. and Christopher Alexander collaborated on a research to illustrate the diversity of components and events that can form the being “house”. The research results published in 1963 in *Community and Privacy*, Chermayeff, S. and Alexander C. (1963). The *Community and Privacy* research used the IBM 704 computer at MIT. Christopher Alexander used the IBM 704 computer at MIT to peruse his Ph D final research, which was one of the early attempts to apply mathematical equations to the design of architecture and urban planning Alexander, C. (1964). The period which followed this and during the days of the Design Methods Movement most of the researchers pinned many hopes on computer and its future as a tool for design.

The era which followed this is the rejection of the rational thinking in design and introducing the humanisation and creativity in design, left no place for computers and it's influential on the design process. They believed that the accuracy needed to perform a method of design using the computer, could ruin the creativity and the principles of thinking that creativity based on. Alexander and others at this period agreed that computers are not suitable for design creativity Broadbent (1981).

In the period that followed, computers had no interference in the design process and in the design methodologies. Their work was limited to visualization and digitalization of the traditional design methods in contrast to the early days were computers form a supporting tool in the design, or even the whole design concepts spring from the analysis that made by computers, as we saw in the design methods movement. The CAD programmes for drawing and visualization is a best resemble to this limited new task for computers.

Computer job has changed in the last years; it is now not only a drafting machine or a tool of visualization for the traditional design methods. They now play a very important role as medium and support for the design process, especially s after they are becoming faster and more powerful ever year. Two notable roles computers have played as suggested by Schmitt (1999) mere tool and as a design support tool.

Schmitt explain how computers play as mere tool when we look at how word processors have replaced typewriters, spread sheets replacing calculators, CAD software replacing electronic pencils, rendering software when their purpose is to impress the customers. For the computers as supportive design medium he explain by these examples, when the internet is used as information data base for the architects to learn from, Simulations and simulation software, Virtual reality and Data management System. The computer to be used as mere tool has no logic and contribution to the design process and if architect want to be more influential in the future they have to grasp the whole potentials that the new powerful computers provides, as added by Schmitt.

May other researchers who are interested in the computer and the role that is playing or going to play in the future as a design medium and support, one concept particularly shines over the others in the opinion of Mitchell (1994). He pointed out three paradigms that computers play, designing as Problem-solving, Designing as Knowledge-based Activity and Designing as Social activity. The first one can resemble the normal CAD system where work is shared between the human being and the computer, in other word, using the computer as mere tool. For the paradigm of using the computers as “designing as Knowledge-based Activity” can be resembled with the knowledge base of the shape grammars and how these shapes can be connected together and logic of combing them.

Mitchell (1994) give credit to the third paradigm, designing as Social activity, and he thinks that it could be the future of the computer-aided design. In this concept which recently appeared there are many parties in the process communicating over a network. These parties could be human or software or software and human together, each with his unique background and knowledge-base and different potentials for finding solutions. Then the parties trade solutions, proposals and point of views to form together as one body that tackle the design problem in hand. The problem and its physical input parameters and potential output parameters and all the knowledge base that related to the problem are

brought in the common virtual pond by each of the party. Then the different arguments, results, proposals and discrepancies must be solved. One condition Mitchell see is important for this concept to work is a very fast network that enables knowledge base, proposals and data to be brought in the virtual pond and to or from each party that is working on the solution.

### **3.2 Design Optimization Methods**

Generally design optimization means: finding the best solution for the design problem within the measurements and constraints of the environment, materials, human being needs and resources to achieve the design goals with a satisfactory output parameters. The tools which could be used for the purpose of optimization can be, but not limited to lab and physical modelling experiments, physical Design of experiments, try and error experiments and Computer Simulation software. Computer simulation and programming tools for optimization has advantages over the other methodologies and more suitable especially for research purposes as we will see in Chapter 3 when talking about methodology.

In computer simulation or programming for optimization the tools could be a simulation software package or a group of analysis programming codes, the constraints could be cost, material manufacturing requirements, location, weather or the available resource in its all forms. The design goal could be manufacturing electronic device, a car, aircraft, a building or a master plan and urban design. The satisfactory output parameters or the parameters of the best solution could be durability, performance and sustainability of the system, form qualities like shape and size, stability or any kind of human comfort and need. In the general definition of optimization the time scale or condition is not specified and could be minutes same as doing feasibility study or could be days or months like when we are designing for a product.

#### **Optimization Methods**

Many optimization methods are available out there; this section will list the most famous optimization methods using computer and the literature around them, in order to validate which method has potentials to be applied to optimize a parametric design for the purpose

of achieving sustainable urban design. The most relevant methods (Genetic Algorithms and Simulated Annealing) which could be applied to this research is going to be reviewed and a comprehensive literature review with comparison between them will be in the next sections when parametric design and parametric design optimization is discussed.

Stochastic Optimization:

- Genetic Algorithms:

Genetic Algorithms (GAs) or Evolutionary Algorithms mimic the natural selection and the survival for the fittest which exist in nature to find the best solution to the problem Holland (1975). The Genetic Algorithms start by calculating random solutions and then handling these solutions to the Genetic Operators. Then new solutions are generated from the first solution using the Genetic Operators. All the solutions are indexed by a fitness value which indicates how much it fit to the solution. The main purpose of this operation is to mate the solutions with higher fitness and using the Genetic operators to produce new generations. Then Best solutions can be generated or chosen from the existing potential solutions by applying re-combinations and mutations. Until a suitable solution is found this process continue forever.

Many advantages differentiate GAs (as we will see in details in the next sections) over the other optimization and searching algorithms when handling a very complex task and domain. It is rarely for them to be caught in local optima or sub local optima which means that GAs always give better solutions. Their ability to handle continuous or discrete or both is another advantage added to GAs. The GAs in order to be effective, they have to be smart when they are searching by balancing exploration with utilization. In the first searches they have to cover as much as possible of the domain by taking as much as possible probes and gradually focusing on the candidate solutions for further examinations.

Genetic Algorithms through history have been applied to many different fields for design optimization in the engineering fields, like in the field of architecture and structural engineering Gero et al (1997) and Rosenman (1997), in the domain of mechanical Chapman et al (1996) and others. Many other genetic algorithms were designed with the ability to compute continuous and discrete values to cope with the more sophisticated



engineering and shape optimization. Genetic Algorithms gain huge attentions by researchers due to their adaptability and their interactive nature and their ability to find better solutions gradually without being trapped on local minima or maxima.

- Simulated Annealing

Simulated Annealing (SA) is built on the basis related to thermodynamics, particularly the physics related to heating and cooling metals and the way how metal anneal from this process Kirkpatrick et al (1983). Simulated Annealing start searching in the domain and move from one point to another for the hope to reach to an optimal solution either maxima or minima. SA uses the probability to evaluate the new point according to the current point, if the new point is more suitable to the solution than the current the probability is one, if the new point is worse than the current the probability is between zero and one. The probability for the SA to drift to a worse point at the start is high and it will decrease by the progress of the search. Simulated Annealing Methods are similar to Genetic Algorithms in the way that they try to avoid being stuck at local optima. More comparisons and discussion will be in the next sections between these two optimizers.

#### Hybrid methodologies:

Many other attempts and research made to combine more than one method so that they complement each other in the search for an optimal solution without being trapped on local optima. For example Rogers et al (1996) combined a Genetic Algorithms and Knowledge-base, Gage et al (1995) GA and Gradient-base and Powell (1990) used GAs and numerical with a smart system to decide when to switch between them.

#### Dynamic Programming:

Historically Dynamic programming was employed to optimize problem in the architectural domain and in the problems of light designing. In the domain of lighting design, Gero et al (1978) studied the minimization of the cost of artificial lighting by examining the effect of the parameters of their location, numbers and intensity. Other propositions were made on

the way that this method can be applied to windows design, the light at roof and the shading devices over windows.

This methodology suffers heavily from the number of variables under study and it become very slowly to execute each phase from the amount of data that must be stored between each iteration and phase. So, this method suffers and become difficult to apply when we are talking about multi variable such in the case of parametric sustainable urban design, which involves many input parameters such as shapes or solar radiations or buildings orientations.

#### None-linear Programming:

None-linear programming was applied to the problem of day lighting, by the use of modified scheme build on Newton's method to achieve the best day lighting in the space. The method used a simulation program for light with a ray tracing capabilities Law (1997). Many other uses for None-linear programming in architectural optimization was done by Mitchell et al (1976), the method used none-linear algorithms to arrange the space and function of a rectangular plan. Mitchell method optimized these function spaces and their locations according to each other in order to satisfy the architectural program and the user needs or requirements.

In the early Sixties and Seventies the application of none-linear programming and optimization on the space functions and on the synthesis of rectangular floor plans was done on grids of rectangular or other forms. The use of none-linear programming to optimize the cost and the constraints of the functions related to synthesis of floor plans was studied and investigated by Mitchell (1977). He used dimensionless representation to the floor plan by dividing it to grids and produces the optimized layout with diminutions in order to fit the functions and space requirements with the least cost.

#### Linear Programming:

The linear programming as the name sound, it deals with linear mathematical functions and this factor removes the possibility of using this type of optimization in architectural domain or even in the engineering practice field as most of parameters and constrains and

their type is none linear. The use of this method has been limited to optimize parameter such as dimension or circumference that is constrained with linear factors like cost, heat Mitchell (1977).

### **3.3 Parametric Design Optimization**

In this section we will discuss the parametric design optimization, algorithms and the literature related to them. Two famous stochastic optimization methods are discussed Genetic Algorithms (Evolutionary algorithms) which is the method used by this research, and Simulated Annealing. Comparison is drawn between them and examples from the literature and history background.

#### **3.3.1 Stochastic Optimization**

Two of the most famous stochastic optimization methods are Genetic Algorithms and Simulated Annealing. These two methods have been used thoroughly in optimization for the engineering problems architecture, structure, urban design, mechanical problems and others like industrial design and manufacturing. Many other researchers used genetic algorithms in the study of economics and financial optimization. These methods are called stochastic methods since they depend on iterations in every iteration calculation is made to search for better solution in the next iteration.

#### **3.3.2 Evolutionary Algorithms (Genetic Algorithms)**

The first Genetic algorithms (GAs) were developed by Holland 1960 at the University of Michigan. The main goal for the first Genetic algorithms developed by Holland is to study the natural adaptations and how can these phenomena be studied or simulated in computers. The first GAs made by Holland team resembled the biological evolution and the adaptation which happen in that process. Holland used genetic operators like mutations, crossover and inversion to generate new populations of chromosomes from the current one. These chromosomes were translated to computer language in the form of strings of zeros and ones or bits in the machine language. By applying the selection operator on the chromosomes which will be allowed to produce to generate the next

population, the fitter chromosomes generate better and more new generation than the less fit. Holland is considered to be the first one who puts evolutionary computations and genetic algorithms in solid start Mitchell (1999).

Recently the terminology of genetic Algorithms had changed a lot from the Holland's GAs, due to the extensive studies and researches which was done on Genetic Algorithms, evolutionary computations, genetic programming and the overlapping of studies done on these fields. The term evolutionary computation is recently coined 1991, this term was used and introduced to represent all the researches and studies that mimic or simulate the process of evolution in nature with software and computers. When any process either in nature or in computer involves selection, completion, reproduction and random variation the outcome will be evolution Fogel (2000).

Fogel (2000) sees that the evolutionary computation comes from four fields of interests in science, engineering and design: Optimization, Robust adaptation, Machine intelligence and Biology.

#### Optimization:

As we will see in this research GAs are very powerful optimization tools and have the ability to search for optimal solutions in a very large space and still achieve good results in all iterations and very suitable and adaptable to the engineering problem in general sense and to the form optimization problem. Fogel explains that the process of evolution is in itself an optimization process and how Darwin was so astonished by the organs of extreme perfection. Exactness and perfection is not always the result of optimizations, although evolutionary processes can lead to very good solutions to some problems and constraints forced by the environment. In this process of optimization natural selection is applied to functions and optimization is done on the functionality by selection and mutations. According to this main principle of evolution it was natural and adequate to translate the main concept of optimization in Natural evolution into algorithms that can solve engineering problems.

### Robust Adaptation:

Fogel explains how the need to study and achieve many optimizations and processes which can change the performance of the system depending on the incremental feedback from the surrounding environment led to the investigation and studies done in the field of evolutionary computation. The dynamical status of the real world problems impose one of the most complicated problems to solve in engineering and science. This state of changing requires tweaking the algorithms and strategies that are employed to achieve solutions and optimizations with the continuous feedback from the successes or failures of the current configurations. The evolutionary computation can learn from natural evolution to reuse the successful group of techniques and how knowledge is increased in the new generations to design very robust and adaptable systems.

### Machine Intelligence:

The type of intelligence that can be inspired from natural evolution is the capability of the system and its individuals to adapt in order to perform its tasks and functions in the whole environmental conditions. The predictability of the environmental conditions in the future is one of the main key of intelligence in the evolution systems with the right tweak to their functionality to achieve performance. The main concept of inspiring intelligence from evolution is creating machine intelligence without the need to duplicate human intelligence and the way how humans think or behave or predict by coding the smart predictive evolution in computer algorithms, which was the basic idea behind evolutionary programming.

### Biology:

This source of research and interest as we saw was the first intent to study evolution and to try to mimic its methods by computer. These types of evolutionary computation were developed to try to understand the evolution process its physics, procedures and mechanism and how it really happens in nature with no reason to use it as a solver or optimizer to engineering and scientific problems. Many models and simulation were successful to answer many questions related to evolution and life on earth.

## Genetic Algorithms as Optimizers:

The Genetic Algorithms can find better solutions by probing the fuzzy domain of space for the solutions possible to the problem in hand; this space may have local or global optima in the case of maximization or minimization. One of the characters that give GAs advantage over others is their ability to overcome being stuck on local optima, since their solutions moves from one population to the other rather than one single point to another. Genetic algorithms start searching for solutions by generating a random population of individual solutions then applying stochastic operators to select the fitter solutions for producing offspring in the next generations Goldberg (1989).

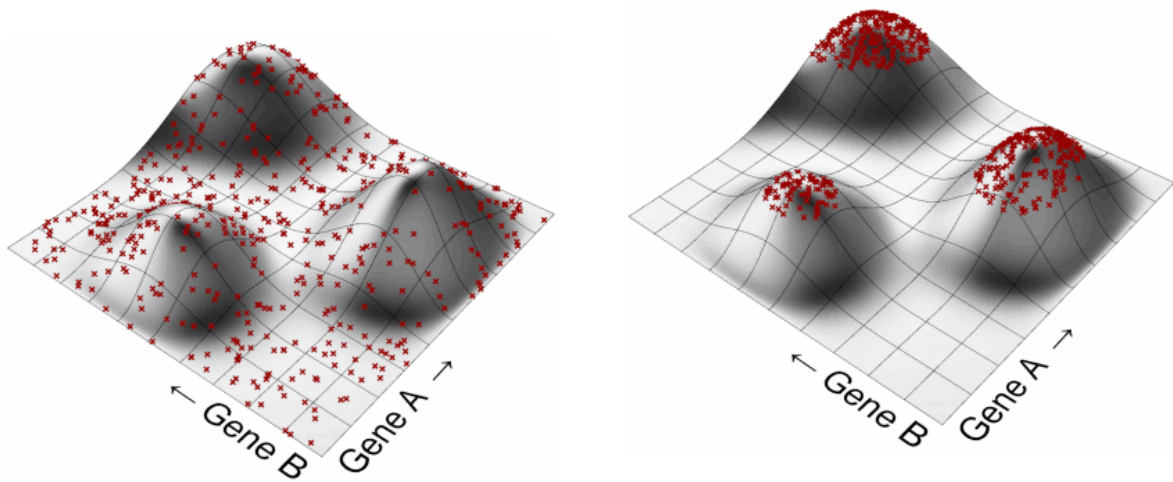


Figure 3.1: GAs search mechanism (left) first population, (right) stochastic operators and peak climbing solutions for next generation, Rutten (2010).

The translation of evolution system into computational system is resembled by chromosomes which represent an individual solution. Chromosomes consist of all the variables and parameters related to that individual solution in the form of alleles as binary. So, each group of solutions is a generation and each individual is a chromosome which resembles the specific parameters for that solution translated to the machine language in binary system.

The generation of each population and the evolution of the current generation to new one is performed through genetic operators mainly reproduction, crossover and mutation.

Reproduction is the selection of the fitter chromosomes for producing next generation. Crossover genetic operator works by performing exchange on the alleles between chromosomes to generate new chromosomes in a random way. Mutation as in nature is a random change on part or parts of the chromosomes in order to fit or optimize organ to function better. Many other Genetic algorithms have different or specialized operators, although the framework in basic is the same.

In general the main principles of the genetic algorithms search begin by randomly distribute the first population over the fuzzy domain space of solutions to produce the initial generation. Genetic operators select the fittest chromosomes and apply on them the main manipulations to generate new population. The fitness value for every generation is higher than the previous one. Then the new generation will be again treated according to their fitness with the main basic genetic operators to produce the future population. These iterations and their numbers are defined by the users. The number of generation and the number of the individuals in each generation depend on the problem complexity, number of parameters, degree of precision, time and the possibility of multiple local or global maxima or minima.

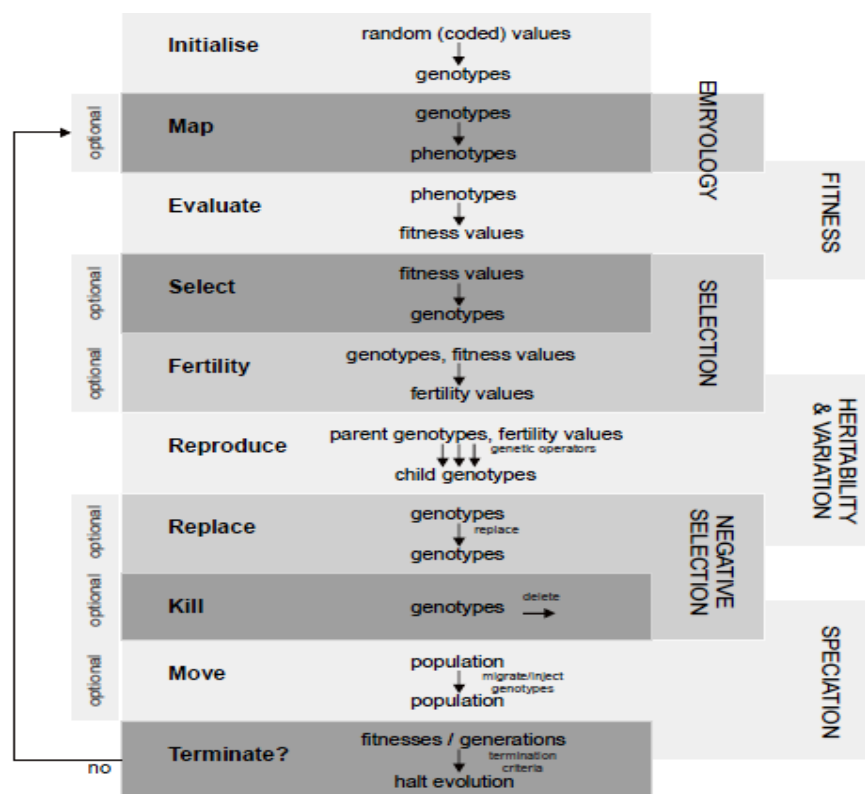


Figure 3.2: General Structure of GAs. From (Bentley, 1999).

However, genetic algorithms tend to run forever when they are searching for solutions and it is the specific requirement of the situation that impose on the genetic algorithms to be designed in such a way that it halts on a degree of accuracy or time or number of generations. This simple genius of the evolution in nature has solved many of the most chaos and difficult problems that faced living things on Earth since live emergence. This genius is the main key behind the power of genetic algorithms in solving and optimizing many of the most difficult engineering problems Bentley (1999).

Literature is very rich of examples related to genetic algorithms and their usage as optimizers in many fields of architecture, engineering, science, and computing. In the following part of this section we will see examples of how genetic algorithms were utilized as optimizers and their ability to solve very complicated problems and their efficiency.

In the field of mechanical engineering GAs were used to tweak the sizes of the ducts and channels with the openings of the returns and diffusers in HVAC systems and to be synchronized with the control in order to optimize and save energy usage and increase the efficiency Wright (1996). The structural engineering field has many researches and applications of genetic algorithms to optimize many structural elements their size, cost, cross-sections and even the layout or configuration. For example Galante (1996) used GAs to optimize the design of trusses; the application of GAs on the design and optimizations of columns was studied by Ishida et al (1995) and the applications on slab configurations were done by Pham et al (1992).

Also in the field of structural engineering some advancement were made on the use of GAs as optimizers by combining them with Finite Element Analysis software that has big data base and precise in calculations Camp et al (1998). The optimization goal was to fide the best weight to the whole structure under study. This study shows the ability to couple the genetic algorithms with other specialized programs for analysis and the feedback to GAs in order to check the fitness of that configuration and its parameters.

O'Reilly et al (1998) investigated applying genetic algorithms as shape generators to give the designer at the early phase of the design by generating design configurations and ideas that the designer can inspire from them then to know the direction that he should take



when imagining his design. The genetic algorithms that were used can be manually iterated to produce or to operate crossover or mutations.

Another use of the GAs in the mechanical design optimizations of an air-conditioning system and the parameters were discrete and continuous in the same problem; a case study done by Wright (1996). This research showed the advantage of GAs and the way that they can handle discrete or continuous problems. In this optimization case the GAs were used to find the maximum flow of the chilling fluid which is continuous, the size and dimensions of the system which are discrete and the maximum flow of the air to the room to achieve the desired comfort temperature. The main global fitness for the system was the total cost of the optimized component.

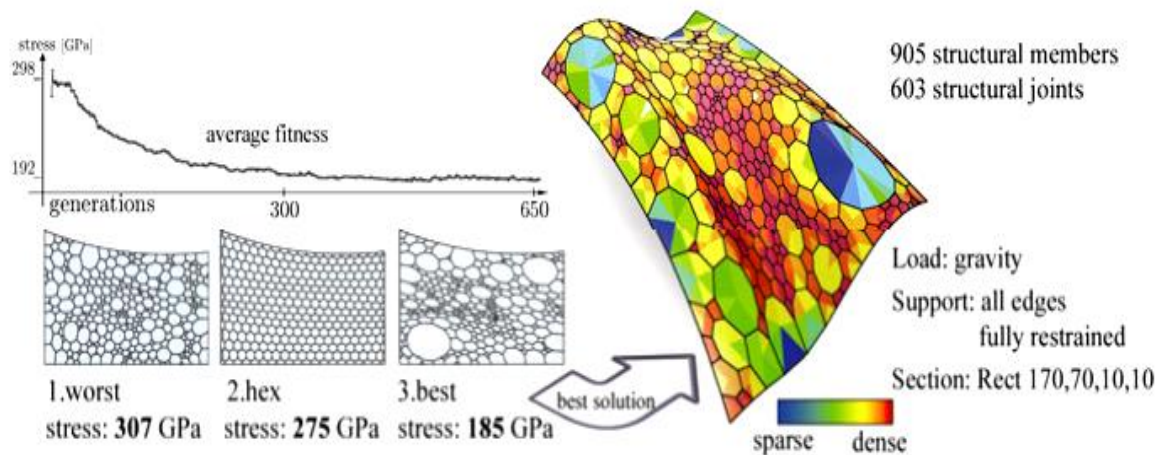


Figure 3.3: GAs for optimizing free-form grid. From Milos Dimcic et al (2011).

Milos Dimcic et al (2011) integrated FEM, NURBS and genetic algorithms to design a free-form Grid shell Figure (3.3). their main concept for developing such system is the infinite number of solutions and configurations when designing a free-form grid over some surface, so their system provide an automated and optimized way of generating the grid and instead of the old manual trial and error way. By using genetic algorithms for optimization they were able to optimize the grid by minimizing stress and displacements in order to save material and get better structure stability.

Another usage of GAs to optimize the structure of a free form roof by Johan et al (2011) the main goal of optimization was minimization of construction cost and effective

structural stability. Johan et al used Grasshopper for generating the parametric form, for the genetic algorithms they used Galapagos (same tools used in this research as we will see), which is a built-in tool inside Grasshopper for optimization and by connecting the resultant optimized shape to FEM solver (ROBOT) to further check the structural behaviour of the roof. In their results they confirmed the advantage of using GAs in the design process and how it is able to solve the problems and generate a variety of solutions that can be inspiring to the designer at the early stage. They highlighted the good potential of using GAs (Galapagos) as an active tool in the design process and a design exploration tool to investigate new designs Figure (3.4).

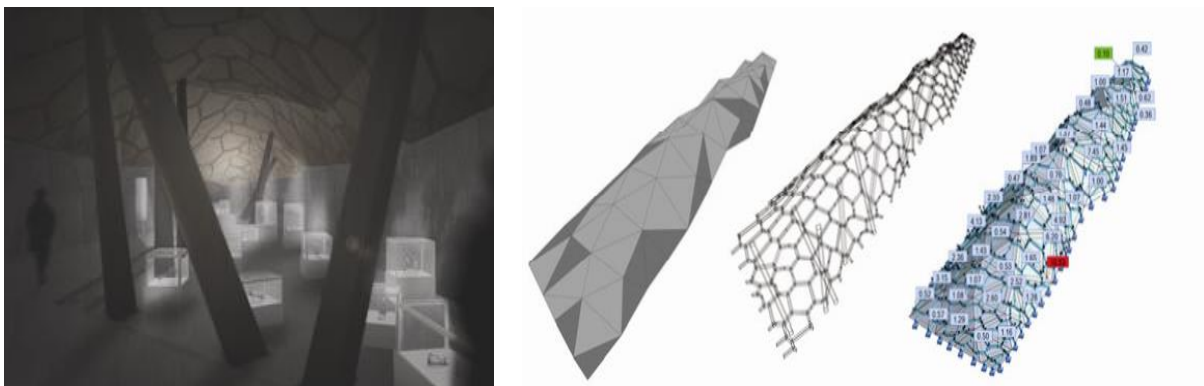


Figure 3.4: GAs to optimize the structure of a free form roof. From Johan et al (2011).

They concluded that the success of these new methods of design depends on the designer skills and intuition to setup the correct domain space of solutions and the functions of fitness to be search against. Setting up the solution space as large as possible with a bigger flexibility in the parameters input domain for the points give a good setup to the system to investigate much wider possibilities of solutions.

Figure (3.5) shows a study of optimization on a Yacht hull using genetic algorithms to optimize its performance in racing. A parametric software generator was used to configure the yacht hull and its curved surface. The variation in the parametric model of the yacht hull was defined by the points on the curves that circumference the yacht and its main form and by applying changes to these points and its location, multiple design configuration can be generated. The optimization process was assessed on the total yacht hull performance in water and its aerodynamics.

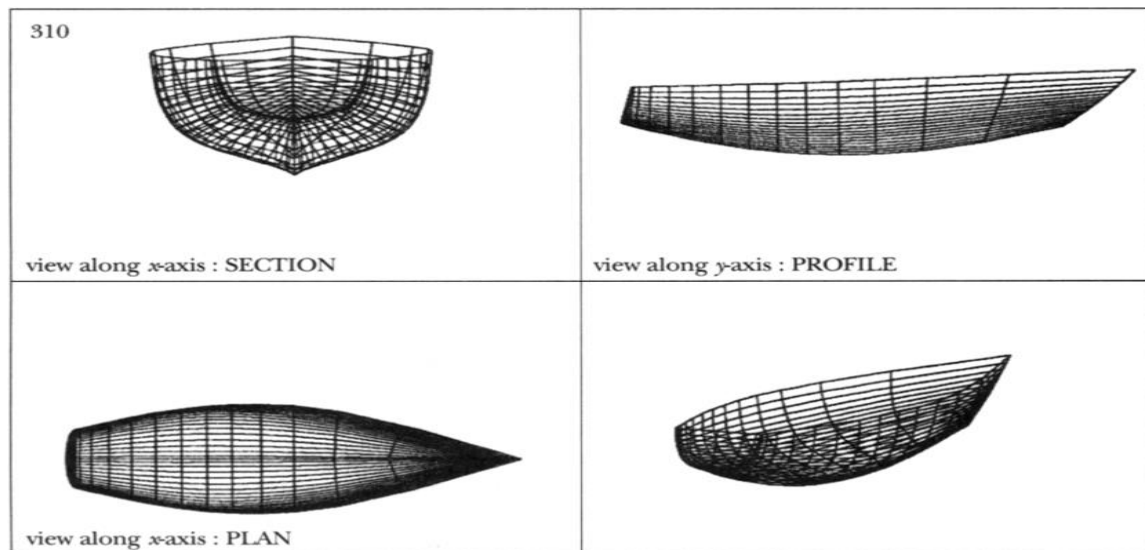


Figure 3.5: Yacht hull optimization with GAs, From Frazer (2002).

Narahara et al (2006) used genetic algorithms to optimize the urban design of 200 residential units, Figure (3.6), the units consist of three and two bed room's type and optimization was evaluated according to solar exposure, best views and the construction economic factors. In order to speed up the GAs processing they used self cross-over with the chromosome, a randomly chosen parts will swap to generate new individuals for the new generation. The fitness evaluation of each parameter was depending on the unit orientation, view to the street, the level in which the unit in and the cost of construction. This case give a good example of the optimization ability of genetic algorithms even if the problem has multiple parameters, more that 200 parameter, still we can get good results in reasonable time.

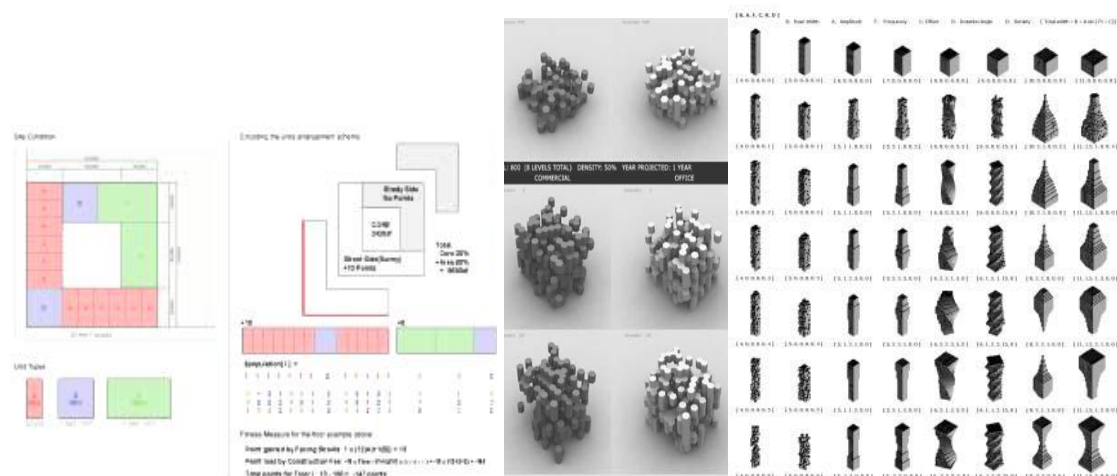


Figure 3.6: GAs in housing design, From Narahara et al (2006).

Angelos et al (2011) used genetic algorithms to optimize a free form surface with respect to the wind loads by coupling GAs and a fast fluid dynamic simulation Figure (3.7). The use of CFD to optimize free form or the design configuration in architectural has been limited in literature (as we saw); most of the CFD studies were on the field of HVAC systems or window sizing. These researches methodologies were done on orthogonal geometries which made them limited when used to form finding. Angelos et al methodology's optimized the form of the shape which has more than three degrees of freedom and allows more possibilities of configurations which lead to more optimized shapes by considering all the available solutions.

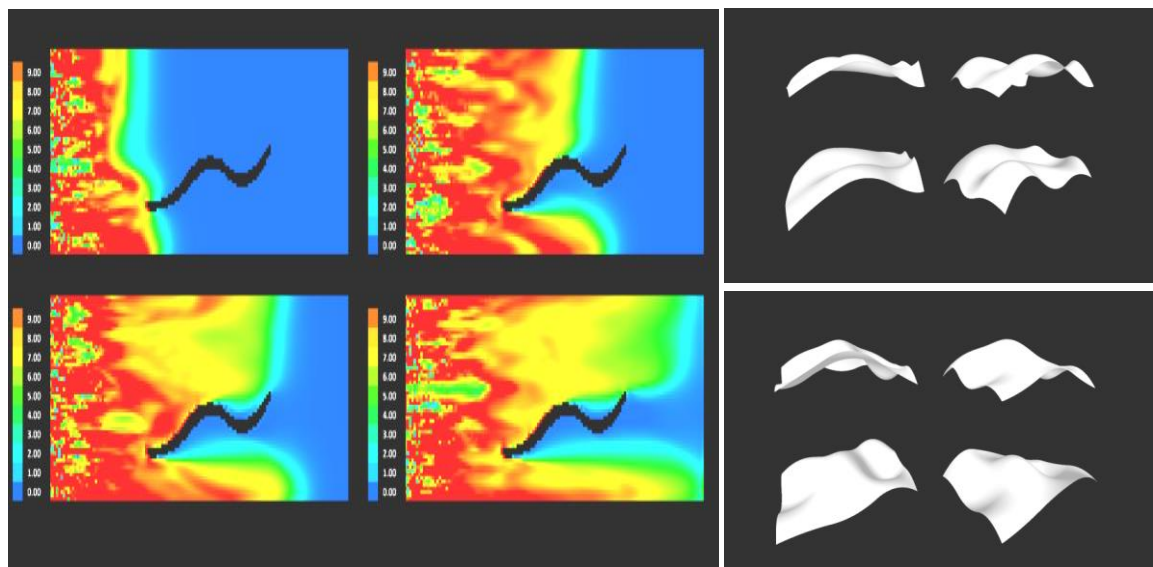


Figure 3.7: Integration of Fast Fluid Dynamics and GAs, From Angelos et al (2011).

Their research showed the ability to generate complete optimized shapes and controlled the whole design performance when integrating genetic algorithms with CFD and a more flexible parametric design that can response to all possible solutions that yields from the optimization process Figure (3.8), which somehow demonstrate the main concept in this dissertation and the possibilities of performance and sustainable aspect when using such methodologies.

Although their main goal off optimization was to design better structural performance and optimizing the free form of the roof, this research apply these methods to optimize the sustainable performance of an urban design which is a much complicated case in term of constraints like the local code and complex environmental input and output parameters to deal with.

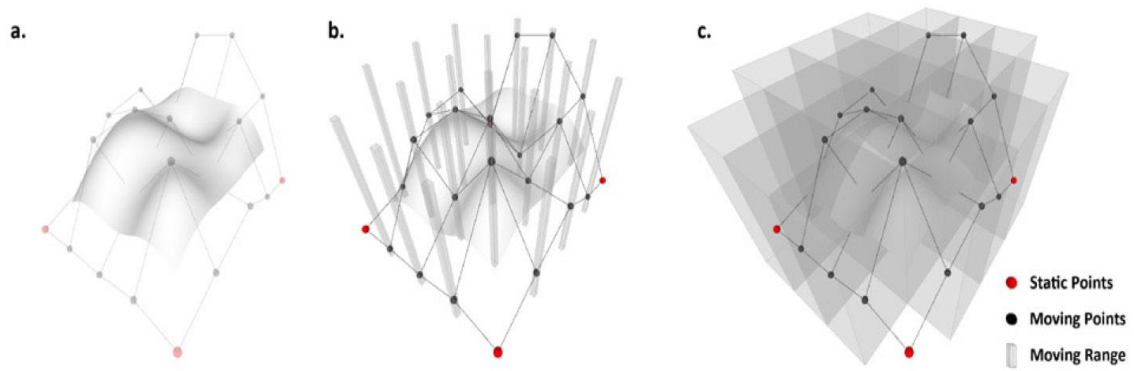


Figure 3.8: Free form configurations and degree of freedom, From Angelos et al (2011).

The CFD which was used in their research depends on a numerical fast analysis with poor accuracy to generate fast results, which is understandable, however the CFD used in this research is one of the most powerful CFD available in the market (CFX ANSYS) and can give good reliable results for such complicated design like in this case. The accuracy in the sustainability optimizations means saving a lot of accumulated energy costs, general health and future advantages.

In another study that used GAs as a multi-objective optimizer by (Chronis et al, 2012) to reduce solar incidents and maximizing daylight penetration on a façade of a large office building Figure (3.9).

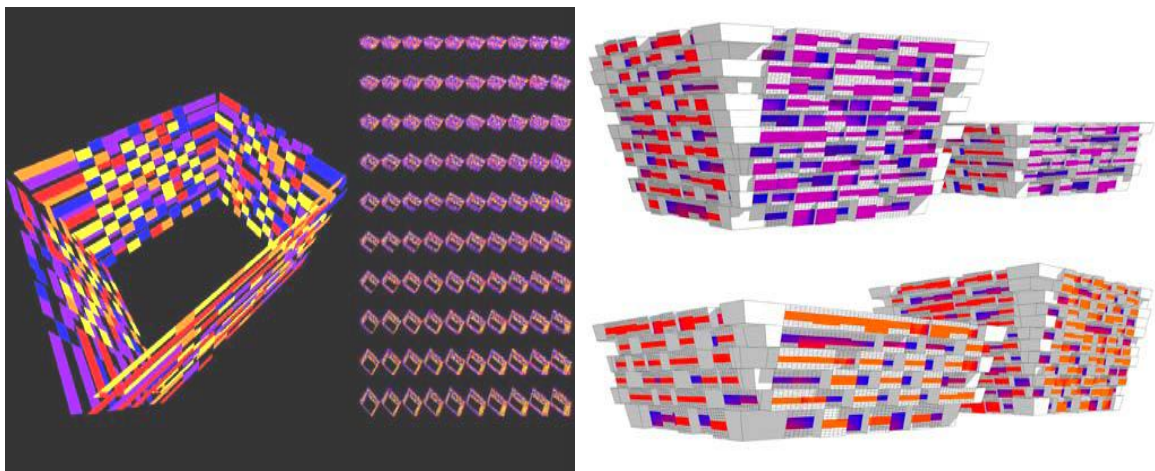


Figure 3.9: Optimization Generation and optimized results, From (Chronis et al, 2012).



The study integrated parametric model, genetic algorithms and a set of data pre-computed results in order to reduce the resource demand of multiple configurations of the façade.

The coupling of the database with the parametric model allowed for real time feedback and allowed the designers to examine multiple design configurations. This pre-computed database form as a design of experiment, which give the designer a sensitivity analysis to the parameters of the configuration with good insight on the complexity of the design. The study results suggested that, although this system of configuration between GAs, A database of results and parametric model was specifics to this case of study , it could be used in the future as mean of system to achieve optimization in such design problems.

From the previous examples Genetic algorithms has proved to be suited for most difficult computational problems in many fields. Most of these computational problems require searching within a vast domain space of solutions; one good example is the search for group of mathematical functions that can forecast the ups and downs of a financial market. This optimization problem can frequently advantage from an efficient parallelism which many solutions are generated in the same time effectively. Another aspect of GAs which makes them competitive in the optimization search problems in the domain of computational is their adaptive to the changing environments and ability to perform well.

Another aspect of GAs is that they are innovative in the mean that they can emerge new ideas that are original such as a new scientific discovery (Mitchell, 1999). The GAs excel in the fields where it is difficult for a programmer in some situation to write a programme by hand, the best example for this is the difficulty to write a program of artificial intelligence for machines, which resemble the paradigm in thinking of AI over the old straight forward which was believed by many programmers.

### **3.3.3 Comparison between GAs and SA**

Literature has many existing researches of comparison between Genetic Algorithms and Simulated Annealing with respect to their performance and capabilities to find optimized solutions. This section will highlight some of these studies and the criteria on which the comparison was made.

A significant comparison was made by (Gallego et al, 1998) with the criteria of four elements: memory usage, intensification, diversification and neighbourhood structures. Gallego et al used these four criteria to evaluate GAs and SA efficiency and potentials.

Since simulated annealing uses statistical process to search for solution it uses very little of memory. SA only uses memory in case of the best solution is found and it is used to restart search after every phase of the temperature reduction. While in GAs the process of copying the best chromosomes to the next generation explicitly uses memory to keep the best individuals in each generation. GAs use memory implicitly to keep track of high performance building blocks by the selection process.

With respect to intensification SA moves less freely during its progress and its probability to accept new points is low according to the current solution and the neighbourhood is limited and decreased. The GAs have different value of intensification, since they use non-systematic search methods and mutations make new individuals different than the existing which lead to search in the vicinity.

The diversification in SA happens since the probability of accepting low performance solutions at the beginning is high which leads to exploration of new regions in the solutions space. The crossover in GAs achieves diversifications by creating new solution points from the existing ones and Micro-GAs have high diversification by using initial random population.

SA requires definition to the neighbourhood and the size of the structured neighbourhood is not significant since it searches point by point. In the contrary GAs don't need definition to the neighbourhood and new solutions are found by the process of applying crossover to generate new solutions from the existing and carry them to the next generation.

Another criterion to draw the comparison between GAs and SA depending on the number of solutions visited and to end the optimization process at that number, 2000 points, this study was made by (Jozefowska et al, 1998). They observed that the increasing number of parameters and jobs affected the performance of SA more than GAs and the GAs have the ability to find the optimal solutions more frequently than SA. In conclusion of the study GAs in general behave better than SA.

In broad comparison Between GAs and SA is their strategy of searching for solutions. SA depends on the strategy of path tracking, the solution move from one point to the next during the optimization process. So, at any moment of the whole simulation there is only one point that represents the current best solution. On the contrary, GAs keeps a multiple points of the current generation in order to work together to generate the fittest point along the optimization line of history.

Another main difference between GAs and SA which spring from their basic strategy to search in the space of solution is how often they switch their concentration from one region to the other. Genetic Algorithms tend to take loner time in searching within the same region and have slow fluctuations and jumps. In the other hand, SA more likely to change its concentration quickly from region to the other especially at the beginning of the optimization when the probability is high to accept any solutions even if they are les fit.

From the previous brief of literature review on the comparison of genetic algorithms and simulated annealing and the case studies especially with genetic algorithms in the engineering cases GAs has more chance to win over simulated annealing due to their ability to keep a population of points instead of only one point. The interaction between these points within the genetic algorithms generations make it painless to find small viable areas toward the fittest solution. The crossover operators in the genetic algorithms give very good advantage over the simulated annealing by the decomposability of a lot of engineering domain space of solutions.

### **3.4 Computer Simulation Tools**

In this section a brief review of the computer simulation tools which are used in this research. Review of their usages and main strengths and limitations is made and some examples from other researcher's case studies and the way they used them. These tools are: Grasshopper which is a parametric modelling and design tool, Galapagos which is a multi-objective genetic algorithm, Diva for Rhino 3D which is a plug-in that utilise Radiance and Energy Plus to simulate solar radiation, energy and lighting fully integrated into Rhino 3D program and finally ANSYS CFX which is a CFD simulator inside Workbench language scripting (Python).



### 3.4.1 Grasshopper and Galapagos GAs

Grasshopper is a visual programming language and visual design scripting built inside Rhinoceros 3D application. Different than design-scripting work flow Grasshopper is a friendly visual interface that allows the creation of algorithmic design in the form of a flow chart with real time feedback from the changing parameters. Grasshopper interface is divided into two main parts: Component tabs and Canvas. The component Tabs contain all the elements and block building visual algorithms that is needed to create and manipulate geometries and parameters. Canvas is the work place where you can from the diagrams of your components and the way they are connected and interact between each other (Khabazi, 2012).

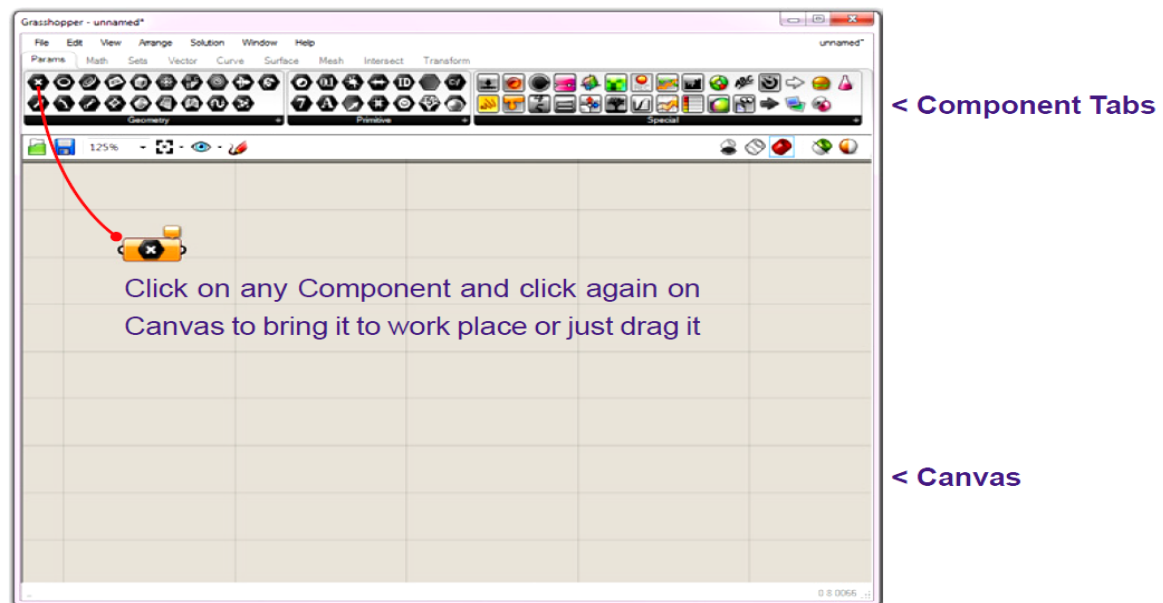


Figure 3.10: Grasshopper interface, From (Khabazi, 2012).

The components in Grasshopper, Figure (3.11), are categorized into component tabs in respect to their role as functions or geometry and their functions can be classified to four:

- Present data
- Control and change data
- Draw Geometry
- Modify Geometry



Figure 3.11: Grasshopper Component example, (point) and its input output.

Grasshopper gives the designer flexibility over the design and the ability to control design process and monitor the effects of changing the input and output parameters in real-time, Figure (3.12) with the ability to connect these parameters to third party software, as in the next section with Diva, Radiance and Energy Plus, then again collect the results to reflect them back on the Rhinoceros 3D model through Grasshopper algorithms.

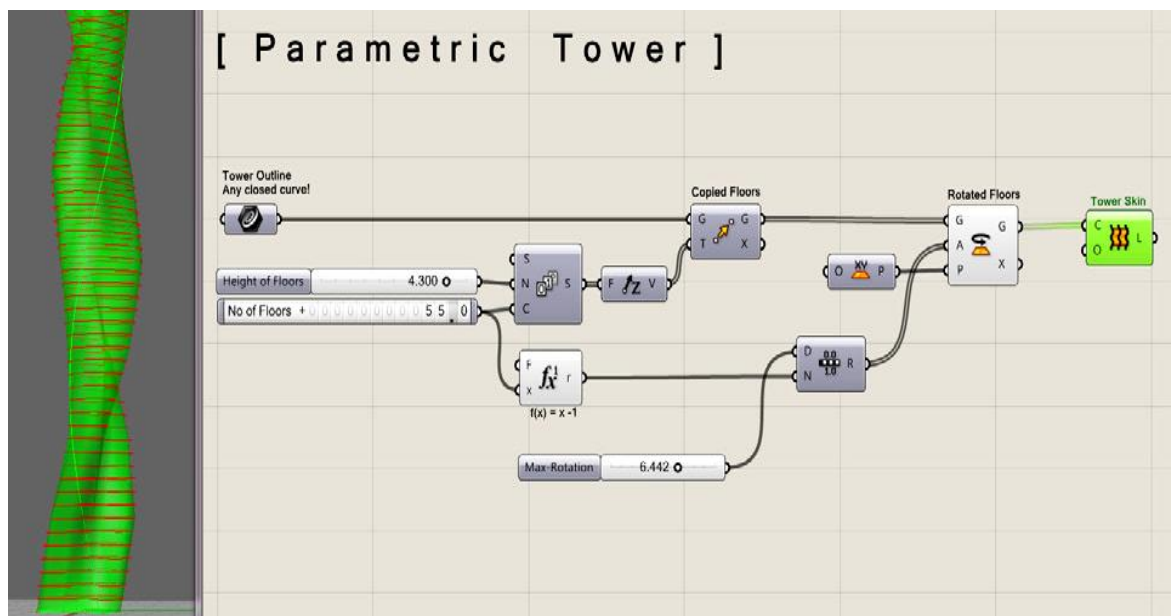


Figure 3.12: Parametric tower façade and its components algorithms in Grasshopper Canvas, From (Khabazi, 2012).

Grasshopper application has been an interest for many researchers from different fields due to its friendly visual interface and flexibility. It has been used not only by architects and urban designers, but also to artists, industrial engineers, Jewellery designers, structure engineers, manufacturers and model builders Figure (3.13).

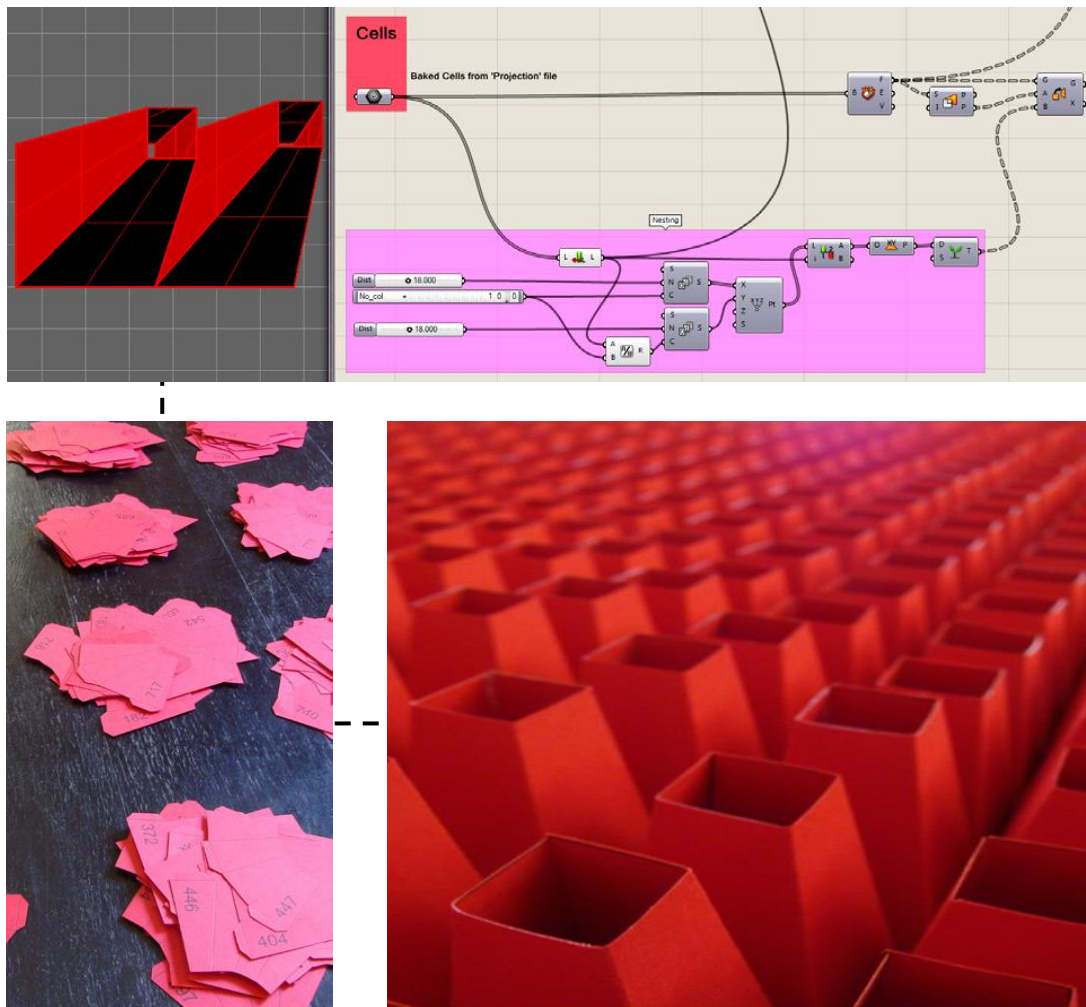


Figure 3.13: From concept in Grasshopper Canvas to real model, From (Khabazi, 2012).

Galapagos is a Genetic algorithm with a user friendly interface built inside Grasshopper as a component. Galapagos is fitted well inside Grasshopper since it allows for the direct use of the input parameters from Grasshoppers Sliders and any definition of fitness function in any form of floating numbers and the goal of optimization either maximization or minimization. Galapagos uses selection, crossover, and mutation operators with the ability for the user to control the initial population, number of population per generation, number of generation (iteration) and the percentage of applying each operator depending on the type of the optimization problem and the probability of multiple local maxima or minima (Johan et al ,2011) Figure (3.14). Mutation operator is exception in that it can be manipulated during the optimization process and the real-time feedback of its effect.

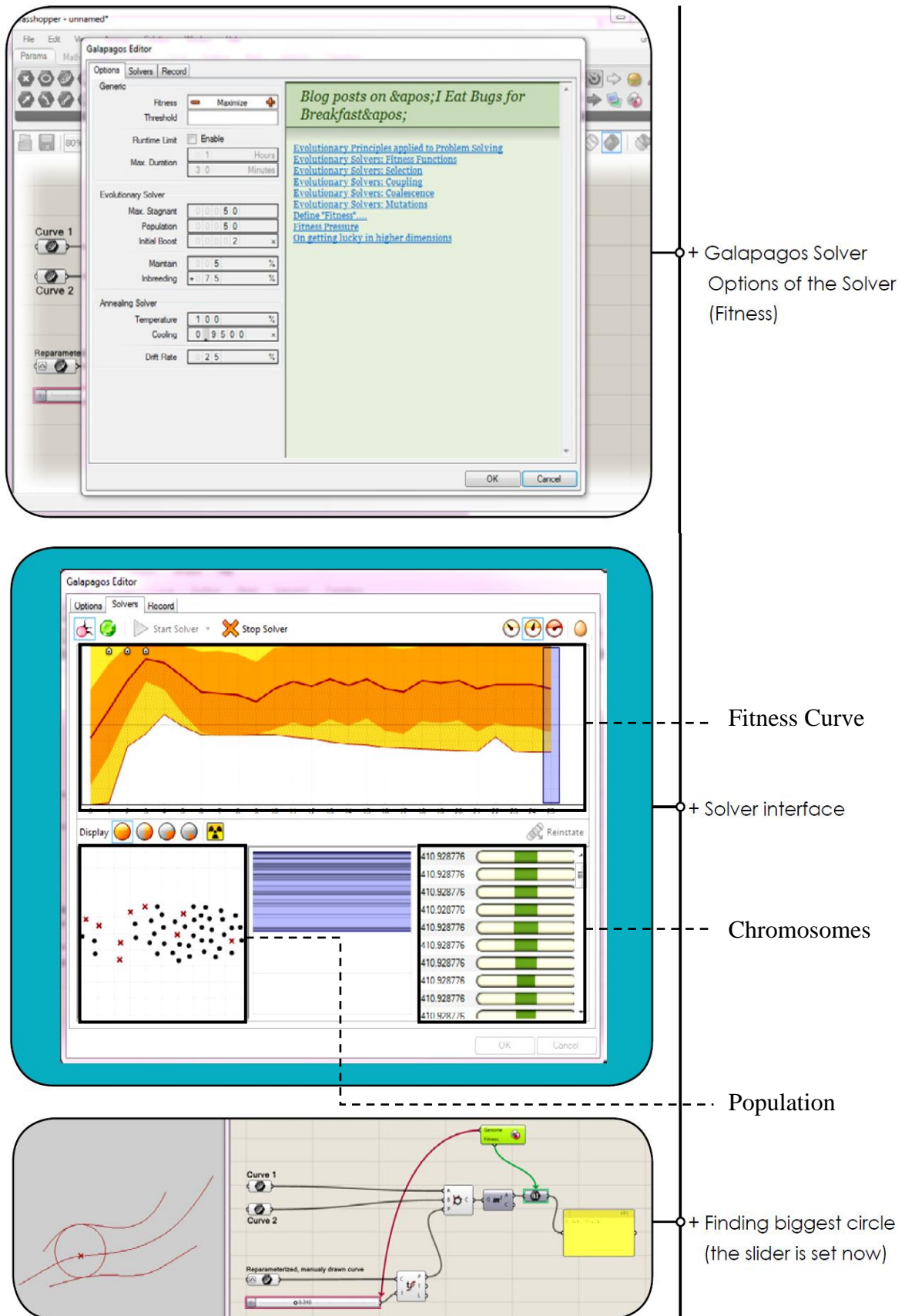


Figure 3.14: Galapagos interfaces and the setup of simple optimization example.

### 3.4.2 Diva for Rhino and Grasshopper

Diva for Rhino was developed at the beginning at Graduate School of Design at Harvard University as a plug-in for simulating daylight and energy then further development was made by Solemma LLC. DIVA-for-Rhino lets users to perform a series of environmental performance evaluations for buildings and urban landscapes including Radiation Maps, Photorealistic Renderings, Annual and Individual Time Step Glare Analysis, LEED and CHPS Daylighting Compliance, and Single Thermal Zone Energy and Load Calculations.

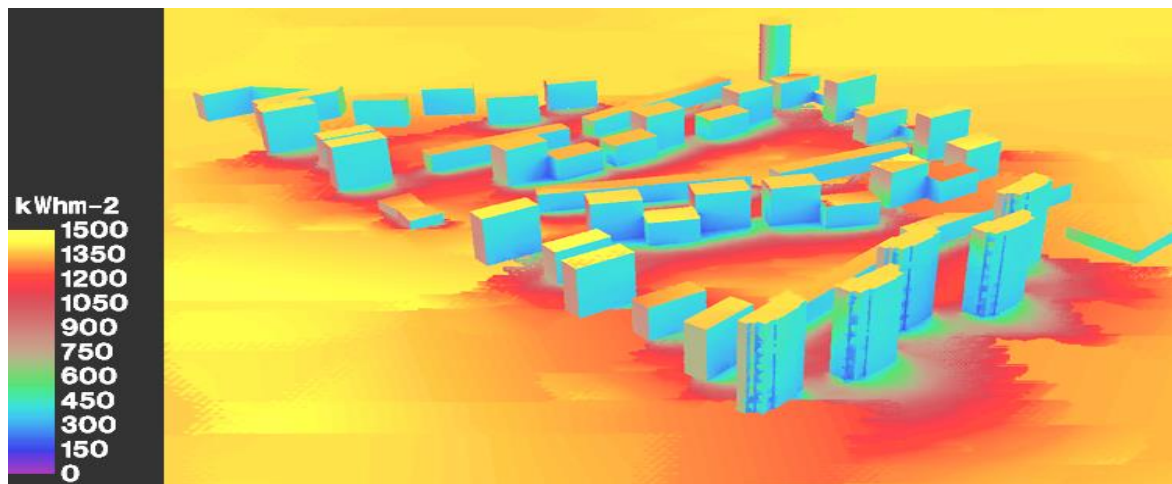


Figure 3.15: Example of a solar radiation map using Diva, [Available online] <http://diva4rhino.com/user-guide/simulation-types/radiation-maps> [accessed October 5, 2012].

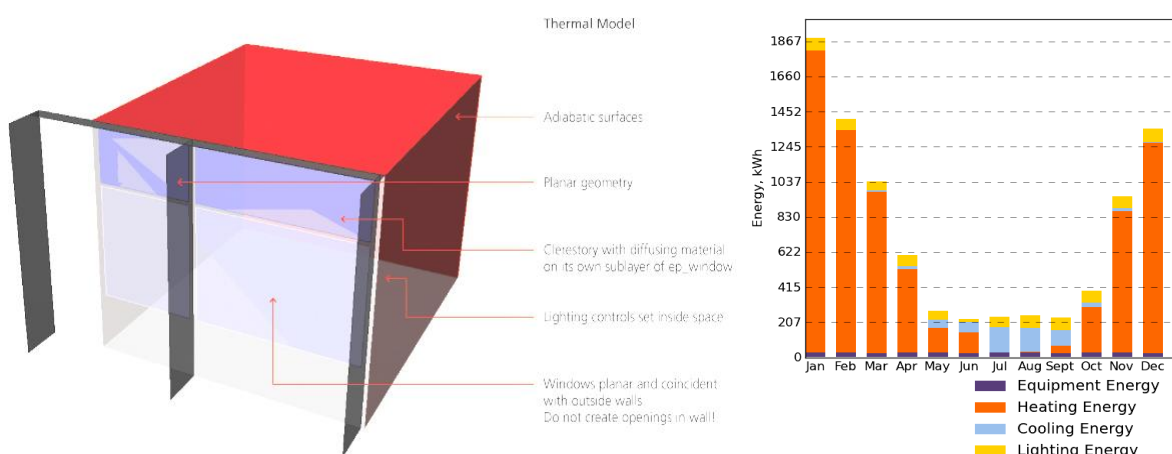


Figure 3.16: Example of a thermal analysis using Diva, [Available online] <http://diva4rhino.com/user-guide/simulation-types/thermal-analysismaps> [accessed October 5, 2012].

Diva for Rhino uses Radiance to simulate solar radiations and generate radiation maps Figure (3.15), render photorealistic images and daylight studies. For the thermal analysis it uses Energy Plus to simulate thermal behavior for a single zone with the ability to generate results of energy consumptions Figure (3.16). Diva is also fully integrated within Grasshopper and uses to components to translate the geometry to Energy Plus via Viper and to Radiance via Diva Daylight Figure (3.17).

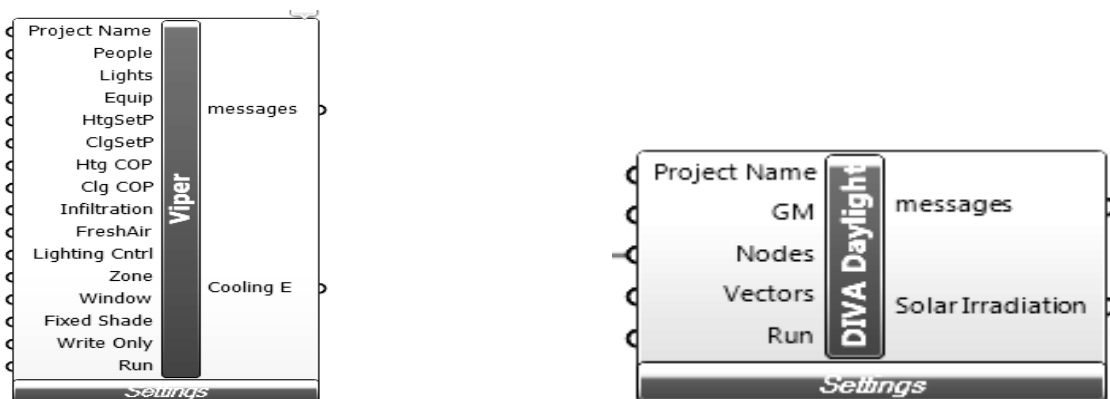


Figure 3.17: Diva components in Grasshopper Viper and Diva Daylight.

### 3.4.3 ANSYS CFX

ANSYS CFX software is a high-performance, general purpose fluid dynamics program that has been applied to solve wide-ranging fluid flow problems. The program is underdevelopment since 20 years and many advance algorithms are implemented in the concepts of ANSYS CFX hard core programming.

Many studies are done using ANSYS CFX for outdoor comfort and urban ventilation (Blocken et al, 2012) used ANSYS CFX for CFD simulation for pedestrian wind comfort and wind safety in urban areas: General decision framework and case study for the Eindhoven University campus, (Figure 3.18).

Many other studies using CFX were made on the indoor climate design for buildings to predict and design ventilation, temperature distribution, HVAC systems sizing and optimization, comfort indicators and others, (Hajdukiewicz et al, 2012) used the CFX CFD to study and design Formal models of naturally ventilated indoor environments



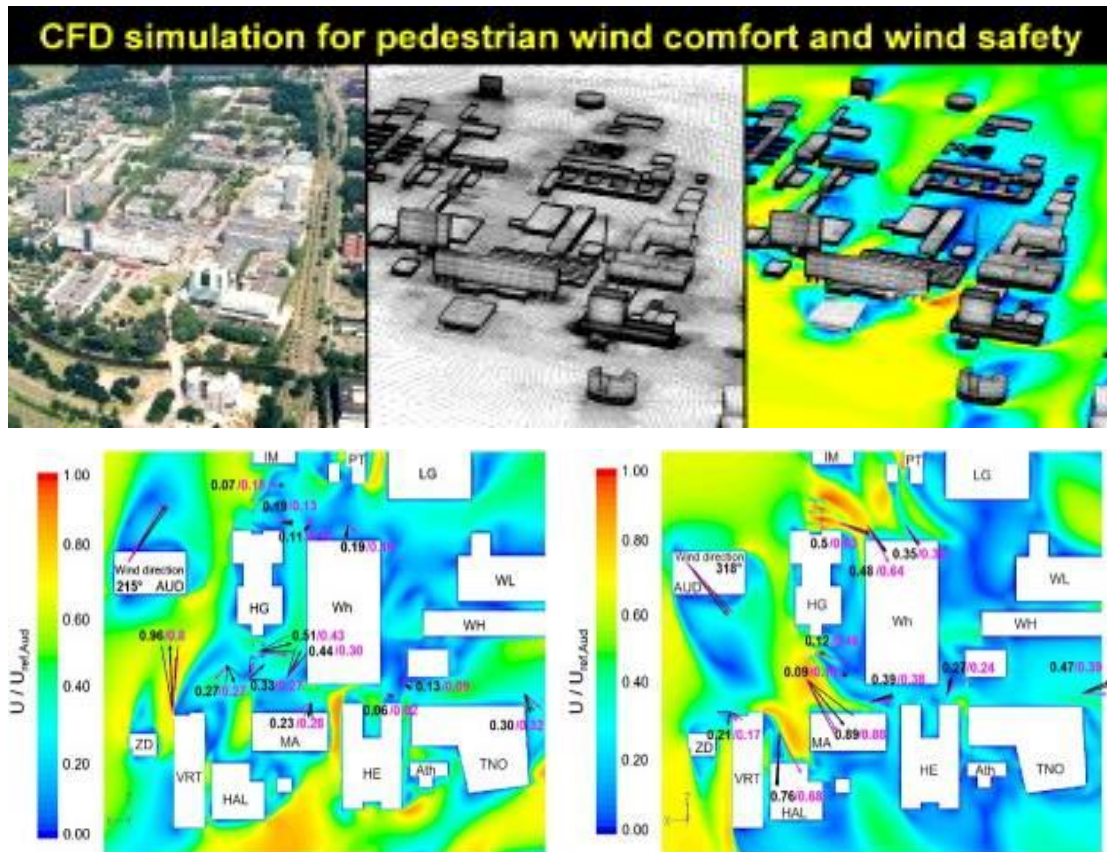


Figure 3.18: ANSYS CFX CFD simulation and analysis From (Blocken et al, 2012)

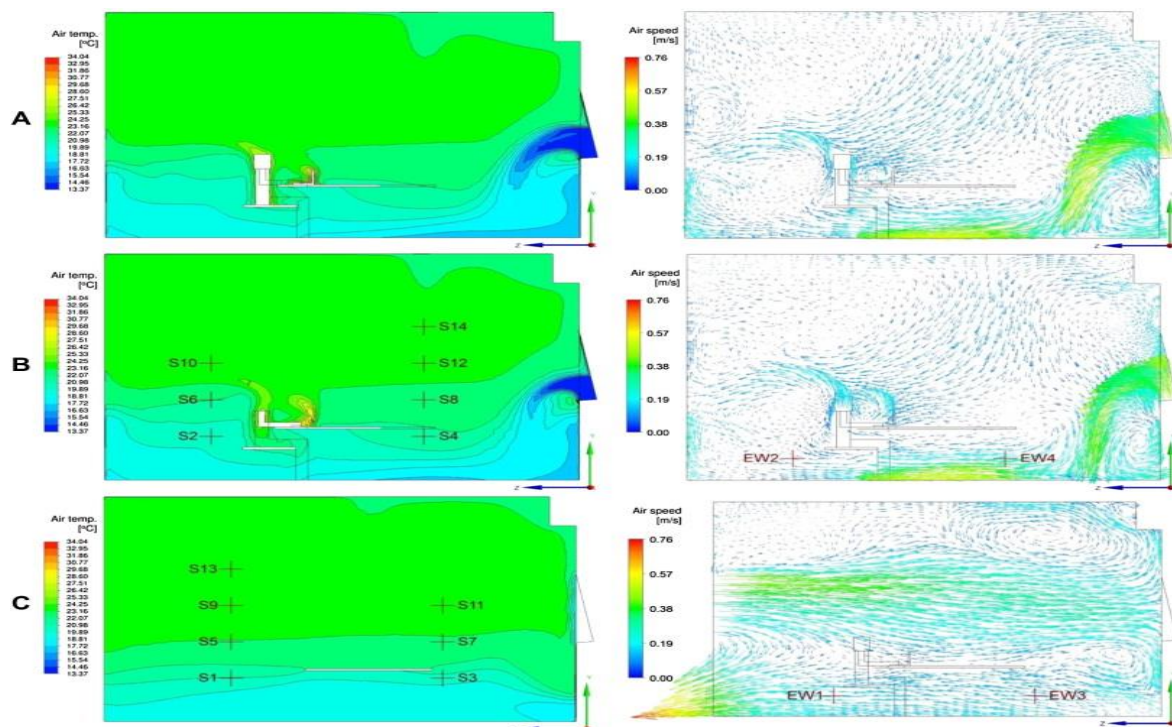
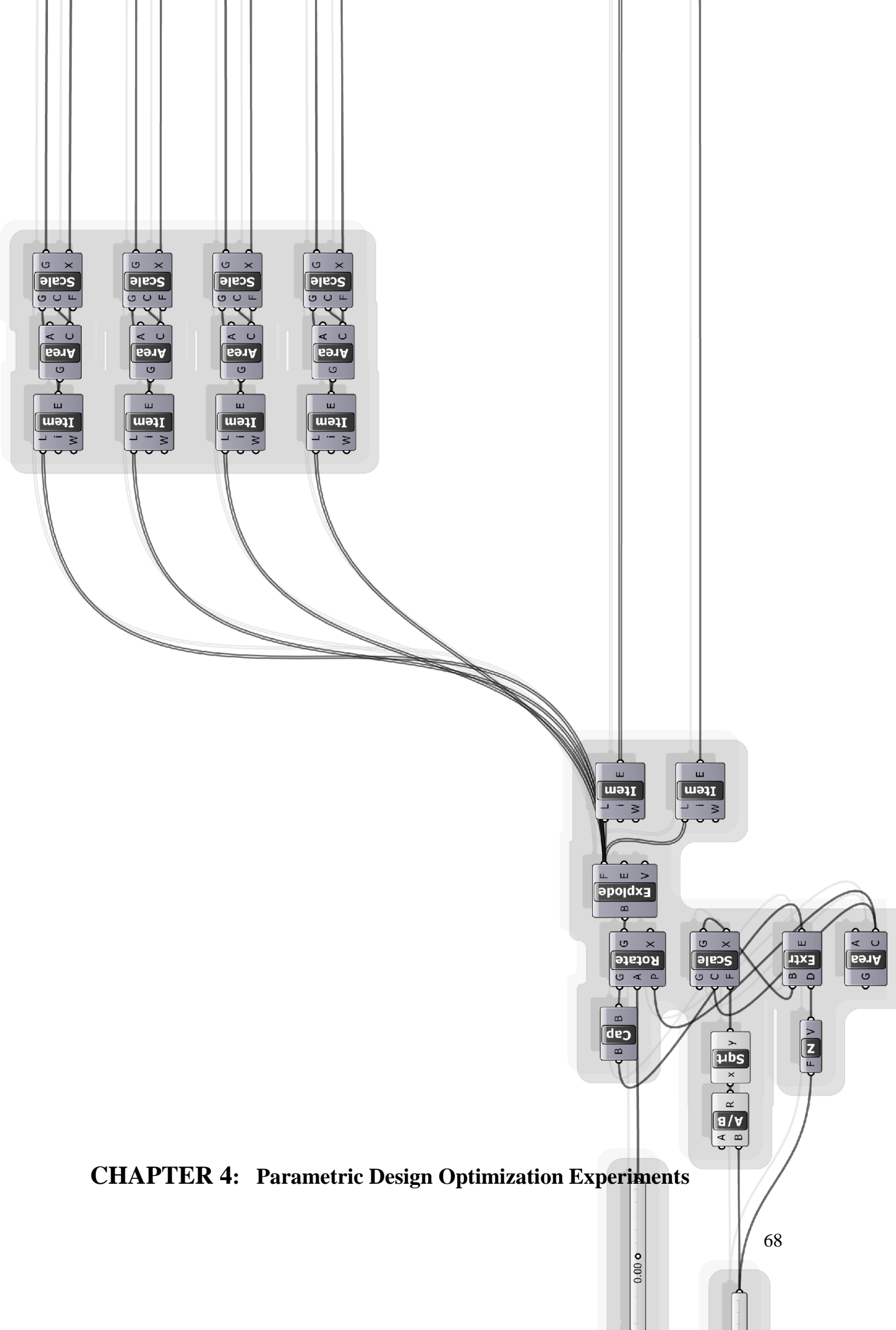


Figure 3.19: ANSYS CFX indoor CFD simulation, From (Hajdukiewicz et al, 2012).

CHAPTER 4: Parametric Design Optimization Experiments





In this chapter the setup of the parametric design experiment and environmental inputs of the experiment are discussed. The first section is Introduction to the experiment location and its urban morphology and style. Then, the climate characteristics and weather data are analyzed to the experiment study. Modelling and optimization setups for the experiments are the last two sections in this chapter, where the input and output data parameters are discussed in more details which in this case represent the initial steps in building the simulation experiment.

#### 4.1 Case Study Location

Dubai Silicon Oasis span on 7.2 million square meter in Dubai city in the United Arab Emirates Figure (4.1). The master plan is divided into five main zones industrial, commercial, educational, living and residential and public facilities with a population of 162,400, Figure (4.2).

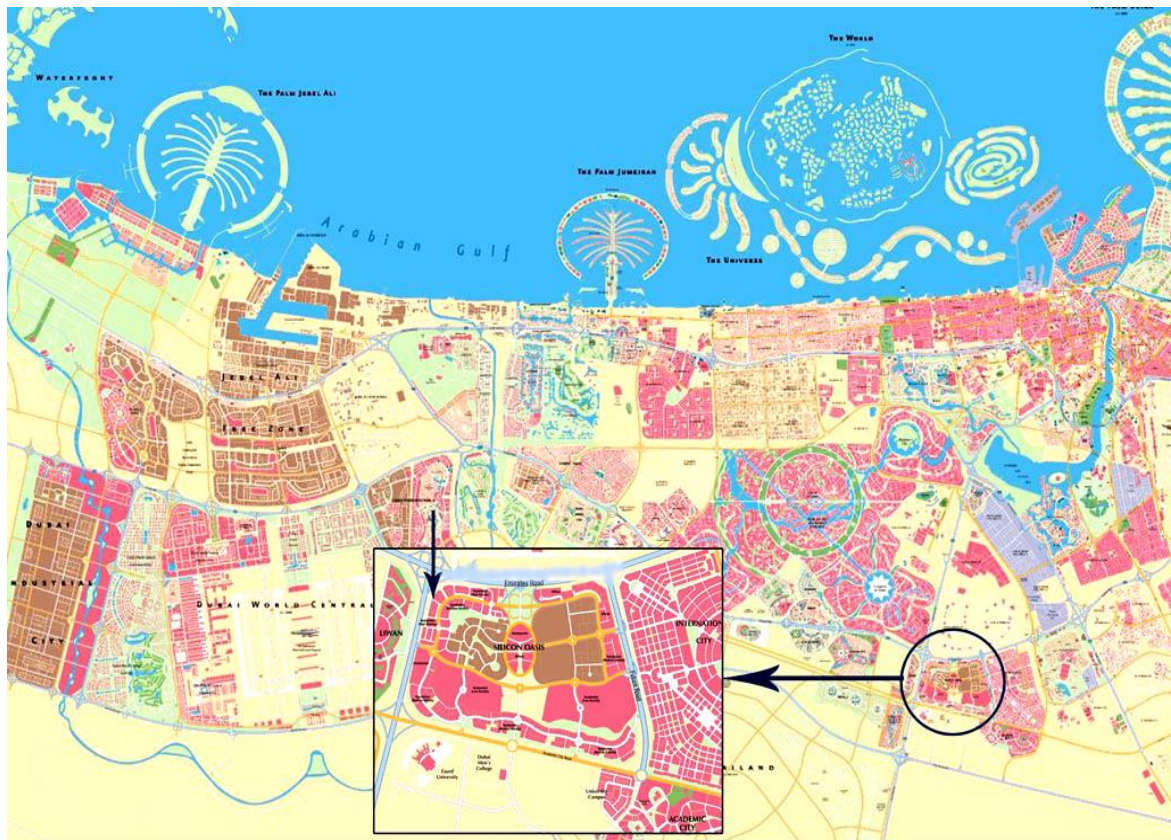


Figure 4.1 Dubai Silicon Oasis locations, From (Google Earth).



Figure 4.2 Dubai Silicon Oasis Zones and master plan. (<http://www.dsoa.ae>, accessed October 5, 2012).



Figure 4.3: Dubai Silicon Oasis main perspective. (<http://www.dsoa.ae>, accessed October 5, 2012)

Dubai Silicon Oasis is designed as a hi-tech ecosystem which offers businesses a plethora of advantages including a state-of-the art infrastructure, in-house business services and strong business support such as technology investment incentives for large enterprises, entrepreneurial support, an incubation centre and venture capital funding.



The multi-zone design of Dubai Silicon Oasis divided the master plan into zones of symmetry. These zones are reflected on the urban morphology of the whole master plan and furthermore, it created big step difference in the building heights, usage and size.

This character of the Silicon Oasis urban morphology was taken into consideration in this research and one of symmetry was taken to be the subject to the experiment for parametric optimization, Figures(4.4, 4.5).



Figure 4.4: Dubai Silicon Oasis urban morphology and research experiment location.



Figure 4.5: Dubai Silicon Oasis main perspective to the subject of experiment.

## 4.2 Climate and Weather Data

Dubai has a unique climatic zone, which affect the design and the strategies that can be employed to achieve a healthy and sustainable ecological design. The outdoor severe weather imposes on us to use the best cutting edge design strategies and technologies to delight it. Another top list issues about Dubai weather and its climatic zone, the hot humid and desert characteristics are the prominent in such climate zone. Scarcity of water for domestic and agriculture in the UAE is a major obstacle when planning new sustainable buildings and master plans. So, UAE climate is a very hot humid tropical desert and dusty climate which make it very challenging to design a social outdoor spaces and sustainable environment.

Winds at the project site are predominantly from west northwest directions with the second most frequent direction being west southwest. Shamals winds (strong winds coming from the northwest) are often associated with storms because they can last several days during the winter season.

Recorded wind speeds at Dubai Airport are shown in Figure (4.6). Based on Dubai Airport data, design wind speeds at the project site (sheltering or funneling effects induced by future structures on neighboring plots should be considered) were assessed for the project.



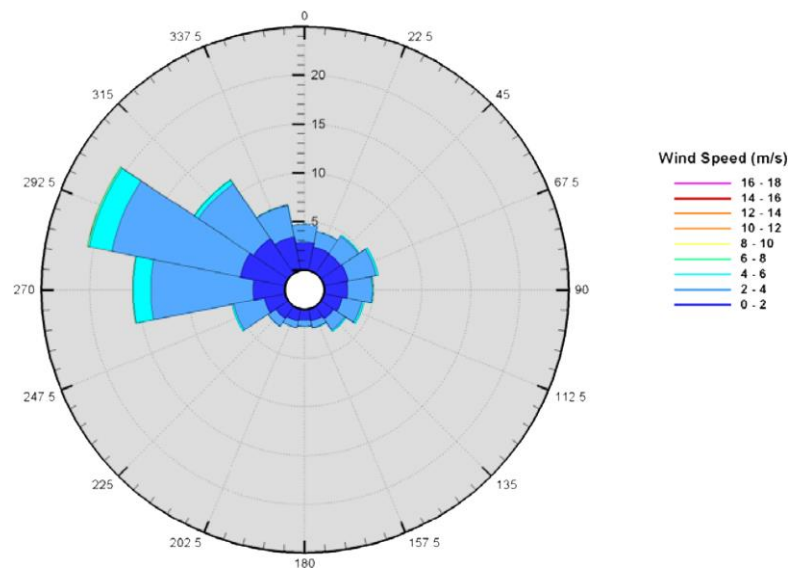
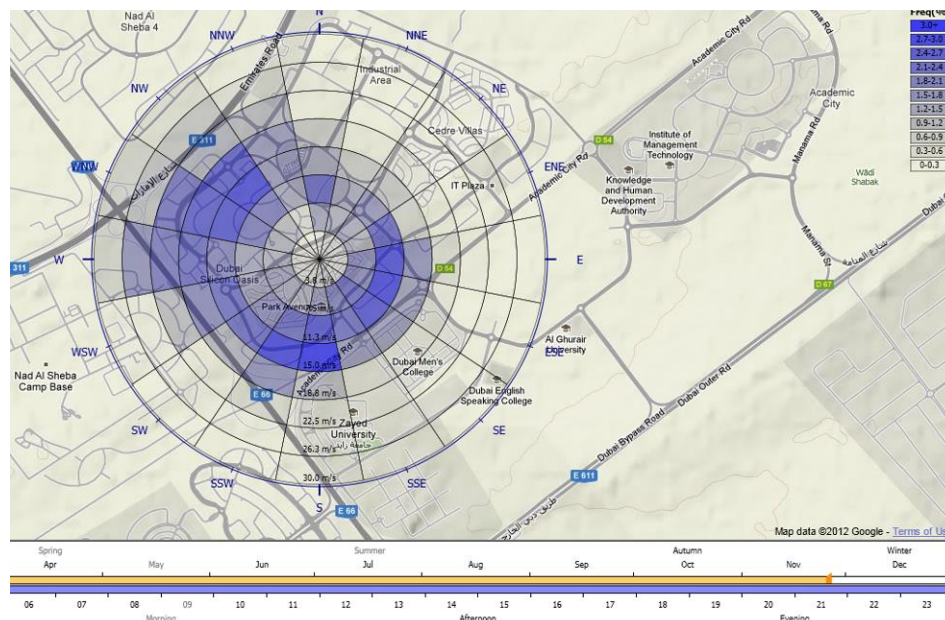


Figure 4.6: Recorded wind speeds at Dubai Airport, Ecotect.

Winds (even slightest breeze) at the project site play a very important job in delighting the severity of the weather, if it is induced and directed with the right urban morphology and architecture features. The continuity of the wind movement over landscape (transpiration) or bond of water can heavily improve the ambient temperatures outside (even inside) noticeably.



### Stereographic Diagram

Location: Dubai,  
Sun Position:  $-64.9^\circ, 0.9^\circ$   
HSA:  $-64.9^\circ$ , VSA:  $2.2^\circ$   
© Weather Tool

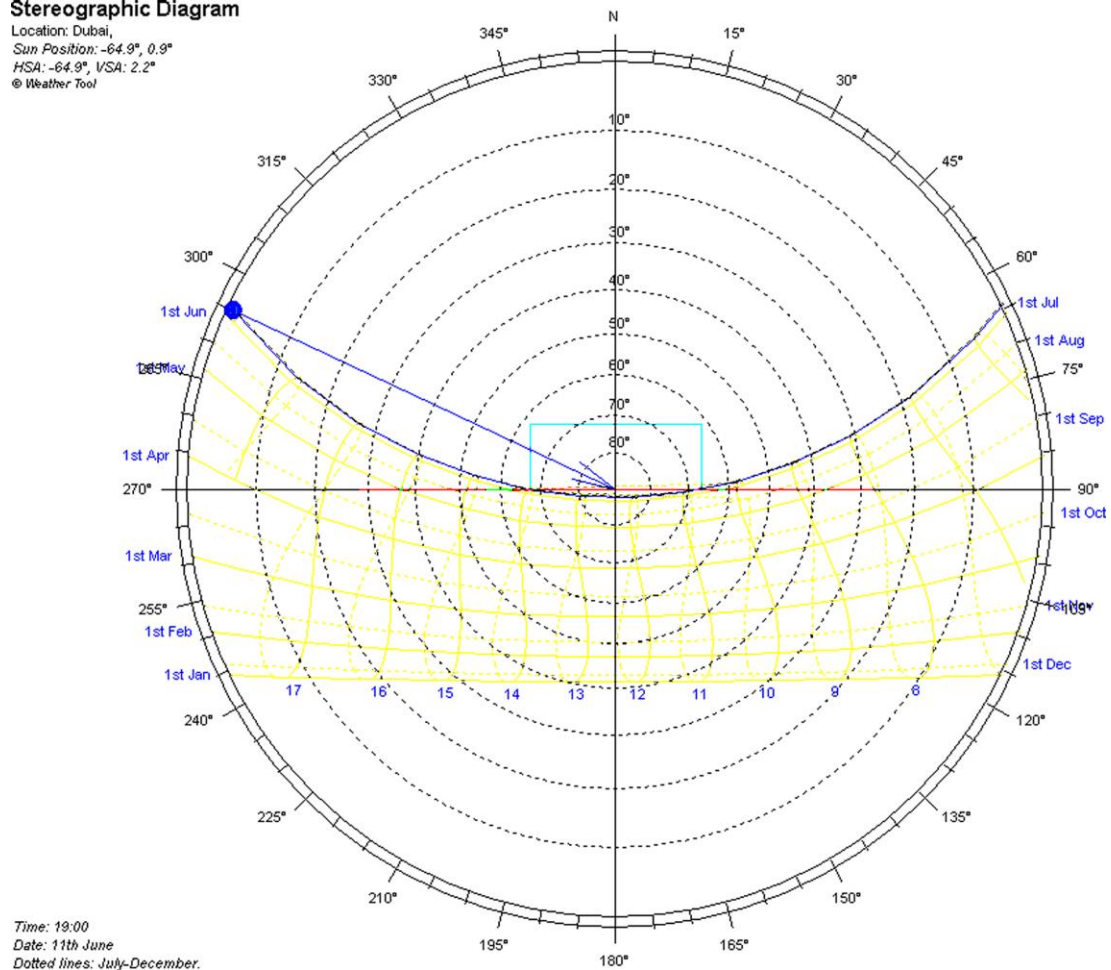


Figure 4.8: Dubai Silicon SUN-Path, Ecotect.

The location of Dubai according to the equator gives the sun a path almost to the center, Figure (4.8). This implies that mutual shadowing is small and difficult to design for it. Sun accesses are available most of the year with some days of partially cloudy and rain fallings are minimal.

The scarcity of the Annual rainfalls in UAE make it very challenging to design urban and architectural features that can use or store storm water for domestic and agricultural usages, and it has made water one of the most valuable resource in UAE. Another conservation measures and technologies should be considered when designing for any usage of water. Conserving water in the UAE in direct way lead to conservation in energy, CO<sub>2</sub> emission and fossil fuel usage.

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Average Maximum Temperature °C (1984-2009)	23.9	25.4	28.4	33.0	37.7	39.5	40.9	41.3	38.9	35.4	30.6	26.2
Average Minimum Temperature °C (1984-2009)	14.3	15.5	17.7	21.0	25.1	27.3	30.0	30.4	27.7	24.1	20.1	16.3
Mean Rainfall (mm) (1967-2009)	18.8	25.0	22.1	7.2	0.4	0.0	0.8	0.0	0.0	1.1	2.7	16.2
Mean # of Days with Rain (1967-2009)	5.5	4.7	5.8	2.6	0.3	0.0	0.5	0.5	0.1	0.2	1.3	3.8
Sunshine Hours / day (1974-2009)	8.1	8.6	8.7	10.2	11.3	11.5	10.7	10.5	10.3	9.9	9.3	8.2
Mean Sea Temperature °C (1987-2009)	20.9	20.6	22.3	25.0	28.5	31.2	32.2	32.8	31.9	29.7	27.1	23.3

Annual Climate and Weather of Dubai

Figure 4.9: Dubai Annual rainfalls Dubai Airport, (<http://www.dia.ae/DubaiMet/MET/Climate.aspx>)

The weather data file that is used in this research is obtained from the US Department of Energy and can be downloaded from the website. Unfortunately, there is no weather file data associated with Dubai specifically instead there is Abu Dhabi file is available and which is going to be used. Furthermore, the file are not updated since recent and may be two to three years old, but it can be acceptable to use it to Dubai for the simulation the input weather data file.

### 4.3 Optimization Experiments Set Up

This section is dedicated to discuss the model set up for the optimization process. Two setting up are described, the CFD model setting up for the optimization and the solar/energy setting up. The natural order of the form transformation is used to follow step by step the transformation on the model from the initialization to the simulation and back to the results and Galapagos fitness. The visual style is used here also to track these transformations in logical order and make a sense of the whole process. At each step the group of Grasshopper simulation components or form transformation components are illustrated and with the status of the model at that step with the internal set up of each component and associated files.

### 4.3.1 Energy and Solar Optimization Experiment Modelling and Setup

Since we are considering concept design optimization on urban morphology scale and the long run and iteration of GAs to optimize and find the best solution, the model of each building is simplified as an abstract single zone box that was generated by taking the offset from the land plot edge as per the local code. The other simplifications are in setting up the glazing facade or windows of the building as taking 45% of the area of the façade, as per Dubai municipality 10% of the floor plate is the minimum( DM, Building regulation Handbook), Figure (4.10).

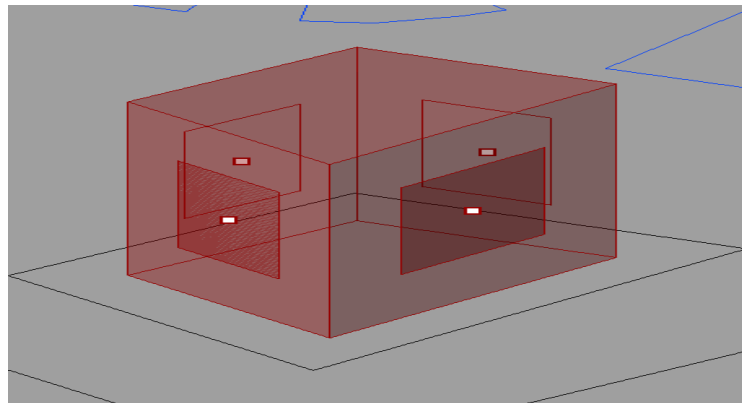


Figure 4.10: The simplified building model for the optimization process.

Figure (4.11) shows the complete one building Grasshopper visual scripting components that transform the model and send it to Energy Plus and Radiance and collect the results of the simulation to be optimized this one process of sending and receiving and evaluating of all the building is single iteration.

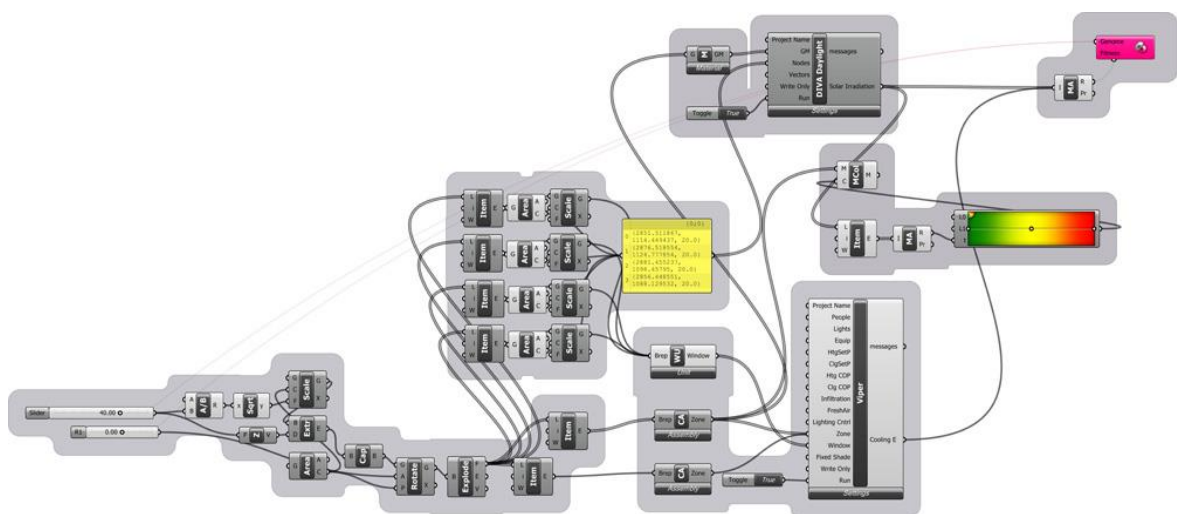
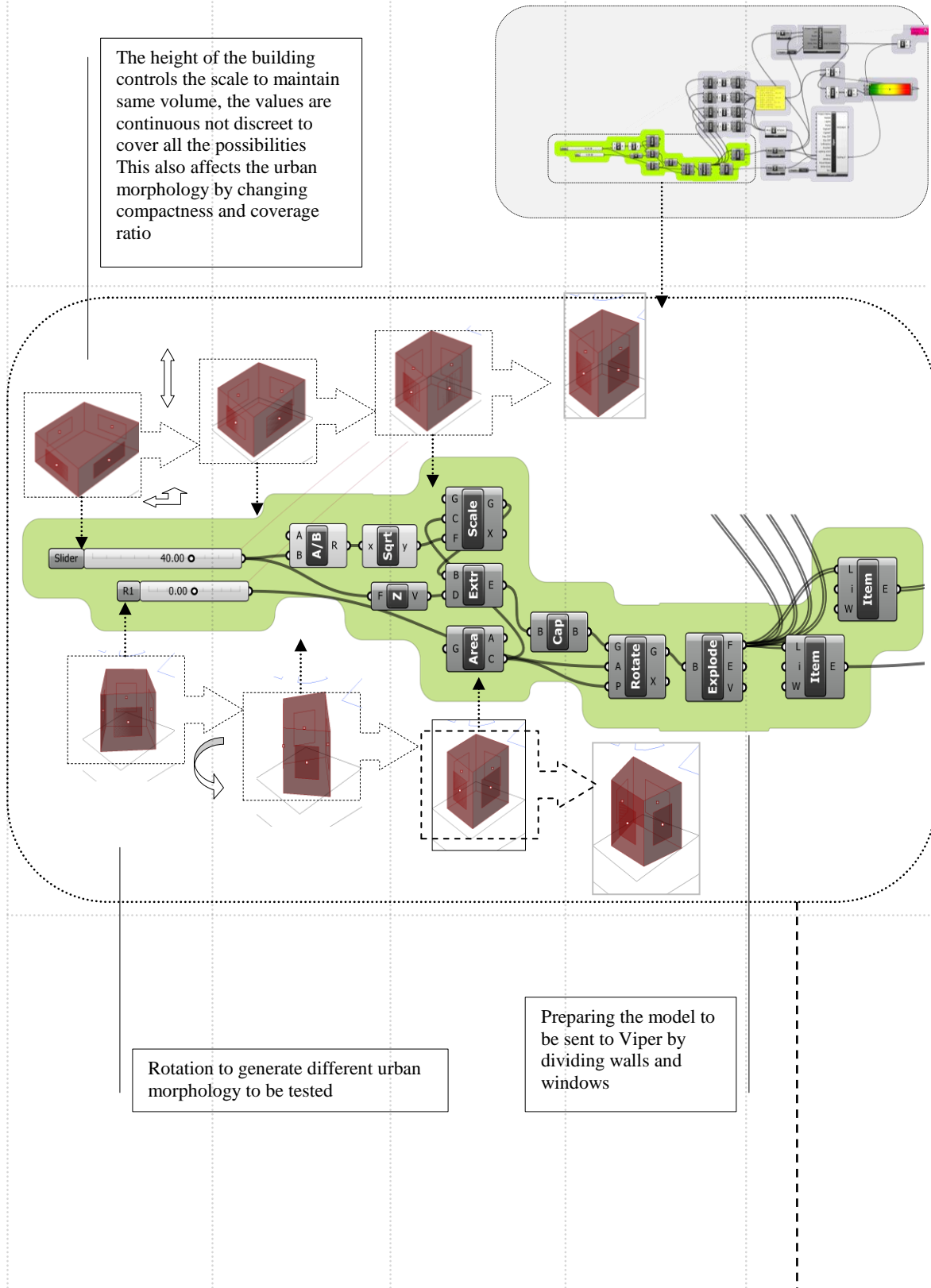
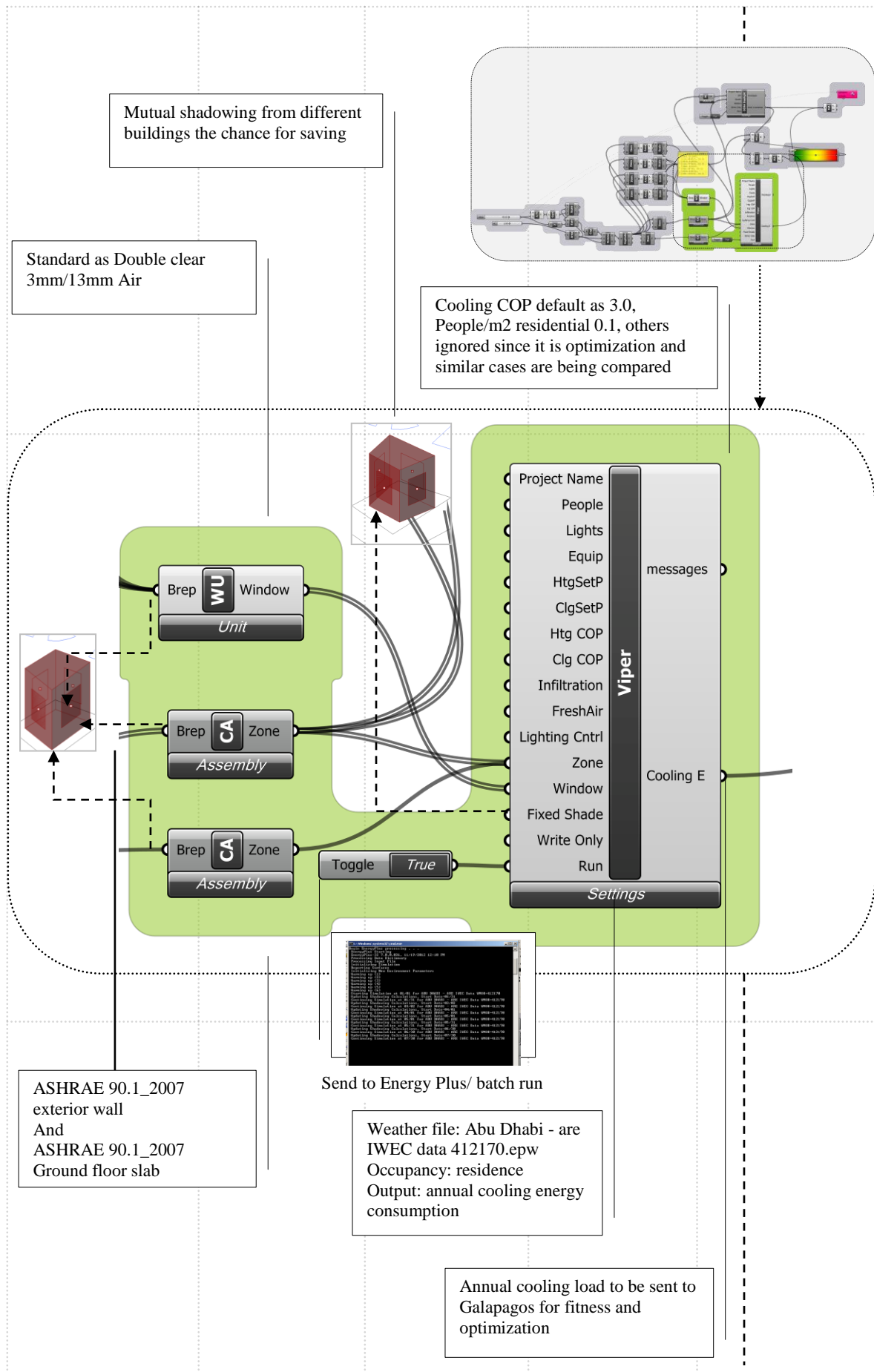


Figure 4.11: Single building unit in Grasshopper visual scripting components

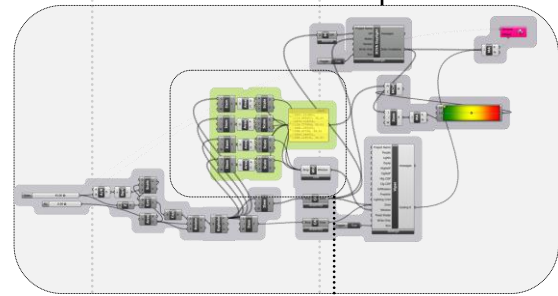


As mention in the introduction of this section a visual walk through of the process of transforming and sending the model to the simulation and retrieving the results in order to be optimized by GAs Galapagos is explained the following part of this section.

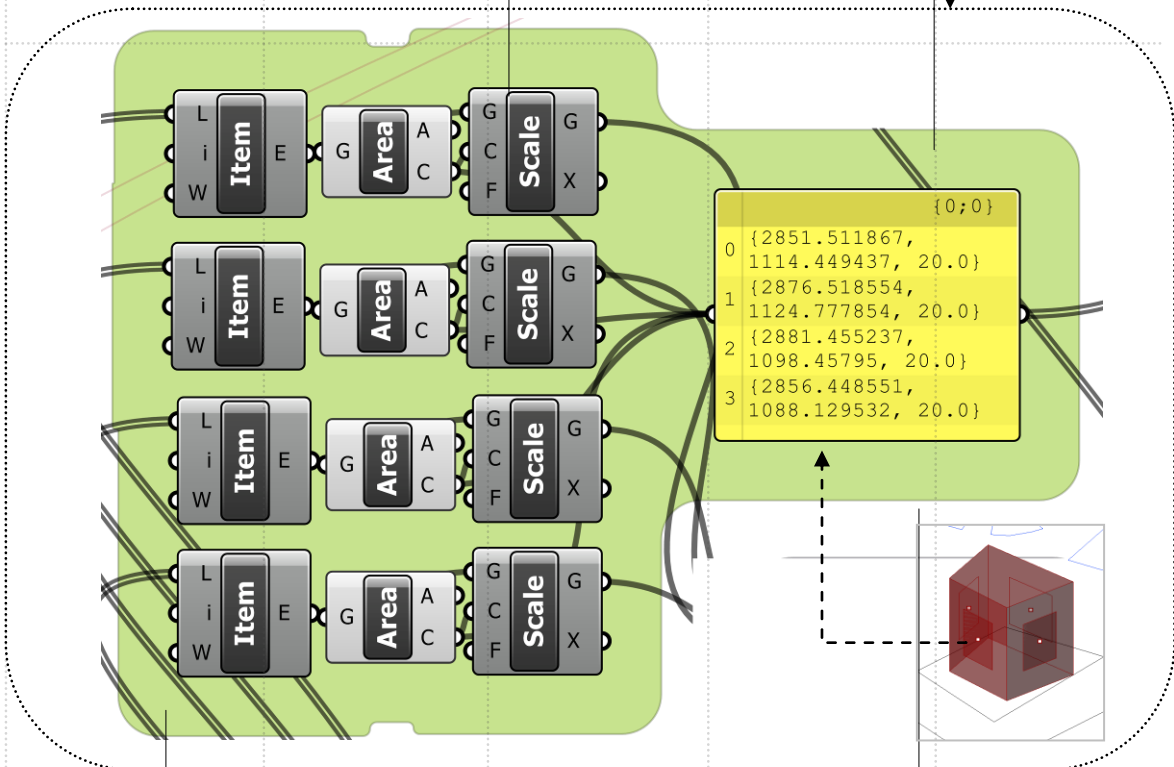




Scaling the wall by 45% to represent the ratio of windows in standard facade



Mutual shadowing from different buildings the chance for saving



The four faces of the block after the exploding to be used as windows and walls

Coordinates of the probing points on the windows faces to collect solar radiation by the Daylight component and radiance



As in case of the villas included in the optimization their morphology is determined only by the rotation in chance to tweak their orientation according to the sun path and angles of radiation. Villas' blocks have another good chance when they fall in the shadow of a tall high residential building that throw shadow on them most of the time and by this their thermal behaviour will be difference and delight.

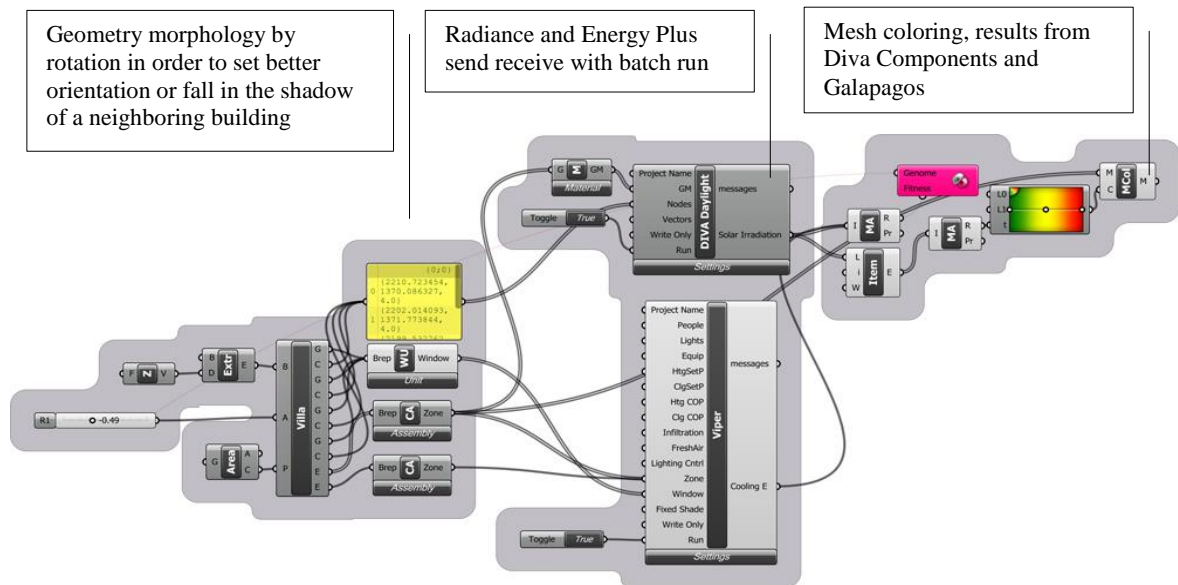


Figure 4.12: Villa unit in Grasshopper visual scripting components

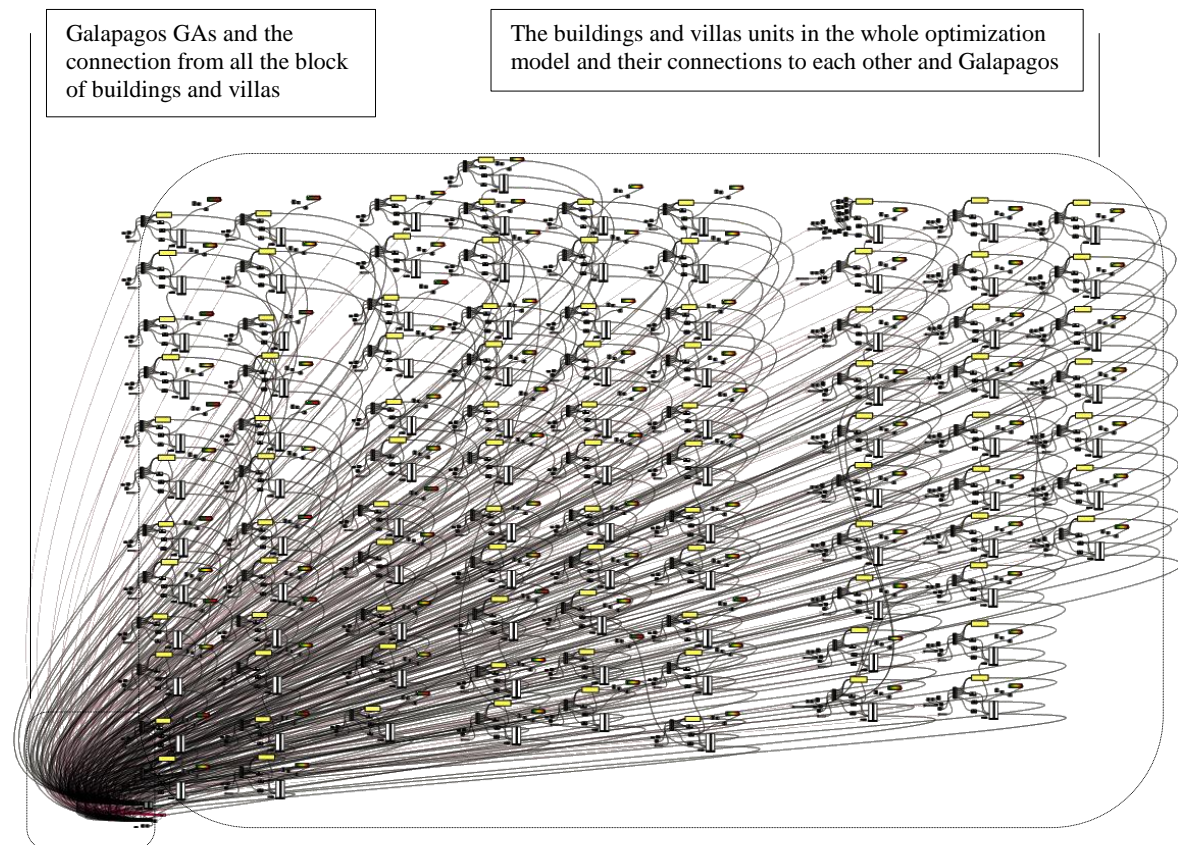


Figure 4.13: Villas and buildings units in Grasshopper in the whole optimization model.



### 4.3.2 CFD Optimization Experiment Modelling and Setup

The optimization set up using CFX as CFD optimizer is done in different ways other than the previous optimization. The differences come from the extra modelling required by the CFD and its meshing requirements. The CFD normally- and specially the way ANSYS CFX works-require fluid medium (tunnel) rather than solid closed separated objects with surfaces. From previous requirements for the CFD to work with a model it is clear that the transformation on building from rotation to scaling and extrusion should be translated into a tunnel for the fluid to flow and which in this case using a subtraction of all the building from the fluid medium and create the tunnel Figure (4.13). Another urban morphological transformation introduced to this experiment other than rotation, scaling and extrusion; smoothness to the edges of the buildings when they rotate to increase their aerodynamics and decrease urban roughness.

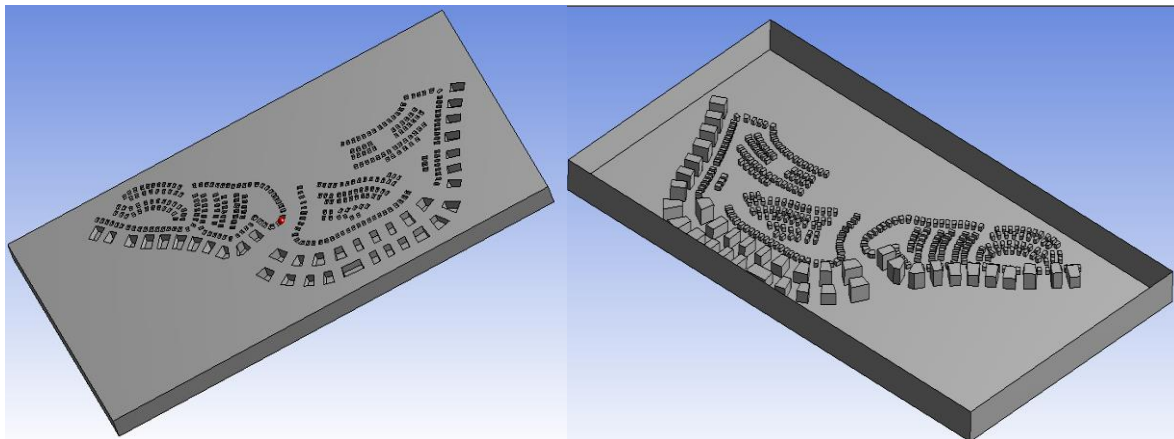


Figure 4.14: The model as a fluid medium in ANSYS CFX Design Modeller top (open)/bottom.

Another issue arises when connecting Grasshopper with ANSYS CFX. The case is different since there is no built-in plug-in or direct communication between the two programs, to overcome this issue a C# language component is used to trigger an auto-run Python script that translates the geometry from Grasshopper to CFX. The auto-run Python script takes in charge of loading the new geometry, launching ANSYS Workbench in batch mode and updating the project. After the update the auto-run Python script reads the output parameters from the CFX Post and writes them back to a file and finally collects them back to Grasshopper to be evaluated for fitness and optimization.

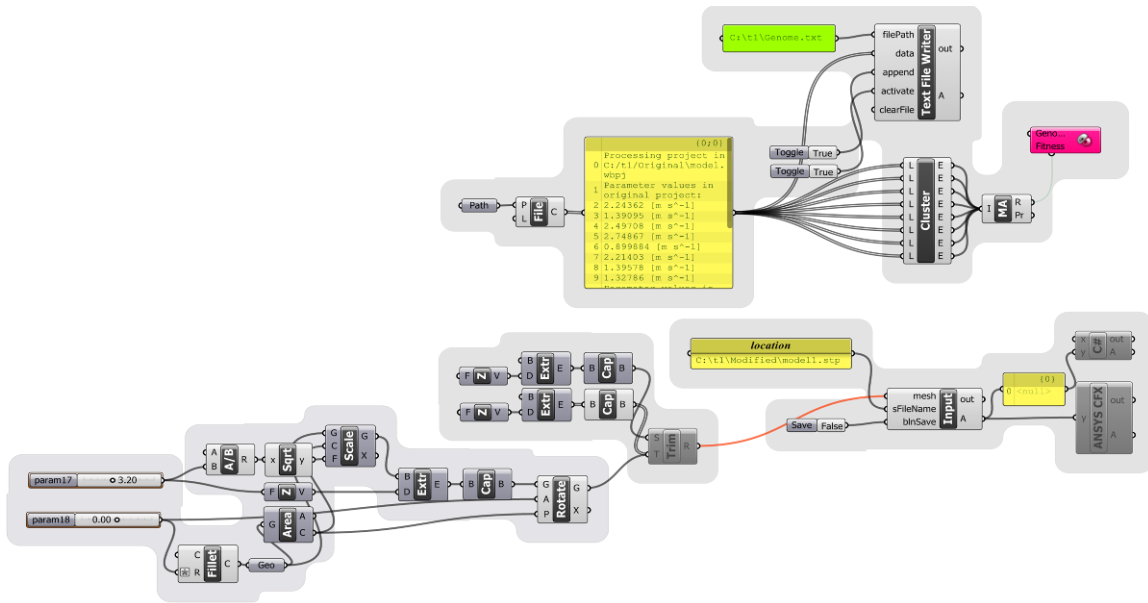


Figure 4.15: Single building representation in Grasshopper CFD experiment.

Figure (4.15) shows a single building representation in the Grasshopper CFD experiment and how it is connected to the exporter to CFX and Galapagos GAs.

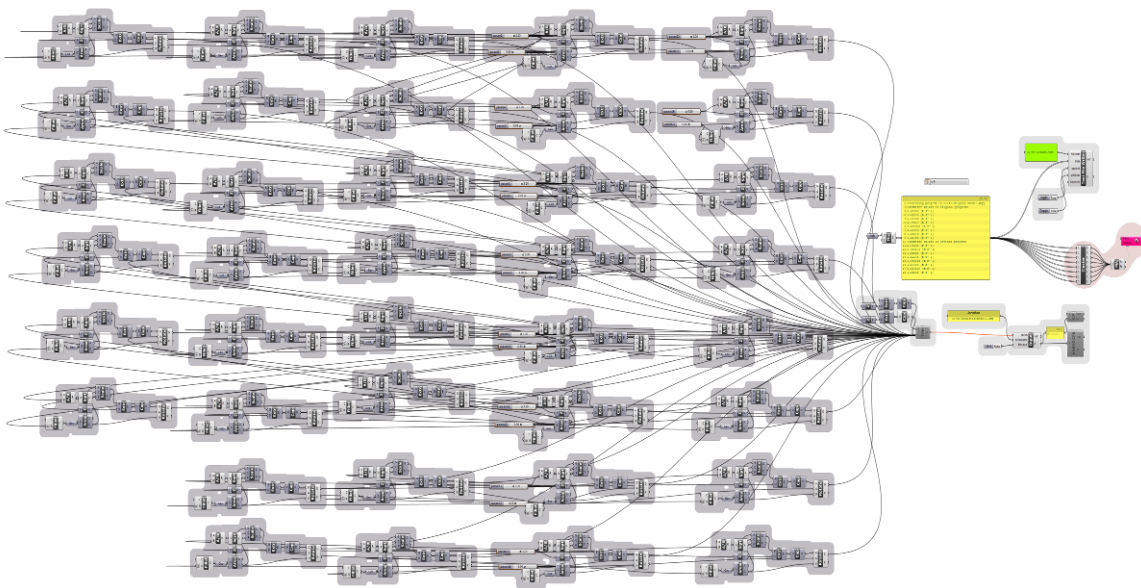
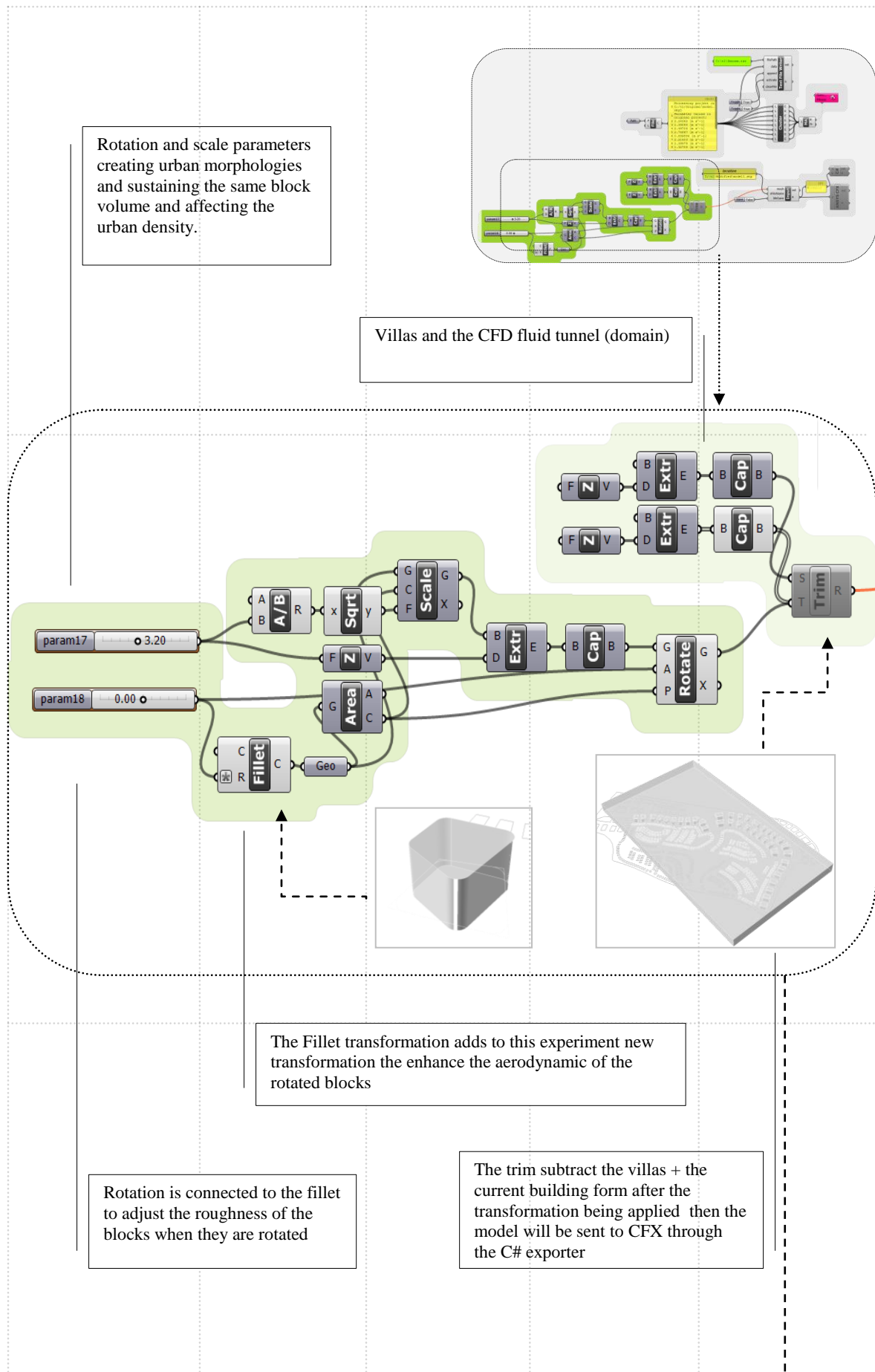


Figure 4.16: The complete representation in Grasshopper CFD experiment.

Figure (4.16) shows the complete Grasshopper CFD experiment with all the connections and transformations. In the following a detailed visual walkthrough is described of the CFD experiment from model to Grasshopper to CFX and back to Galapagos for optimization.





File location to the exported geometry from Grasshopper to \*.stp for CFX to start the analysis

```

C# script make Galapagos wait for the results from CFX before exporting another Genome (see Appendix):
private void RunScript(object x, object y, ref object A)
{
    System.Threading.Thread.Sleep(5000);
}

```

location  
C:\t1\Modified\model1.stp

Save False

mesh sFileName bInSave Input out A

{0}  
0 <null>

C# out A

ANSYS CFX out A

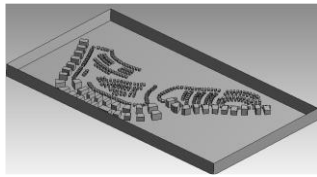
Toggle true/false to export the geometry to CFX

VB script exports Geometry from Grasshopper to CFX in the format \*.stp (see Appendix):  
app.RunScript("\_export " & sFileName & " \_Enter")  
app.RunScript("\_delete")  
A = 0

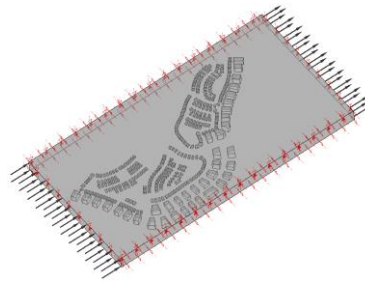
```

C # scripts initiate (SendtoCFX) Python script which loads the exported geometry to CFX, run the simulation and write the results to a text file (see Appendix):
{
System.Diagnostics.Process ANSYS = new System.Diagnostics.
ANSYS.StartInfo.FileName = "C:\\Program Files\\ANSYS Inc\\
ANSYS.StartInfo.Arguments = "-B -R C:\\t1\\SendtoCFX.py";
ANSYS.Start();
}

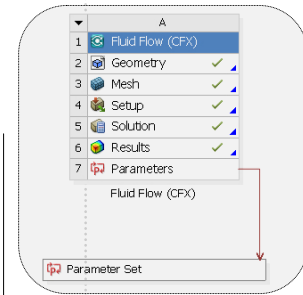
```



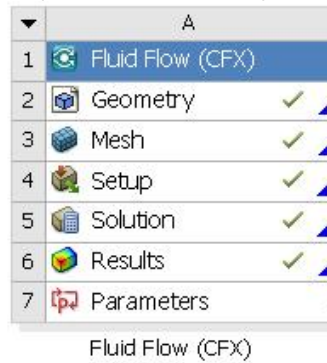
CFX Design Modeler attaching the \*.stp file exported from Grasshopper ready for meshing (see Appendix)



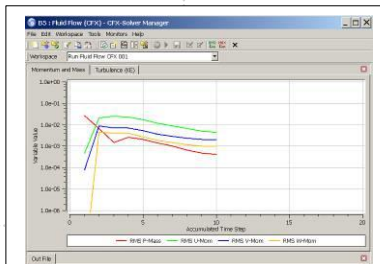
CFX setup with inlet of (4m/s) as most dominant wind on experiment location  
Fluid model K-Epsilon (see Appendix)



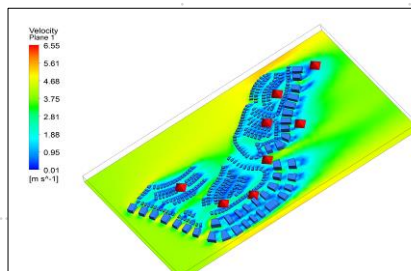
ANSYS Workbench and CFX



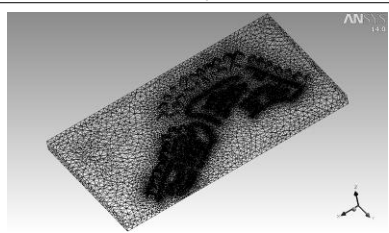
Parameter Set



CFX Solver (see Appendix)



CFX Post complete solution showing the location of the probing points-red (see Appendix)

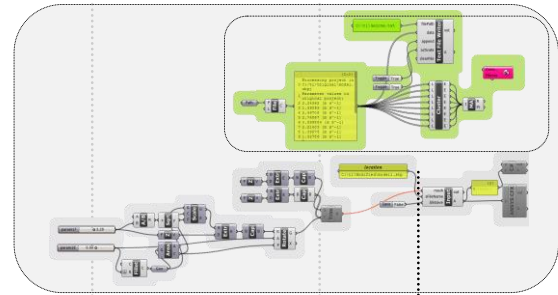


CFX meshing the model to be ready for solution setup (see Appendix)

Outline of All Parameters			
	A	B	C
	ID	Parameter Name	Value
1			
2	Input Parameters		
*	New input parameter		
		New name	New expression
4	Output Parameters		
5	Fluid Flow (CFX) (A1)		
6	P4	point3	2.2436
7	P2	point1	1.391
8	P3	point2	2.4971
9	P5	point4	2.7487
10	P6	point5	0.89988
11	P7	point6	2.214
12	P8	point7	1.3958
13	P9	point8	1.3279

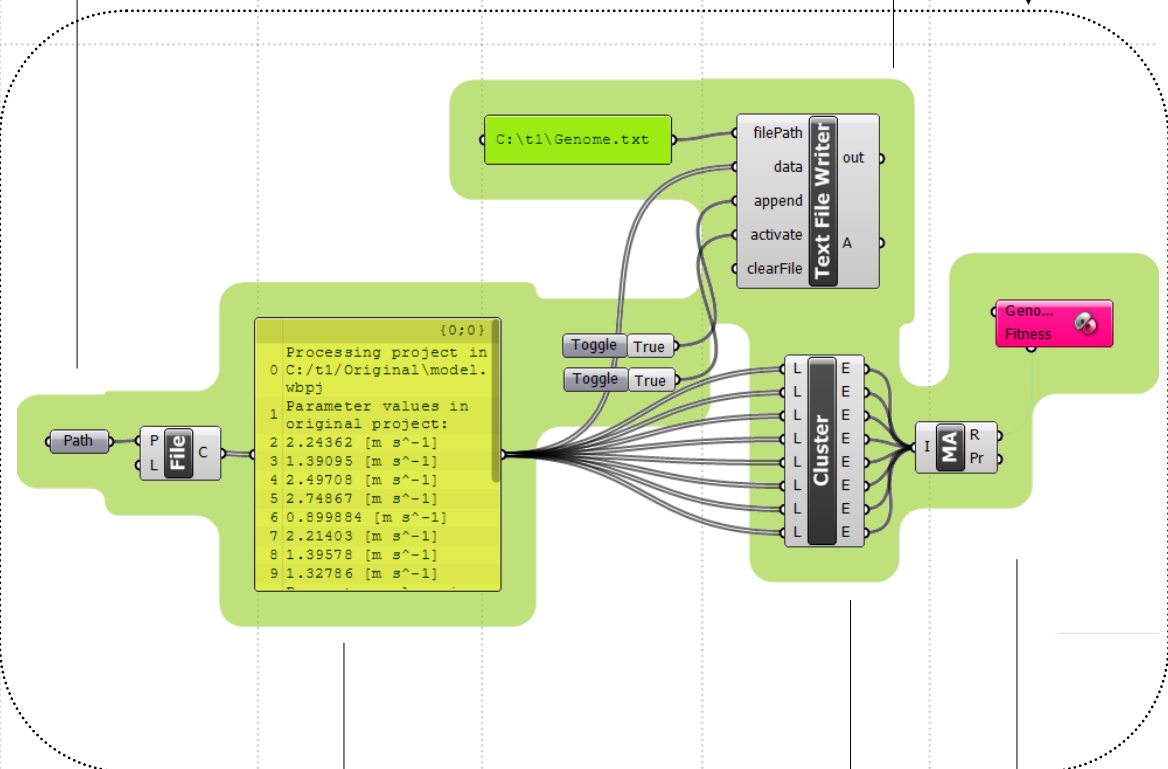
CFX output parameters wind speed at points to be sent back to Grasshopper via text (see Appendix)

Read the results after the CFX simulation batch run finish to be analysed and sent to Galapagos for fitness



VB script to write to a text file (see Appendix):

```
103 Dim objWriter As New System.IO.StreamWriter(filePath, append)
104 For i = 0 To data.Count - 1
105     objWriter.WriteLine(data(i))
106 Next
```

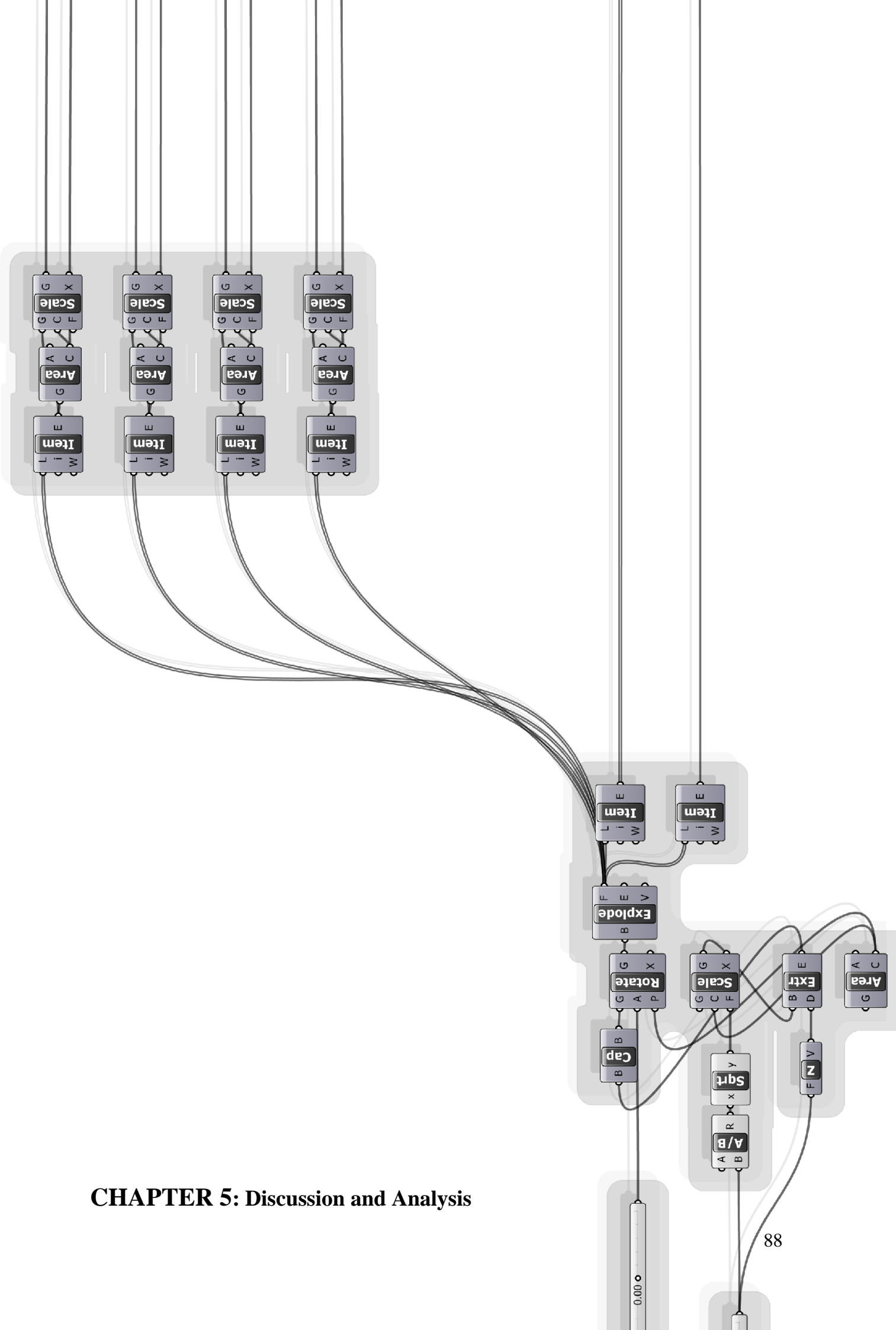


The results of the of the probing points for the wind speed from CFX Post and parameters

All the results from the point parameters from CFX separated to get a list of numbers to be send to Mass addition

Mass addition add all the points after separation to one number to be the fitness function that Galapagos will evaluate and compare to the other generation in order to optimize the urban morphology

CHAPTER 5: Discussion and Analysis



This chapter is a discussion and analysis of the results of the two experiments of optimization energy/solar and CFD optimization. Based on the base case study and as built, a comparison between all the optimized points and the base case is concluded at the end of each experiment analysis. The first section looks at the base case from the point of view of each experiment and tries to highlight the conflicting factors affecting the optimization process. The second section is a detailed analysis of the optimized point and their generation with comparison with the base case to highlight the amount of optimization.

## 5.1 Base Case Study Analysis

The base case study and its urban morphology from the first glimpse doesn't reflect any solar logic neither it reflect any interactive elements. The main basis that formed this morphology in the imagination of the designer probably is the dominance of the car roads, regularity and cubism, international style and the quest for formalism as it is a trend – especially in Dubai-in the mind of the current generation of architect and urban designers Figures (5.1, 5.2).



Figure 5.1: Coloured Base case experiment based on the total solar radiation on windows



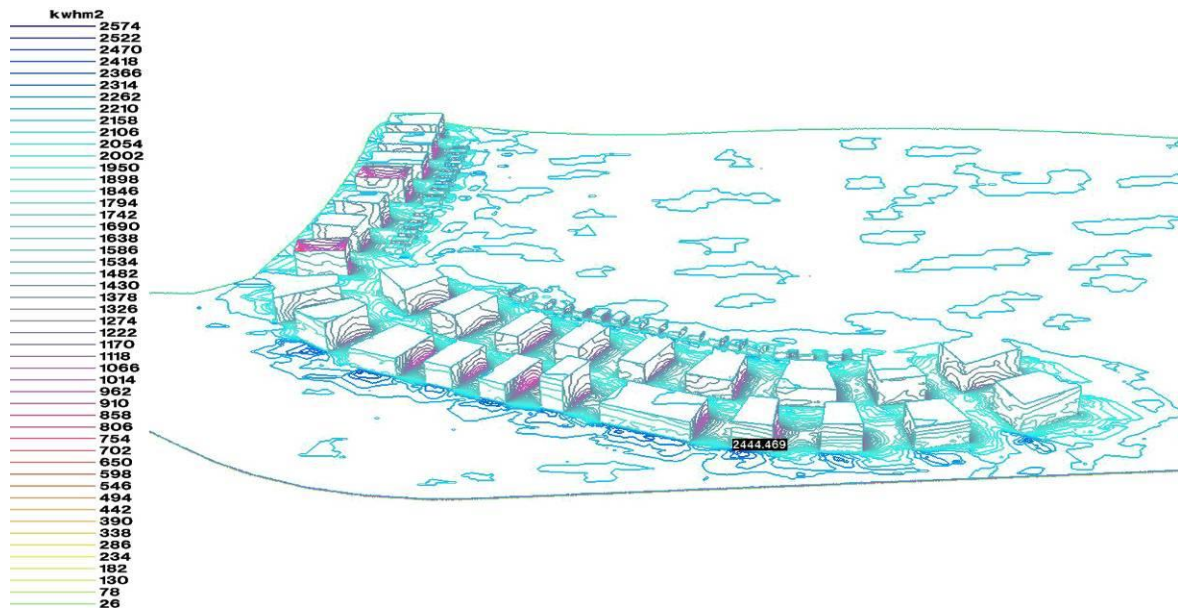


Figure 5.2: Solar irradiation contour lines on the base case experiment.

If the this urban morphology is left to evolve according to solar logic, energy consumption and their interaction between each other to reach the least energy and solar , the urban morphology must had took different paths to achieve these goals and totally different morphology had emerged.

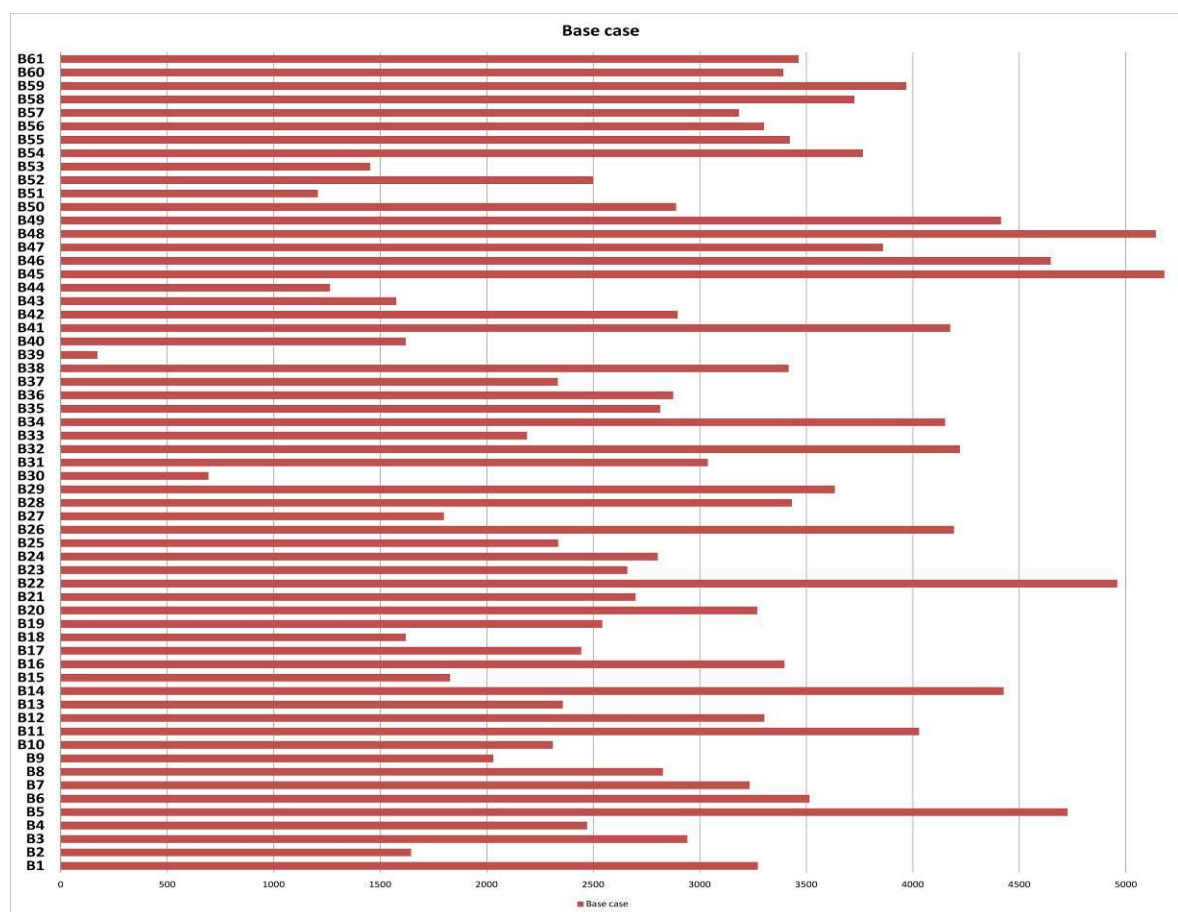


Figure 5.3: Annual total solar irradiation on all widows of each block using centre point.

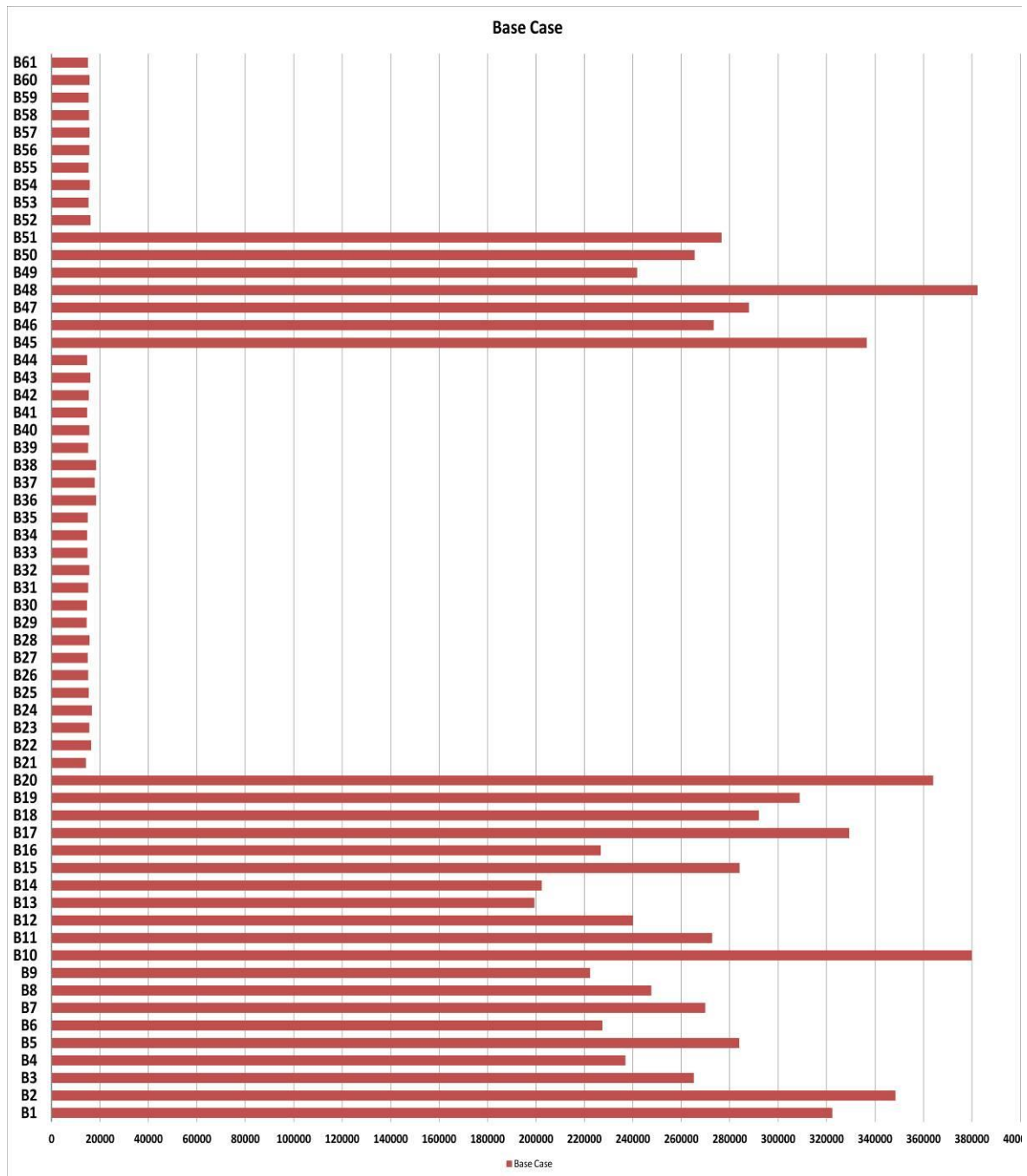


Figure 5.4: Annual total cooling load of summer months for each block as single zone.

Figures (5.3, 5.4) represent the annual total solar irradiation received from appoint cantered on the middle of each glazing and the annual total cooling loads of summer months for each building block respectively. These diagrams will be used later to compare every optimization and generation that will come from Galapagos.

In the process of optimizing against solar and cooling loads in this urban morphology many conflicting parameters are interactive with each other and Galapagos is trying to find the logical balance in between, these are but not limited to:

- Total annual mutual shadowing between blocks and the blocks with themselves
- Total surface area to volume ratio
- Total glazing surface to volume ratio
- Total solar exposed areas ratio to the total surface area of the blocks

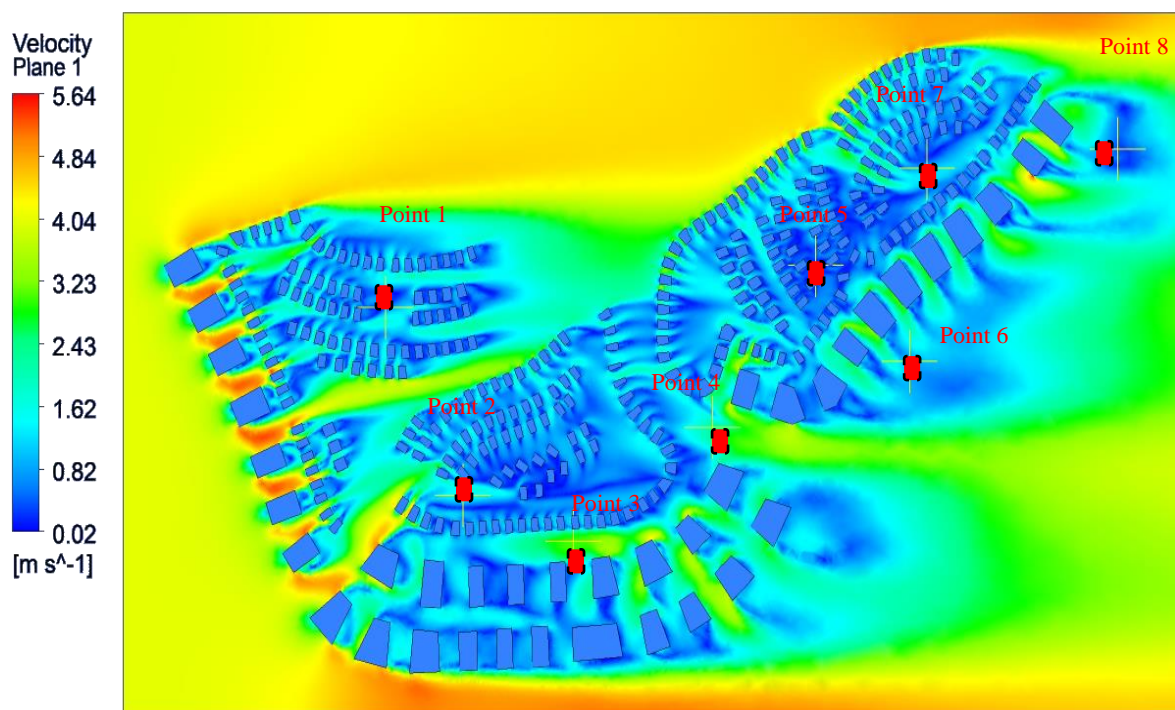


Figure 5.5: Base case CFD wind speeds results, Cut plan at 1.8m and selected points.

Figure (5.5) shows the result of the CFX CFD wind speeds at a cut plan of 1.8m high from the ground and represents the pedestrian ventilation available at those areas. The direction of the prevailing winds at the experiment location and the current urban morphology where there is a big drop in height between the buildings and the neighbouring villas creates a serious urban ventilation problems in the streets and in the open public areas in the villas community. The logic behind selected points either it is the worst location in the urban morphology and suffer from poor ventilation or it is the only main spring that channels the wind to a worse location.



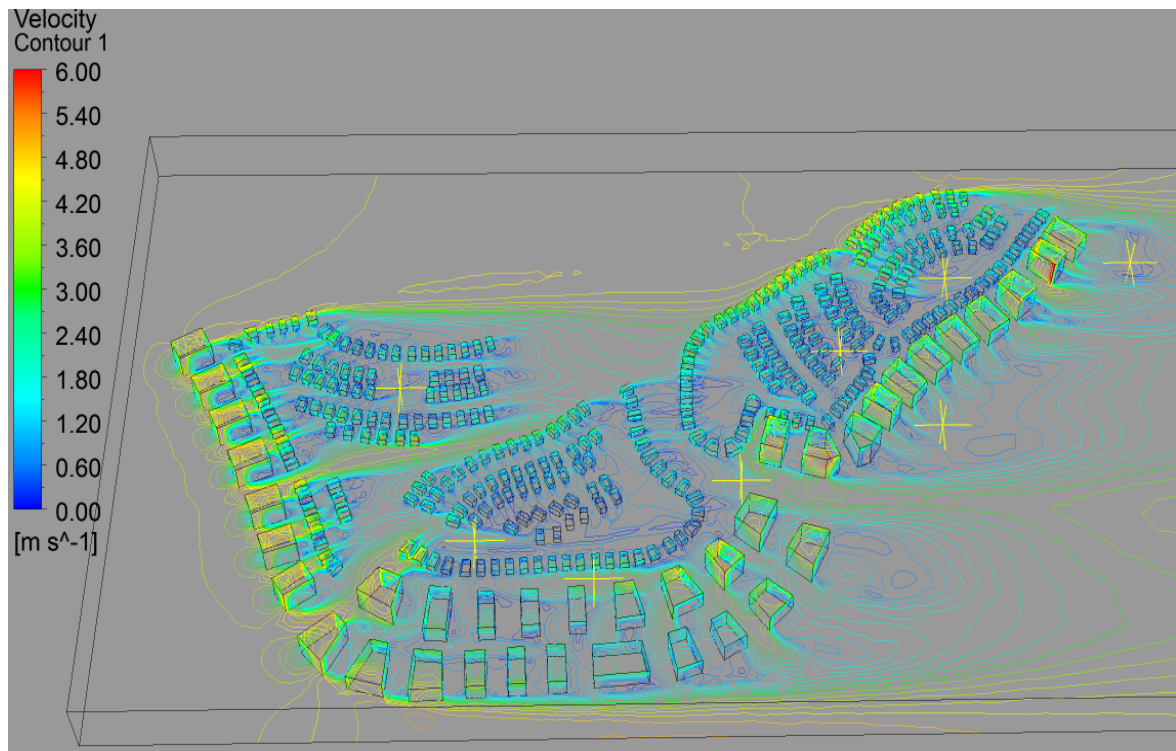


Figure 5.6: Base case CFD wind speeds as contours on block faces and selected points.

The big wind shadowing from the neighbouring building on villas affect the general environmental behaviours of the villas and leave to place for urban ventilation or passive natural ventilation for the villas Figures (5.6, 5.7).

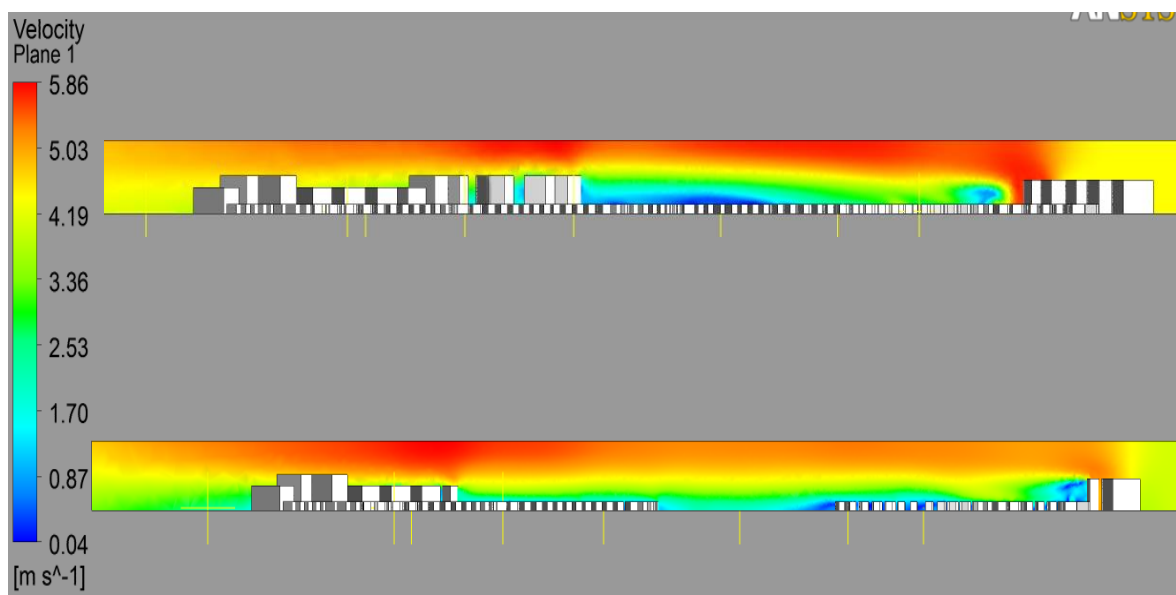


Figure 5.7: Wind shadowing from the neighbouring building on villas.

Outline of All Parameters				
	A	B	C	D
1	ID	Parameter Name	Value	Unit
2	Input Parameters			
*	New input parameter	New name	New expression	
4	Output Parameters			
5	Fluid Flow (CFX) (A1)			
6	P4	point3	3.0396	m s <sup>-1</sup>
7	P2	point1	0.48458	m s <sup>-1</sup>
8	P3	point2	1.4508	m s <sup>-1</sup>
9	P5	point4	2.2065	m s <sup>-1</sup>
10	P6	point5	0.28086	m s <sup>-1</sup>
11	P7	point6	1.0294	m s <sup>-1</sup>
12	P8	point7	0.33474	m s <sup>-1</sup>
13	P9	point8	0.74013	m s <sup>-1</sup>
14	P10	Output Parameter	9.5665	m s <sup>-1</sup>
*	New output parameter		New expression	
16	Charts			

Figure 5.8: Wind speeds at selected points and their total as fitness function to Galapagos.

Figure (5.8) shows the results of the wind speeds at the selected point and it is obviously reflects how much poor is the urban ventilation at these points-especially if we are talking of 4 m/s prevailing wind speed which is not always the case-and what effects on the whole neighbourhood and public areas.

The main CFD optimization conflicting parameters that will generate the urban morphology in this experiment are:

- The ratio between the height of the buildings and their width (extrude and scale)
- The smoothness and roughness of the building shape and edges (Fillet)
- The prevailing wind channelling and building orientations ( rotate)
- The total balance of open spaces between buildings and the buildings them self ( urban compactness and built-up area ratio)

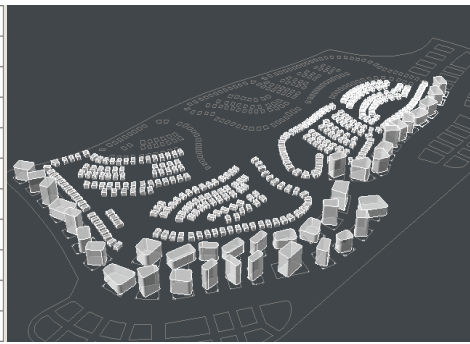
## 5.2 Simulation Results and Optimization

Analysis of each selected genome will be discussed in the following section. Each best selected genome will be compared to the base case experiment analysis and the degree of optimization and its location according to the parameters. The analysis takes the form of visual breakdown graphic presentation to highlight the results of optimization.



First Generation

4	Output Parameters				
5	Fluid Flow (CFX) (A1)				
6	P4	point3	1.7387	3.0396	m s <sup>-1</sup>
7	P2	point1	0.62612	0.48458	m s <sup>-1</sup>
8	P3	point2	1.5924	1.4508	m s <sup>-1</sup>
9	P5	point4	2.3349	2.2065	m s <sup>-1</sup>
10	P6	point5	0.7692	0.28086	m s <sup>-1</sup>
11	P7	point6	1.2448	1.0294	m s <sup>-1</sup>
12	P8	point7	0.81712	0.33474	m s <sup>-1</sup>
13	P9	point8	1.4199	0.74013	m s <sup>-1</sup>
14	P10	Output Parameter	10.543	9.5665	m s <sup>-1</sup>



Results of Best Genome

Base Results

Best Genome in First Generation

Overall there is improvement of around 1m/s when we look at the total addition of the parameters. Although Point3 decreased to more than half, there is distributed improvement and optimization in: Points 1, 2, 4, 5, 6, 7 and point 8 has received a double the speed of the base case.

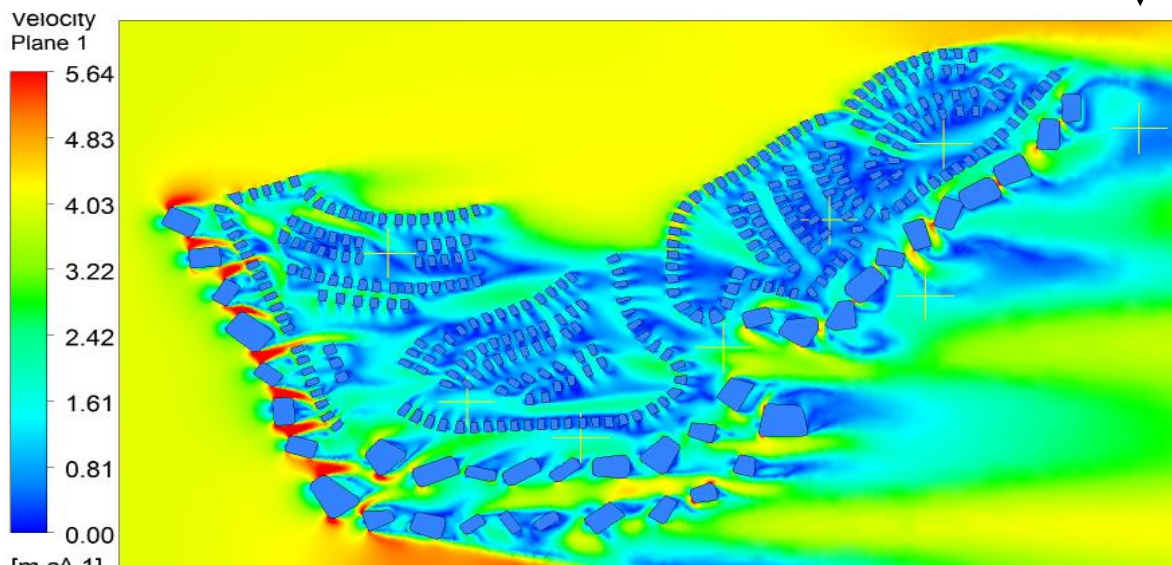
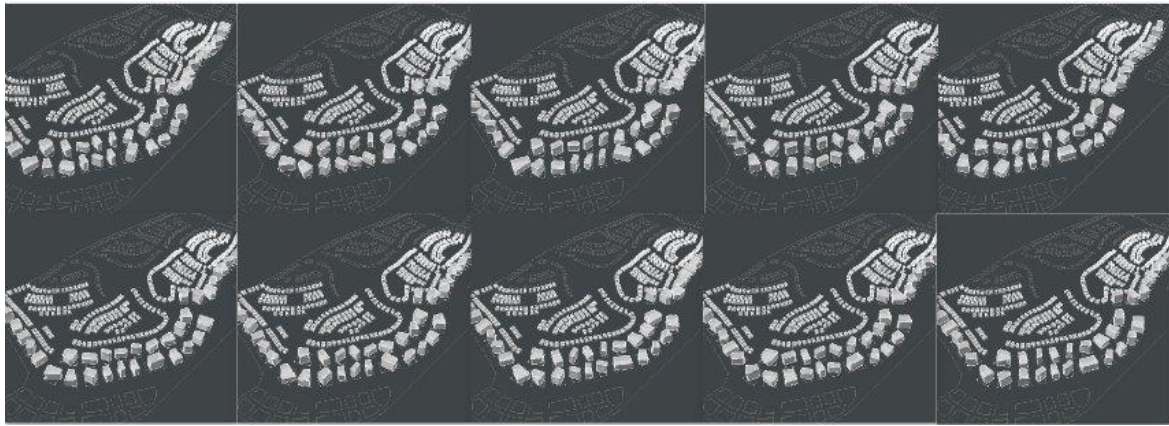


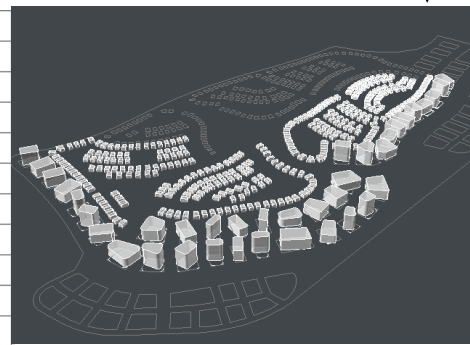
Figure 5.9: Wind Speed analysis on the Selected Genome of the first generation.





## Second Generation

4	Output Parameters				
5	Fluid Flow (CFX) (A1)				
6	P4	point3	2.716	3.0396	m s <sup>-1</sup>
7	P2	point1	0.68062	0.48458	m s <sup>-1</sup>
8	P3	point2	2.5437	1.4508	m s <sup>-1</sup>
9	P5	point4	2.2114	2.2065	m s <sup>-1</sup>
10	P6	point5	0.61994	0.28086	m s <sup>-1</sup>
11	P7	point6	1.0905	1.0294	m s <sup>-1</sup>
12	P8	point7	0.80759	0.33474	m s <sup>-1</sup>
13	P9	point8	0.5594	0.74013	m s <sup>-1</sup>
14	P10	Output parameter	11.229	9.5665	m s <sup>-1</sup>



Results of Best Genome

Base Results

Best Genome in Second Generation

In the second generation best genome there is improvement of around 2m/s. Point 3 gained another boost in this generation and another overall improvement in the wind speeds at point 2. The fillet of the rotated block generated a better wind speeds at point 2 channeling the prevailing winds to the open space between the villas.

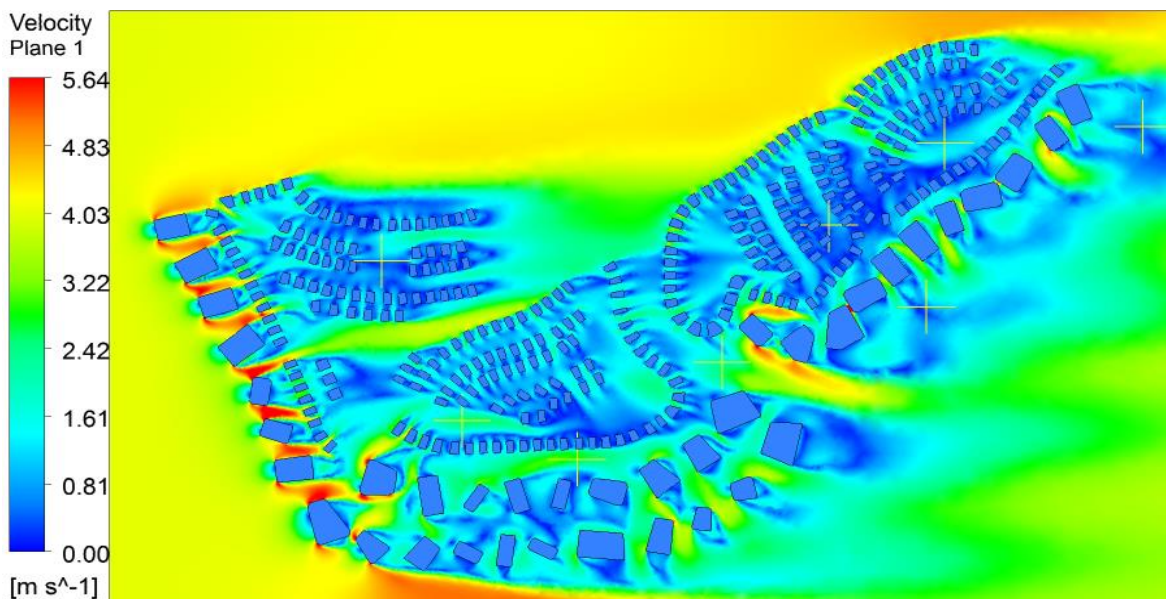
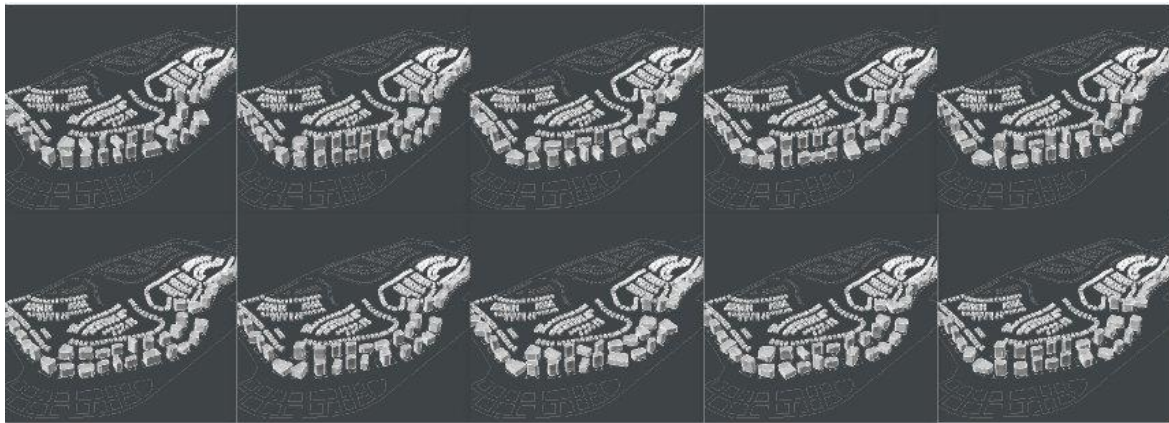
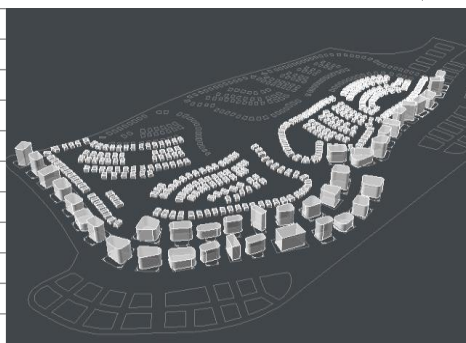


Figure 5.10: Wind Speed analysis on the Selected Genome of the Second generation.



Third Generation

4	Output Parameters				
5	Fluid Flow (CFX) (A1)				
6	P4	point3	2.5061	3.0396	m s <sup>-1</sup>
7	P2	point1	0.8903	0.48458	m s <sup>-1</sup>
8	P3	point2	1.4255	1.4508	m s <sup>-1</sup>
9	P5	point4	2.3592	2.2065	m s <sup>-1</sup>
10	P6	point5	0.28986	0.28086	m s <sup>-1</sup>
11	P7	point6	1.3818	1.0294	m s <sup>-1</sup>
12	P8	point7	1.4534	0.33474	m s <sup>-1</sup>
13	P9	point8	1.606	0.74013	m s <sup>-1</sup>
14	P10	Output Parameter	11.912	9.5665	m s <sup>-1</sup>



Results of Best Genome

Base Results

Best Genome in Third Generation

In the Third generation best genome there is not that much improvement over the second generation. Its overall improvement is around 0.7 m/s and this is one of the characters of genetic algorithms, although the best selected genome in each generation could not be a drastic improvement over the previous but GAs always find better solution if available or continue searching for better ones.

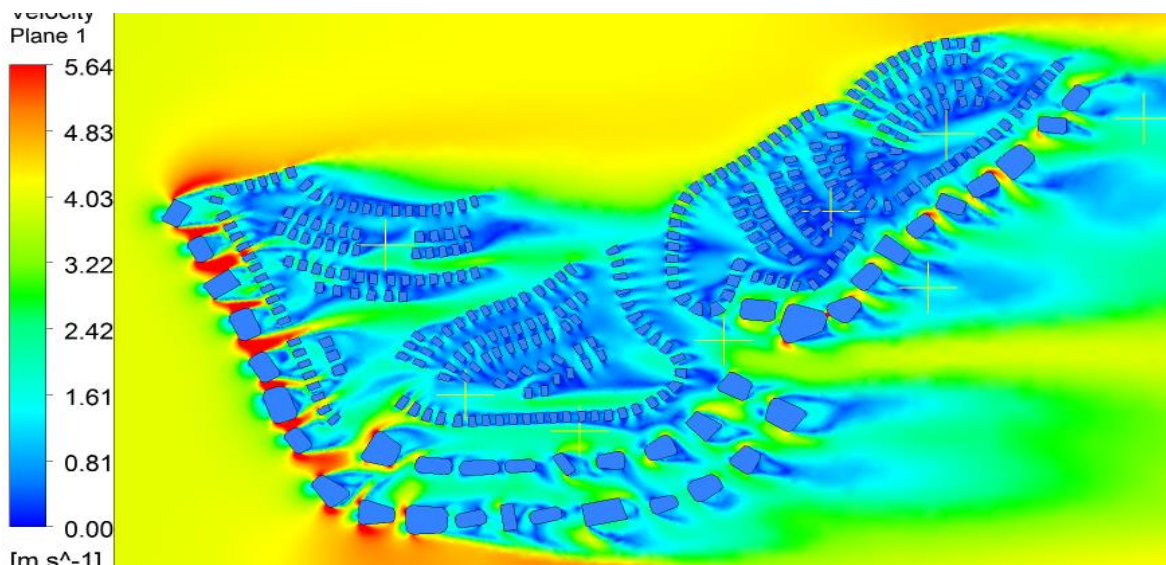
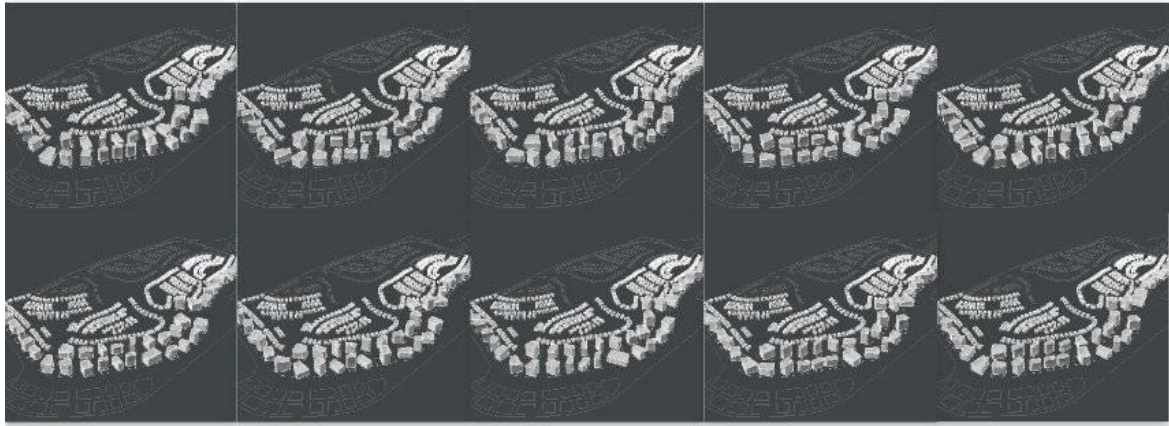


Figure 5.10: Wind Speed analysis on the Selected Genome of the Third generation.





Fourth Generation

4	Output Parameters				
5	Fluid Flow (CFX) (A1)				
6	P4	point3	3.1197	3.0396	m s <sup>-1</sup>
7	P2	point1	1.5196	0.48458	m s <sup>-1</sup>
8	P3	point2	1.7849	1.4508	m s <sup>-1</sup>
9	P5	point4	1.9039	2.2065	m s <sup>-1</sup>
10	P6	point5	0.1529	0.28086	m s <sup>-1</sup>
11	P7	point6	1.1791	1.0294	m s <sup>-1</sup>
12	P8	point7	0.86849	0.33474	m s <sup>-1</sup>
13	P9	point8	2.314	0.74013	m s <sup>-1</sup>
14	P10	Output Parameter	12.843	9.5665	m s <sup>-1</sup>



Results of Best Genome

Base Results

Best Genome in Fourth Generation

In the Fourth generation best genome there is overall improvements in the total wind speeds over the selected points of 3.7 m/s. These improvements happen in point 3 as it merely gain it original value and point 1 and 8 almost double the wind speeds of the base case experiment values. From the fourth generation there is more than 30% optimization and improvement of the wind speeds at the probing points.

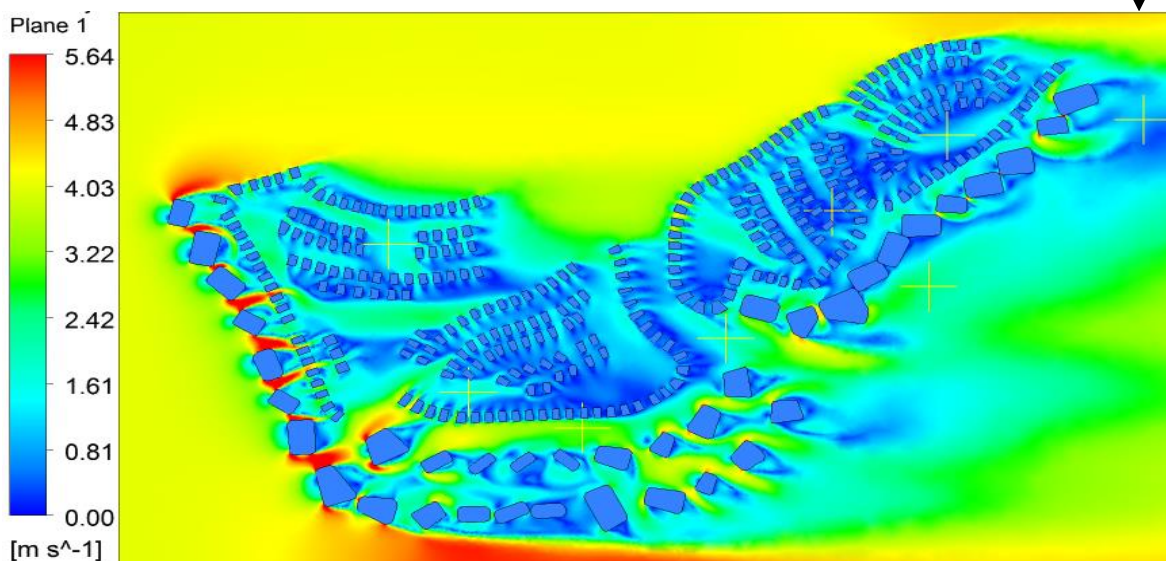


Figure 5.10: Wind Speed analysis on the Selected Genome of the Fourth generation.



Figure 5.11: Best selected genome in the first Solar/energy experiment generation.

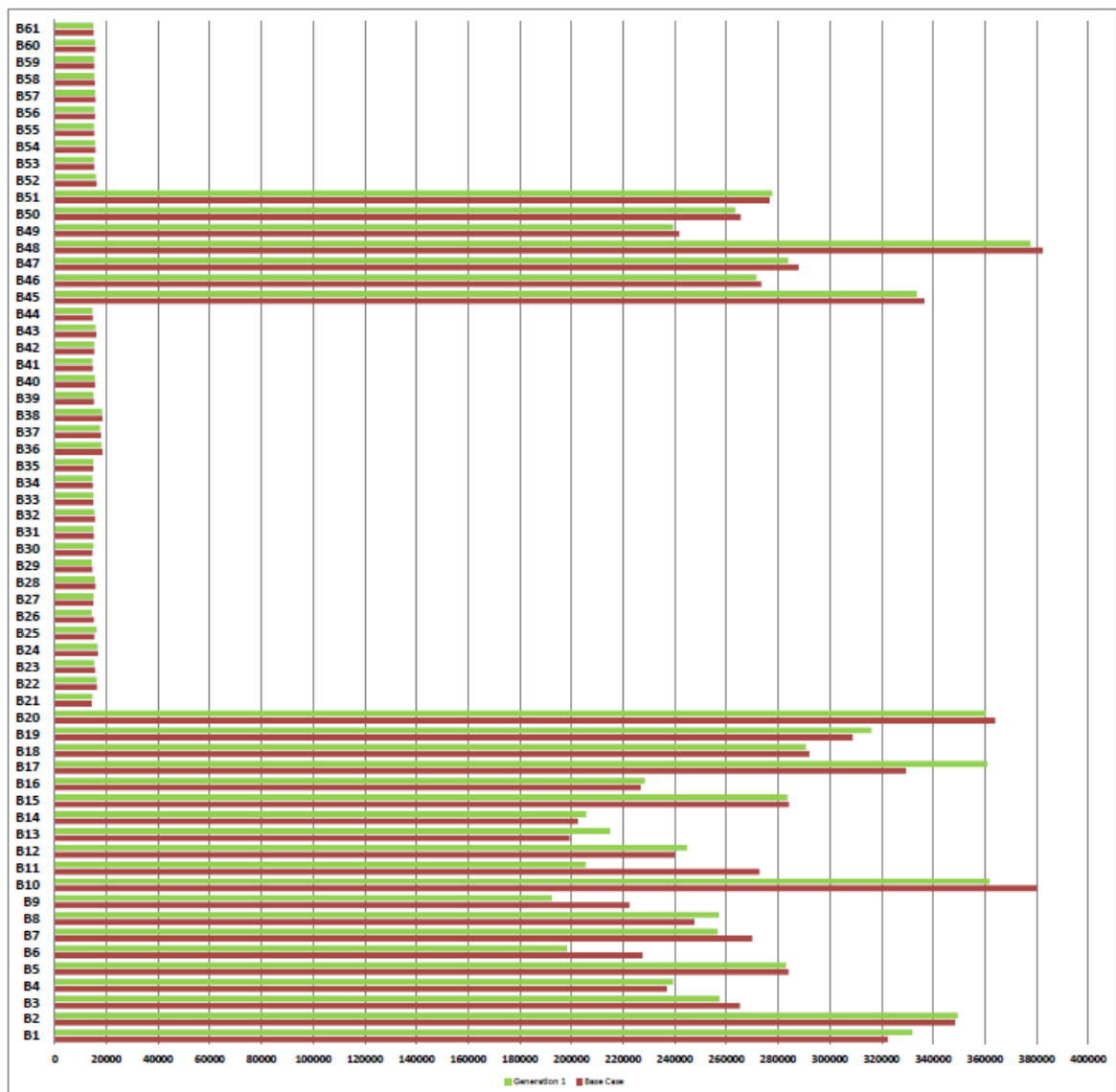


Figure 5.12: Annual Cooling loads of the selected Genome and base case (Kwh)



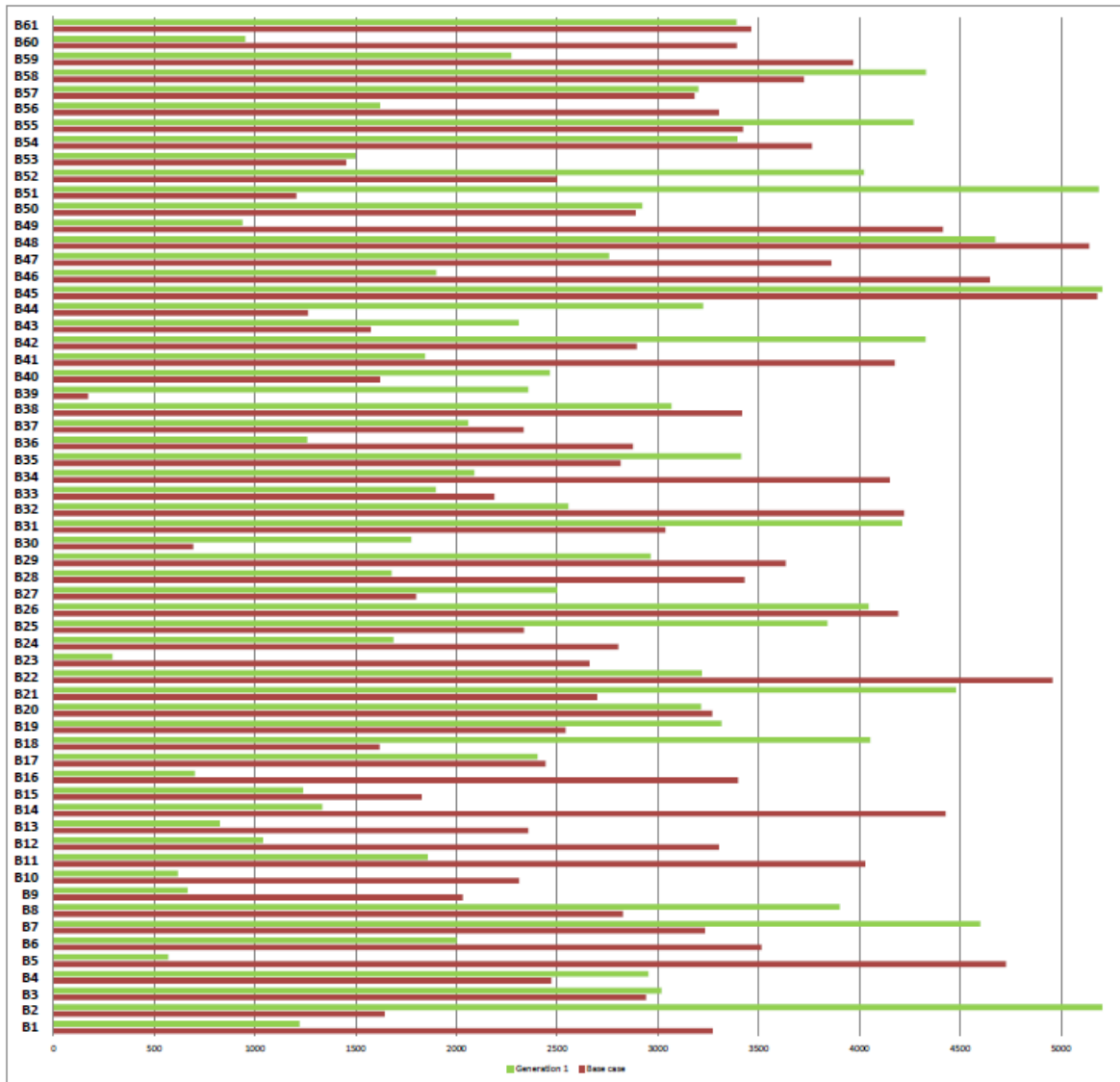


Figure 5.13: Total annual solar irradiation on glazing points, Selected and Base (Kwhm2)

The first generation from Galapagos gave around 1% optimization in the total amount of solar irradiation and energy as one fitness function. However, the savings in the cooling loads were minimal and in some blocks there were worse results from the base case study results (since the optimization is on the fitness function as total), Figure 5.12.

The optimization on the solar irradiation fluctuated between more than 50% optimization and savings to increase to the double, although still there is a saving in the whole urban morphology of around 1%, Figure 5.13. This is a best example of how GAs works in the case of using the totals to optimize. GAs are very slow especially in the first few generation which then will pick up building solution over solution and selecting from population.



Figure 5.14: Best selected genome in the Second generation.

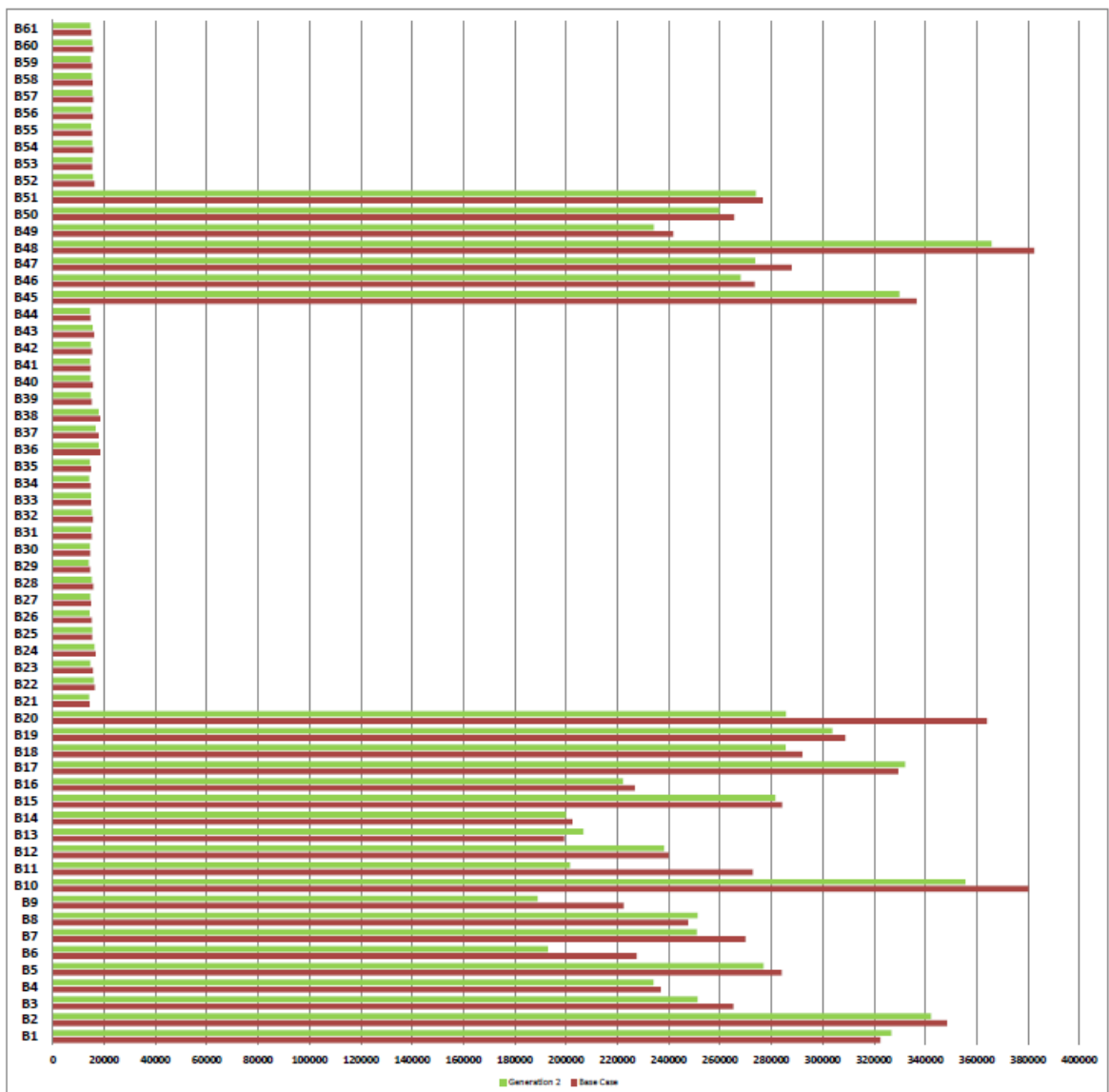


Figure 5.15: Annual Cooling loads of the selected Genome and base case, Second (Kwh)

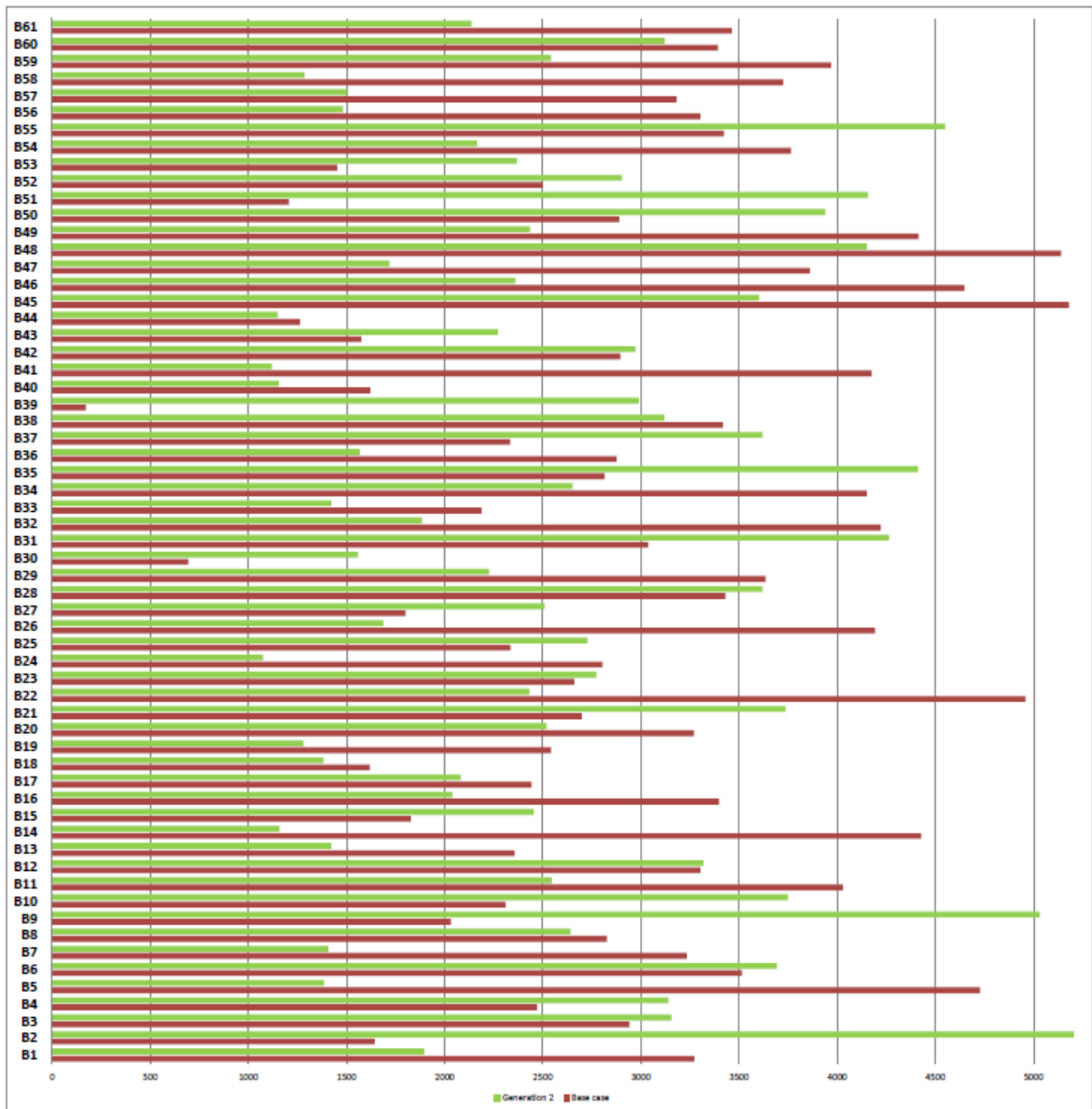


Figure 5.16: Total annual solar irradiation on glazing points, Selected and Base (Kwhm2)

The second generation from Galapagos gave around 3% optimization in the total amount of solar irradiation and energy as one fitness function. The saving in the cooling loads start to appear more, although still some block that gain more cooling load, but overall optimization is noticeable, Figure 5.15.

The optimization on the solar irradiation is still fluctuating between increase and savings, Figure 5.16.



Figure 5.17: Best selected genome in the Third generation.

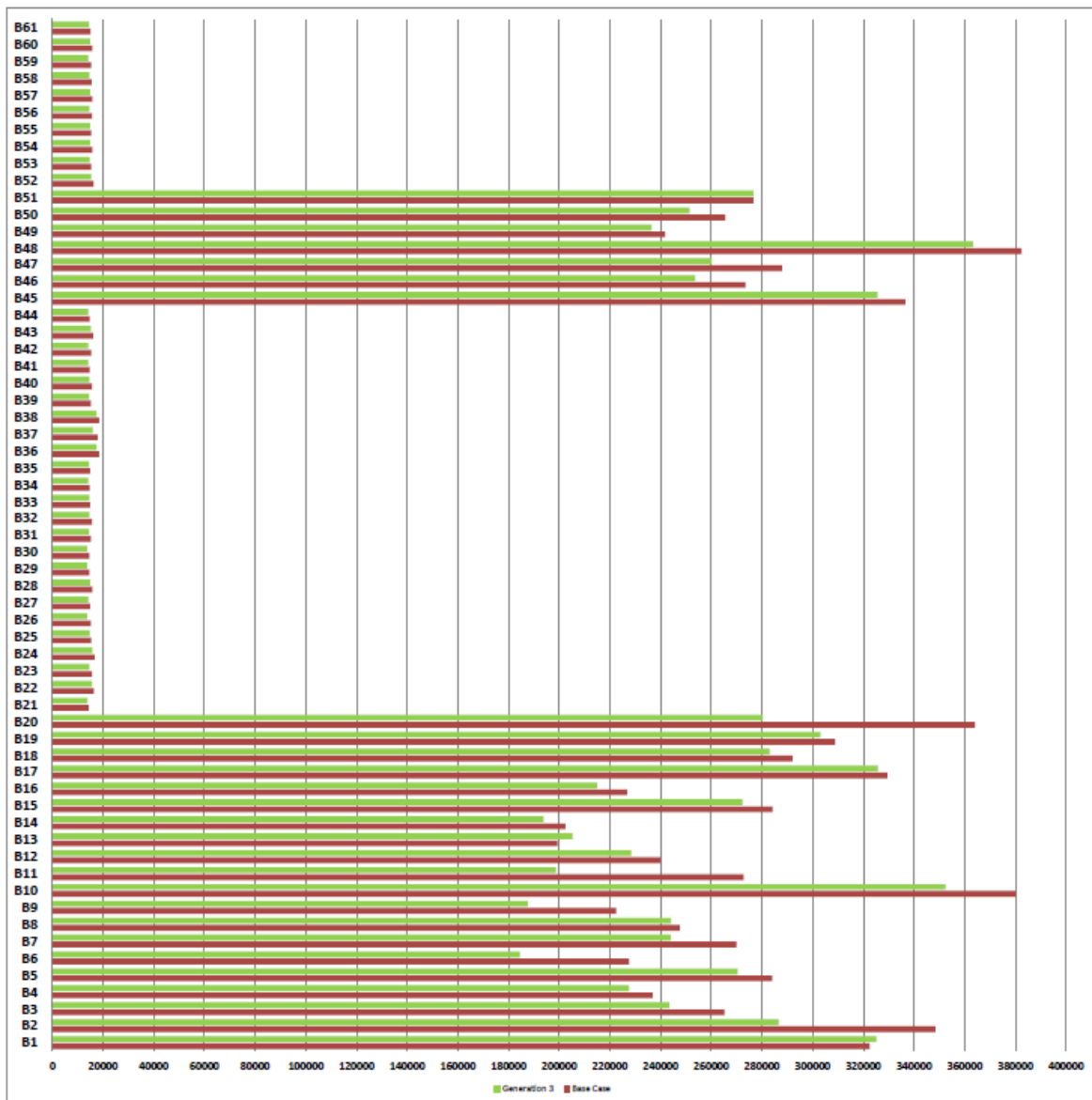


Figure 5.18: Annual Cooling loads of the selected Genome and base case, Third (Kwh)

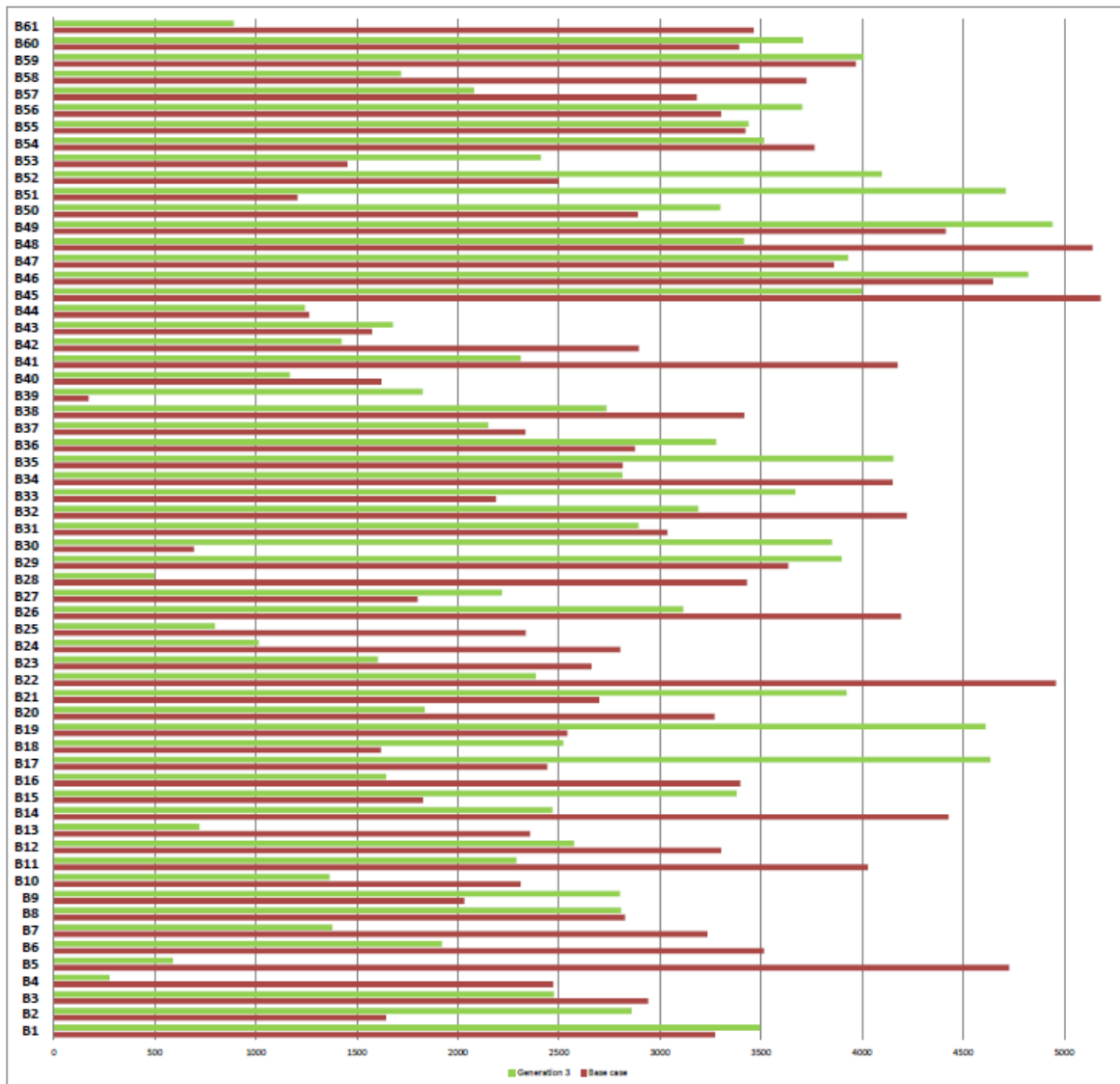


Figure 5.19: Total annual solar irradiation on glazing points, Selected and Base (Kwhm2)

The Third generation from Galapagos gave around 5% optimization in the total amount of solar irradiation and energy as one fitness function. The saving in the cooling loads almost happens in all blocks with no exceptions, Figure 5.18.

The optimization on the solar irradiation fluctuates less between increase and savings, but converging to a good oval soar radiation optimization than the second, Figure 5.19.



Figure 5.20: Best selected genome in the Fourth generation.

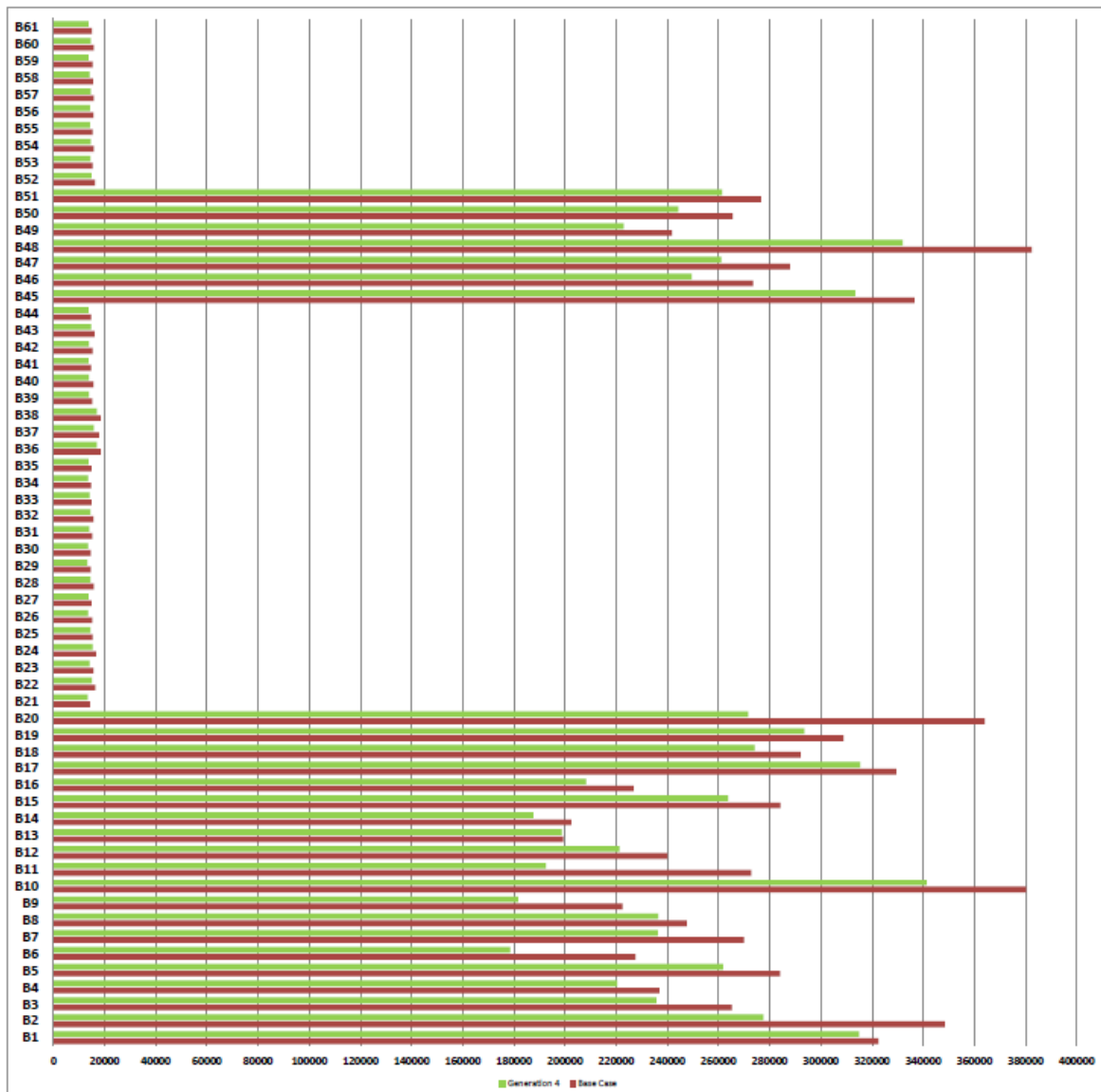


Figure 5.21: Annual Cooling loads of the selected Genome and base case, Fourth (Kwh)

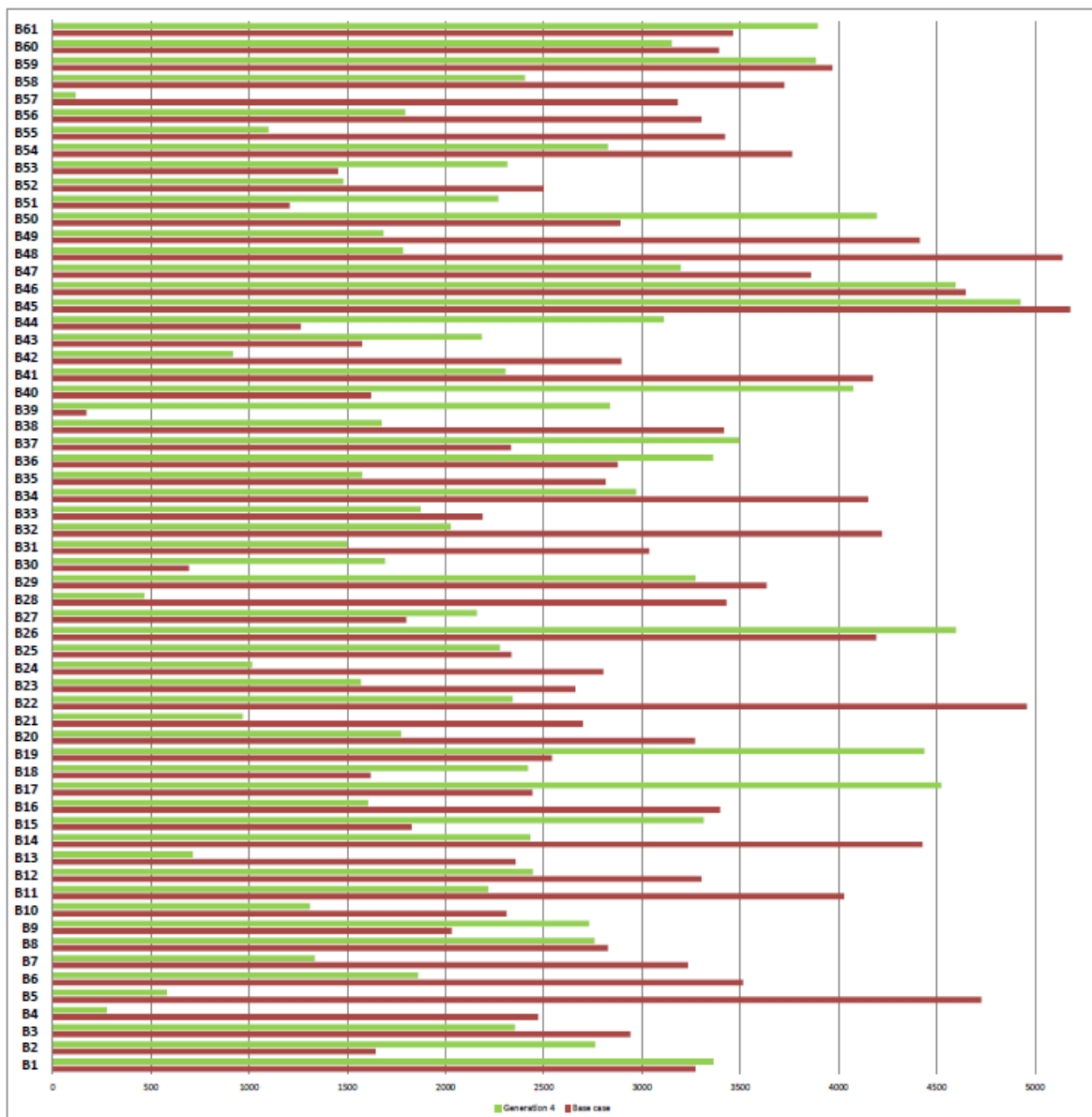


Figure 5.22: Total annual solar irradiation on glazing points, Selected and Base (Kwhm2)

The Third generation from Galapagos gives around 8% optimization in the total amount of solar irradiation and energy as one fitness function. The savings in the cooling loads are appearing in all blocks and no increase appears. The optimization process is achieving a total decrease in the fitness function which is in the same time reflected on the individuals which from the t fitness function, furthermore GAs doest stop on any beat genome and may be it will continue to find new potential for optimization if the system continuo running , Figure 5.21.

The optimization on the solar irradiation reflects a good overall optimization with remaining block that still face increase which is left to the designer to decide, Figure 5.22



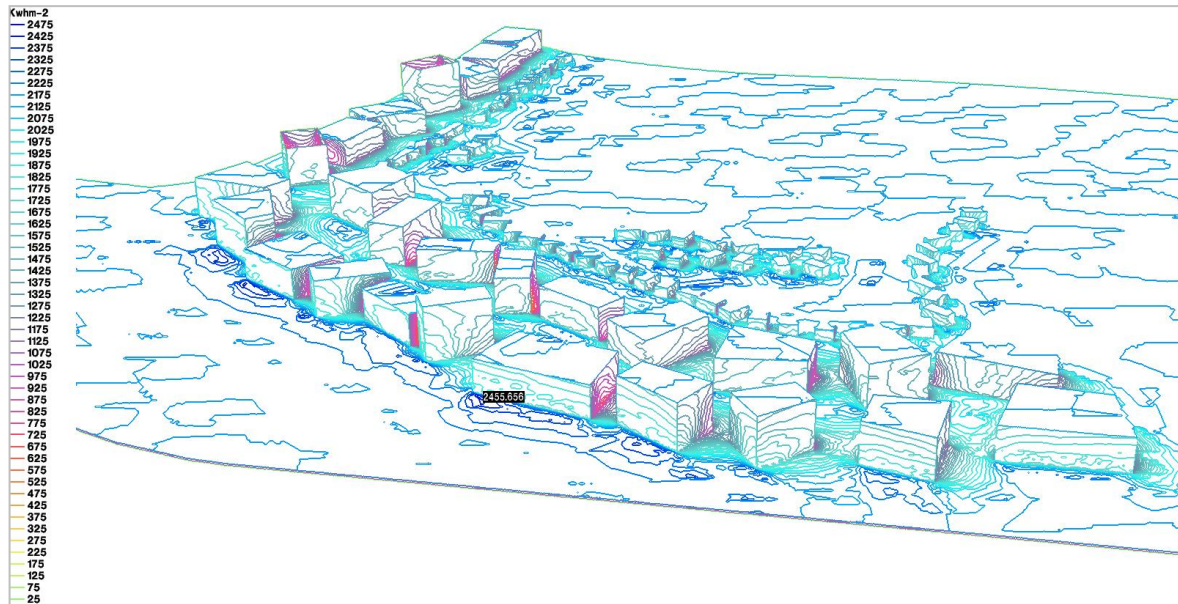


Figure 5.23: Total annual solar irradiation on blocks of the best select genome in generation four (Kwhm2)

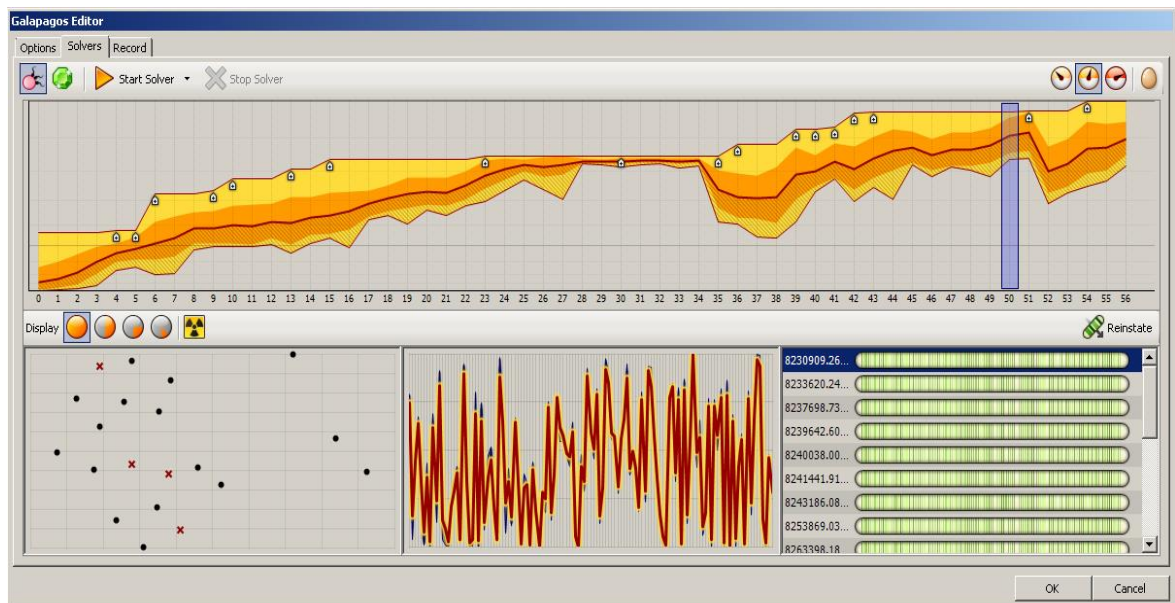
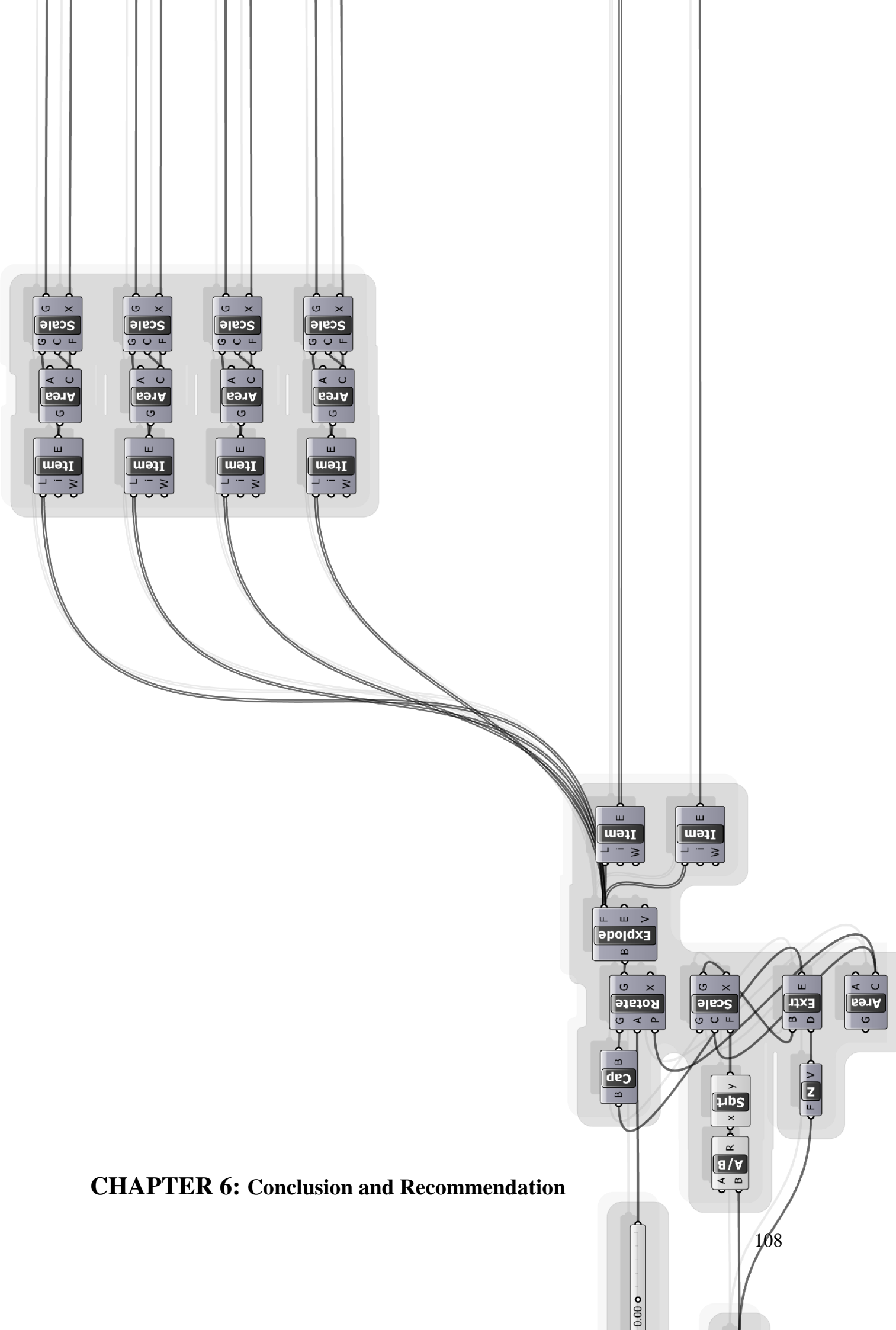


Figure 5.24: Galapagos window showing the whole optimization process.

Although the resultant urban morphologies does not look aesthetically appealing in any experiment, but it carries a good practical analysis for the urban designer to predict the behaviour of his design and it also reflects as a good indicator on how is sustainably the best arrangement, orientations, heights and urban compactness of his concept design and to carry the design from there to further improvements and developments.

CHAPTER 6: Conclusion and Recommendation



## 6.1 Conclusions

**Summary of objectives:** The aim of this research is to investigate the potentials of applying parametric design optimizations processes over the conventional urban design processes in a achieving a more sustainable urban design, and incorporating the computational design methodologies in the design process giving the computer a more active role in the design process and the benefits that could come to architects and urban designer from adopting such methodologies in enhancing the process of design.

In the process of developing such methodology six main contributions has been made: first, design methodology for achieving sustainable urban design. Second the viability of genetic algorithms for optimization with parametric modelling for urban sustainability. Third, a system for generating urban design morphologies. Fourth, the viability of using computational design for designing complex systems. Fifth, the adaptability and integration of such systems with conventional methodologies. Sixth, changing role for computers in the deign process for sustainability. These contributions are detailed below:

- **A design methodology for achieving sustainable urban design:** the proposed methodology performed well during the optimization experiments on the solar, energy and CFD. The results show improvements in the whole urban system ranging from 1% to 8% in the solar/energy experiment and around 30% performance in the CFD experiment during the early generations. The potentials of such methodologies in designing for urban sustainability indicate a good future for creating a more sustainable cities and neighbourhoods. The ability to apply these methodologies in the concept urban design can inform the designer much more than the conventional analysis processes and can lead the designer to a more creative, sustainable and liveable design.
- **Genetic algorithms for optimization with parametric modelling for urban sustainability:** the integration of genetic algorithms with a parametric model for optimization in the system of the proposed methodologies gives the methodology a strong flexibility and controllability over the design problems. There are almost no limitations in the possibilities for parameters to be investigated and optimized, nor there are limitations on how much the

parametric model can be adaptable to interact with the environmental constraints. The most common limitations that can come to this system are the limitation of the designer during building the setup for the optimization process, such as neglecting an important input or output that could affect the overall performance of the design problem or limitation of the computer to process fast enough to cope with GAs. Genetic algorithms behave well in both experiments and gave a good optimization in the performance.

- **System for generating urban design morphologies:** the proposed methodologies can be used as generating system for generating different design ideas and morphologies, but more sustainable than the current trends in computer design generation's tools which can be seen in the CFD experiment. Modern design common trends use tools and algorithms such as fractals, random generation and graphical mathematical manipulation algorithms for only aesthetic or social purpose, such as building a complete urban morphology based on country symbols, the generated design has no interaction of adaptation to the surrounding environment. on the other hand, the design generations from GAs with parametric emerge shapes that correspond to factors environmental factors of the surroundings in a very similar way to the evolution that happen in nature to reach a stable durable design.
- **Computational design for designing complex systems:** when considering the interactions of the system under design with the surroundings, this gives a better design when designing for complex systems such as urban design. Since, most of the complexity of the urban systems comes from micro- and macro- interactions between systems; the proposed parametric optimization system is built on these interactions and is adapting the design to set in harmony with the surrounding and to fit in the complex system without the result of bad intervention.
- **Adaptability and integration of such systems with conventional methodologies:** the flexibility of the proposed methodology can be adaptable and adjustable to handle as much as the designer wish to optimize his design from only single parameter in a building to a full scale complex urban design.

This flexibility makes it easy to integrate the proposed methodology in any system such as the experiments done in this research on rotation, scaling and built up area ratio.

- **Changing the role for computers in the urban design process for sustainability:** parametric design optimization with genetic algorithms can change the role of computers in the design process. It teams up the computer with the designer to complement each other strength and weakness, on the contrary to the conventional computer usage as an analysis and visualization tool.

## 6.2 Recommendations and future Studies:

- Different modelling flexibility to the constraints of the environments which can lead to a more adaptable model to GAs optimization process.
- Investigation on the best connectivity between GAs, Parametric scripting and the physical analysis tools that can give more efficient system in terms of time and flexibility.
- More studies on GAs to fit to the task of parametric design optimization and the interaction between the designer who monitor the optimization process to boost or enhance the fitness, such as mutation button in Galapagos.
- Different investigations of adapting other algorithms than GAs to the optimization process such as the Tabu-search algorithms and improving simulated annealing.
- The investigations of integrating these analysis tools as built in components and algorithms in the parametric software such as CFD, Radiance and EnergyPlus inside Grasshopper.
- More studies on using system distribution tasks to a network of computers to enhance the process speed and time.
- Other investigation on the urban elements of sustainability in term of privacy, proximity, commuting, roads and transportation systems, land division and day lighting factors.

## Reference

A.L.S. Chan (2012). Effect of adjacent shading on the thermal performance of residential buildings in a subtropical region, *Applied Energy*, Volume 92, April 2012, Pages 516-522, available online (<http://www.sciencedirect.com/science/article/pii/S0306261911007690>) [accessed October 5, 2012]

Alan Dempsey (2008). From parameter to production. In *Conference Proceedings, Advances in Architectural Geometry Vienna, Austria September, 2008*.

Alexander, C. (1964). *Notes on the Synthesis of Form*. Cambridge: Harvard University Press.

Angelos Chronis, Alasdair Turner and Martha Tsigkari (2011). Generative Fluid Dynamics: Integration of Fast Fluid Dynamics and Genetic Algorithms for wind loading optimization of a free form surface, In Christoph Gengnagel, Axel Kilian, Norbert Palz, and Fabian Scheurer editors (2011). *Computational Design, Modelling Proceedings of the Design Modelling Symposium Berlin 2011*

Angelos Chronis, Martha Tsigkari, Evangelos Giouvanos, Francis Aish1, Anis Abou Zaki(2012). Performance Driven Design and Simulation Interfaces: A Multi-Objective Parametric Optimization Process, In Lira Nikolovska & Ramtin Attar editors (2012). *Proceedings of the Symposium on Simulation for Architecture and Urban Design Orlando FL USA, 2012*

B. Blocken, W.D. Janssen, T. van Hooff,(2012) CFD simulation for pedestrian wind comfort and wind safety in urban areas: General decision framework and case study for the Eindhoven University campus, *Environmental Modelling & Software*, Volume 30, April 2012, Pages 15-34, ISSN 1364-8152, 10.1016/j.envsoft.2011.11.009, Available online(<http://www.sciencedirect.com/science/article/pii/S1364815211002647>) [accessed October 5, 2012]

Banham R. (1960). *Theory and Design in the First Machine Age*. Cambridge. Mass: The MIT Press.

Baruch Givoni (2010). *Thermal Comfort Issues and Implications in High-Density Cities*, In Edward, Ng editor (2010). *Designing High-Density Cities for Social and Environmental Sustainability*, Earthscan, UK ,USA, 2010

Bloeken, B. and Carmeliet, J. (2004). Pedestrian Wind Environment Around Buildings: Literature Review and Practical Examples, *Journal of Thermal Environment and Building Science*, VOL. 28, N 2

Branko Kolarevic (2009). *Architecture in the Digital Age: design and manufacturing*, Taylor & Francis e-Library, 2009.

Broadbent G. (1981). The Morality of Designing. In Jacques R. Powell J. editors (1981). *Design: Science: Method. Proceedings of the 1980 Design Research Society Conference*. Westbury House, Guildford, UK.

C. D. Chapman, and M. J. Jakiela (1996). Genetic algorithm-based structural topology design with compliance and topology simplification considerations, *Journal of Mechanical Design*, 1996.

Camp, C., Pezeshek, s., Cao, G. (1998). Optimized Design of Two-dimensional Structures using a genetic algorithm, *Journal of structure Engineering*, Vol. 124

Chermayeff, S. and Alexander, C. (1963). *Community and Privacy. Toward a New Architecture of Humanism*. Garden City, N. Y. Doubleday.

Chiu-Ying Lam. (2010). Climate Changes Brought About by Urban Living, In Edward, Ng editor (2010). *Designing High-Density Cities for Social and Environmental Sustainability*, Earthscan, UK ,USA, 2010

Cross N. (1993). A history of Design Methodology. In de Vries, Cross N, Grant, D. P. editors, *Design Methodology and relationships with science*. Dordrecht, Netherlands: Kluwer Academic Publishers.

Cross N. (1999). *Natural Intelligence in Design*. Design Studies.

Cross N. (2001). *Designer Ways of Knowing: Design Discipline versus Design Science*. Design Issue.

D. Powell (1990). Inter-GEN A hybrid approach to engineering design optimization. Technical report, Rensselaer Polytechnic Institute Department of Computer Science, December 1990. Ph. D. Thesis.

David Rutten (2010). *Evolutionary Principles Applied to Problem Solving*, available online <http://www.grasshopper3d.com/profiles/blogs/evolutionary-principles> [accessed October 5, 2012]

David B Fogel (2000). Introduction to evolutionary computation. In Thomas Back, David B Fogel and Zbigniew Michalewicz editors (2000). *Evolutionary Computation 1 Basic Algorithms and Operators*, Institute of Physics Publishing Bristol and Philadelphia

Edward, Ng (2010). Designing for Urban Ventilation, In Edward, Ng editor (2010). *Designing High-Density Cities for Social and Environmental Sustainability*, Earthscan, UK, USA, 2010

Galante, M. (1996). Genetic Algorithm as an approach to Optimize real-world trusses, *International Journal for Numerical Methods in Engineering*, Vol. 39

Gallego, R., Monticelli, A., Romero, R. (1998). Comparative Studies on none-convex optimization for transmission network expansion planning, *IEEE Transaction on Power Systems*, V. 3

Gero, J. and Radford, A. (1978). A Dynamic Programming Approach to the Optimum Lighting Problem, *Engineering Optimization*, 3.



Gert de Roo, Ward S. Rauws (2012). Positioning Planning in the World of Order, Chaos and Complexity: On Perspectives, Behaviour and Interventions in a Non-linear Environment. In Juval Portugali, Han Meyer, Egbert Stolk, Ekim Tan editors (2012). Complexity Theories of Cities Have Come of Age: an Overview with Implications to Urban Planning and Design. Springer, Heidelberg, Dordrecht, London, New York.

Goldberg, D. (1989). Genetic Algorithms in Search, Optimization and Machine Learning, Addison-Wesley Publishing Company

Gomez, P. (1983). Architecture and the Crisis of Modern Science. Cambridge. Mass: The MIT Press.

Hii, Danie Jun Chung, Heng, Chye Kiang, Malone-Lee, Lai Choo, Zhang, Ji, Ibrahim, Nazim1, Huang, Yi Chun and Janssen, Patrick (2011). Solar Radiation Performance Evaluation for High Density Urban Forms in the Tropical Context, Proceedings of Building Simulation 2011, 12th Conference of International Building Performance Simulation Association, Sydney

Isaac Lun, Akashi Mochida and Ryoza Ooka (2009). Progress in Numerical Modeling for Urban Thermal Environment Studies, In Mat Santamouris, editor-in-chief (2009).Advances in Building Energy Research, Earthscan, UK ,USA, 2009

Ishida, R., Sugiyama, Y. (1995). Proposal of constructive Algorithm and Discrete Shape Design of the Strongest Column, AIAA Journal, Vol. 33

J. H. Holland (1975). Adaptation in Natural and Artificial Systems. University of Michigan Press, Ann Arbor, 1975.

James L. Rogers, Collin M. McCulley, and Christina L. Bloebaum (1996). Integrating a Genetic Algorithm into a knowledge-based System for Ordering Complex Design Processes. In Fourth International Conference on Artificial Intelligence, In Design 96, 1996.

Jeffrey Johnson (2012). Cities: Systems of Systems of Systems. In Juval Portugali, Han Meyer, Egbert Stolk, Ekim Tan editors (2012). Complexity Theories of Cities Have Come of Age: an Overview with Implications to Urban Planning and Design. Springer, Heidelberg, Dordrecht, London, New York.

Johan Kure, Thiru Manickam, Kemo Usto, Kenn Clausen, Duoli Chen, and Alberto Pugnale(2011). Parametric Design and Construction Optimization of a Freeform Roof Structure, In Christoph Gengnagel, Axel Kilian, Norbert Palz, and Fabian Scheurer editors (2011). Computational Design, Modelling Proceedings of the Design Modelling Symposium Berlin 2011

John Frazer (2002). Creative Design and the Generative Evolutionary Paradigm, In John S. Gero, Vladimir A. Kazakov, and Thorsten Schinier.(1997) Genetic engineering and design problems. In Evolutionary Algorithms Engineering Applications, Springer-Verlag, 1997.

Jozefowska, J., Mika, M., Rozycki, R., Waligora, G., Weglarz, J. (1998). Local search Metaheuristics for Discrete-Continuous scheduling problems, *European Journal of Operational research*, Vol. 107

Juval Portugali (2012). Complexity Theories of Cities: Implications to Urban Planning. In Juval Portugali, Han Meyer, Egbert Stolk, Ekim Tan editors (2012). *Complexity Theories of Cities Have Come of Age: an Overview with Implications to Urban Planning and Design*. Springer, Heidelberg, Dordrecht, London, New York.

Kolokotroni, M., Giannitsaris, I., Watkins, R. (2006). The Effect of the London Urban Heat Island on Building Summer Cooling Demand and Night Ventilation Strategies. *Solar Energy*, 80

Law, Sinyan (1997) Daylighting Design Using a Non-linear Optimization Technique, Master in Architecture Thesis, M.I.T, Cambridge.

Lawson B. R. (1972). Problem Solving in Architectural Design. Doctoral Dissertation, University of Aston, Birmingham.

M. A. Rosenman (1997). The generation of form using an evolutionary Approach. In *Evolutionary Algorithms in Engineering Applications*, Springer-Verlag 1997.

Magdalena Hajdukiewicz, Marco Geron, Marcus M. Keane, Formal calibration methodology for CFD models of naturally ventilated indoor environments, *Building and Environment*, Available online 31 August 2012, ISSN 0360-1323, 10.1016/j.buildenv.2012.08.027, Available online (<http://www.sciencedirect.com/science/article/pii/S0360132312002296>) [accessed October 5, 2012]

Maizia, M., Sèze, C., Berge, S., Teller, J., Reiter, S., Ménard, R. (2009). Energy requirements of characteristic urban blocks, *Proc. of CISBAT 2009 - Renewables in a changing climate – From Nano to urban scale*, Lausanne, Switzerland

Milos Dimcic and Jan Knippers (2011). Integration of FEM, NURBS and Genetic Algorithms in Free-Form Grid Shell Design, In Christoph Gengnagel, Axel Kilian, Norbert Palz, and Fabian Scheurer editors (2011). *Computational Design, Modelling Proceedings of the Design Modelling Symposium Berlin 2011*

Mitchell, Melanie (1999). *An Introduction to Genetic Algorithms*, the MIT Press, Cambridge, Massachusetts, London, England

Mitchell, W. (1977). *Computer Aided Architectural Design*, Petro celli, Charter, New York.

Mitchell, W. J. (1994). Three Paradigms for Computer-aided Design. In Carrara, G. and Kalay, Y. editors, *Knowledge-Based Computer-Aided Architectural Design*. Elsevier Science B. V.

Mitchell, W., Steadman, J., Ligget, R. (1976). Synthesis and Optimization of Small Rectangular Floor Plans, In *Environment and Planning B*, Vol. 3.

- Monedero, J. (2000). Parametric Design: a review and some experiences. *Automation in Construction*, Vol.9.
- Nikos A. Salingaros (2012). Urbanism as Computation. In Juval Portugali, Han Meyer, Egbert Stolk, Ekim Tan editors (2012). *Complexity Theories of Cities Have Come of Age: an Overview with Implications to Urban Planning and Design*. Springer, Heidelberg, Dordrecht, London, New York.
- O'Reilly, U-M, Ramachandran, G. (1998). A preliminary Investigation as a Form Design strategy, In Adami, C., Belew, R., Kitano, H. and Taylor, C., editors (1998). *Proceedings of the 6<sup>th</sup> Conference on Artificial Life*, MIT press
- P. Gage I. Kroo, and I. Sobieski (1995). Variable-complexity Genetic Algorithm for Topological Design. *AIAA Journal*, 33.
- P. J. Littlefair, M. Santamouris, S. Alvarez, A. Dupagne, D. Hall, J. Teller, J. F. Coronel, N. Papanikolaou (2000). *Environmental Site Layout Planning: solar access, microclimate and passive cooling in urban areas*, BRE Publications, 2000
- Peter Bentley (1999). *Evolutionary Design by Computers*, Morgan Kaufmann publishers, Inc, 1999
- Peter J. Bentley, David W. Corne, editors (2002). *Creative Evolutionary Systems*, Academic press, 2002
- Pham, D. and Onder, H. (1992). A Knowledge-based System for optimizing workplace Layout Using a Genetic Algorithm, *Ergonomics*, Vol. 35
- Rajagopalan Priyadarsini (2009). Urban Heat Island and its Impact on Building Energy Consumption, In Mat Santamouris, editor-in-chief (2009). *Advances in Building Energy Research*, Earthscan, UK ,USA, 2009
- Rasheed, A., (2009). Multi-scale Modeling of Urban Climate, Ph.D. Thesis. 4531, EPFL, Lausanne, Switzerland
- Ratti, C., Baker, N., Steemers, K. (2005). Energy consumption and urban texture, *Energy and Buildings*, vol. 37
- S. Kirkpatrick, C. D. Gelatt, M. P. Vecchi (1983). Optimization by Simulated Annealing, *Science* 220. 1983.
- Schmitt, G. (1999). *Information Architecture: basis of CAAD and its future*. Birkhauser, Basel, Switzerland.
- Steffen Lemmerzhl, and Ludger Hovestadt, (2008). Bitmap-driven Parametric Façades. In *Conference Proceedings, Advances in Architectural Geometry Vienna, Austria September, 2008*.

Stephen Marshall (2012). Planning, Design and the Complexity of Cities. In Juval Portugali, Han Meyer, Egbert Stolk, Ekim Tan editors (2012). Complexity Theories of Cities Have Come of Age: an Overview with Implications to Urban Planning and Design. Springer, Heidelberg, Dordrecht, London, New York.

Stromann-Andersen J., Sattrup P.A. (2011). The urban canyon and building energy use: Urban density versus daylight and passive solar gains, Energy and Buildings, vol. 43, no. 8, 2011,

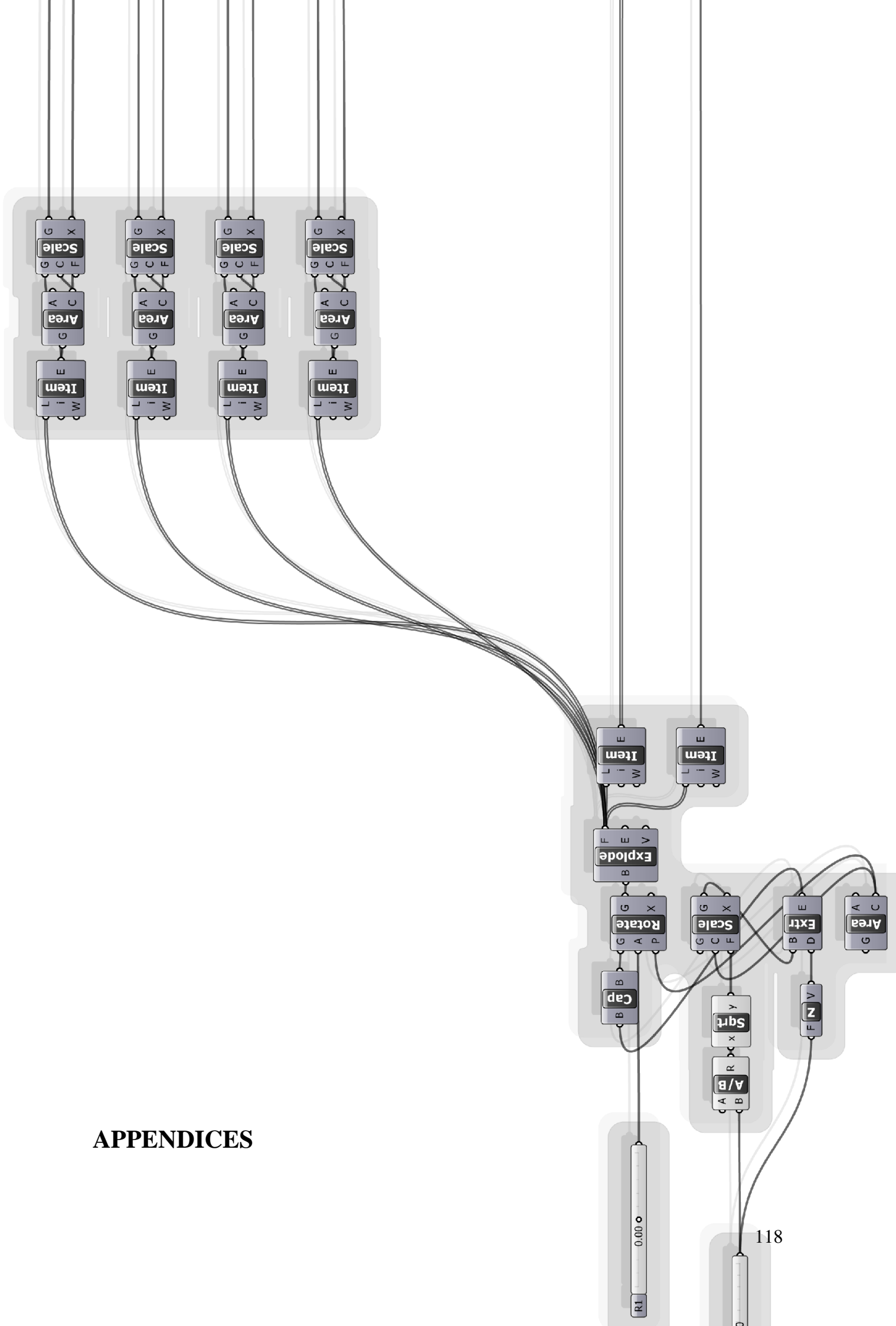
Taro Narahara, Kostas Terzidis (2006). Multiple-constraint Genetic Algorithm in Housing Design, ACADIA, 2006: Synthetic Landscapes, Digital Exchange, Available online <ftp://ftp.forum8.co.jp/forum8lib/pdf/VRsymposium/harvard-2-2.pdf> [accessed October 5, 2012]

Wong, N.H., Jusuf, S.K., Syafii, N.I., Chen, Y., Hajadi, N., Sathyanarayanan, H., Manickavasagam, Y. V (2011). Evaluation of The Impact of the Surrounding Urban Morphology on Building Energy Consumption, Solar Energy, vol. 85

Wright, J. (1996). HVAC Optimization Studies: Sizing by genetic algorithms, Building Services Engineering Research and Technology, Vol. 17

Zubin Khabazi (2012). Generative Algorithms: using Grasshopper [www.morphogenesisism.co](http://www.morphogenesisism.co)

## APPENDICES



## C# Script ANSYS CFX Exporter:

```
//Import SDK and Framework namespaces
using Rhino;
using Rhino.Geometry;
using Rhino.Collections;

using Grasshopper;
using Grasshopper.Kernel;
using Grasshopper.Kernel.Data;
using Grasshopper.Kernel.Types;

using GH_IO;
using GH_IO.Serialization;

using System;
using System.IO;
using System.Xml;
using System.Xml.Linq;
using System.Linq;
using System.Data;
using System.Drawing;
using System.Reflection;
using System.Collections;
using System.Windows.Forms;
using System.Collections.Generic;
using System.Runtime.InteropServices;

//Code generated by Grasshopper(R) (except for RunScript() content and Additional
content)
//Copyright (C) 2012 - Robert McNeel & Associates
[System.Runtime.CompilerServices.CompilerGenerated()]
public class Script_Instance : GH_ScriptInstance //IGH_ScriptInstance
{
    #region Members
    /// <summary>List of error messages. Do not modify this list directly.</summary>
    private List<string> __err = new List<string>();

    /// <summary>List of print messages. Do not modify this list directly, use the Print() and
    Reflect() functions instead.</summary>
    private List<string> __out = new List<string>();

    /// <summary>Represents the current Rhino document.</summary>
    private RhinoDoc doc = RhinoDoc.ActiveDoc;

    /// <summary>Represents the Script component which maintains this script.</summary>
    private IGH_ActiveObject owner;
```

```

    /// <summary>Represents the number of times that RunScript has been called within this
    solution.</summary>
    private int runCount;
#endregion

#region Utility functions
    /// <summary>Print a String to the [Out] Parameter of the Script component.</summary>
    /// <param name="text">String to print.</param>
    private void Print(string text)
    {
        __out.Add(text);
    }

    /// <summary>Print a formatted String to the [Out] Parameter of the Script
    component.</summary>
    /// <param name="format">String format.</param>
    /// <param name="args">Formatting parameters.</param>
    private void Print(string format, params object[] args)
    {
        __out.Add(string.Format(format, args));
    }

    /// <summary>Print useful information about an object instance to the [Out] Parameter of
    the Script component. </summary>
    /// <param name="obj">Object instance to parse.</param>
    private void Reflect(object obj)
    {
        __out.Add(GH_ScriptComponentUtilities.ReflectType_CS(obj));
    }

    /// <summary>Print the signatures of all the overloads of a specific method to the [Out]
    Parameter of the Script component. </summary>
    /// <param name="obj">Object instance to parse.</param>
    private void Reflect(object obj, string method_name)
    {
        __out.Add(GH_ScriptComponentUtilities.ReflectType_CS(obj, method_name));
    }
#endregion

    /// <summary>
    /// This procedure contains the user code. Input parameters are provided as regular
    arguments,
    /// Output parameters as ref arguments. You don't have to assign output parameters,
    /// they will be null by default.
    /// </summary>
    private void RunScript(object y, ref object A)
    {
        System.Diagnostics.Process ANSYS = new System.Diagnostics.Process();

```



```

    ANSYS.StartInfo.FileName          =          "C:\\Program          Files\\ANSYS
Inc\\v140\\Framework\\bin\\Win32\\runwb2.exe";
    ANSYS.StartInfo.Arguments = "-B -R C:\\t1\\SendtoCFX.py";
    ANSYS.Start();
}

//<Custom additional code>

//</Custom additional code>

}

```

### Python Script (SendtoCFX):

```

# import 'os' module
import os

# helper function to write parameters to the log file
def writeParams(logFile):
    for param in Parameters.GetAllParameters():
        prmString = param.Value.ToString()
        logFile.write(prmString + "\n")
    logFile.flush()

# define the original and target directories
origDir = AbsUserPathName("C:/t1/Original")
newDir = AbsUserPathName("C:/t1/Modified")

# define new geometry file
newGeom = AbsUserPathName("C:/t1/Modified/model1.stp")

# open a log file to record script progress
logFile = open(AbsUserPathName("C:/t1/GeometryReplace.log"), "w")

# create new directory if necessary
if not os.path.exists(newDir):
    os.makedirs(newDir)

# find all the projects in the original directory
projList = []
for fileName in os.listdir(origDir):
    if fileName.endswith(".wbj"):
        projList.append(fileName)

# process each project one at a time
for projFile in projList:

    # open the project into Workbench and clear any starting messages

```

```

    projPath = os.path.join(origDir, projFile)
    logFile.write("Processing project in " + projPath + "\n")
    Open(FilePath=projPath)
    ClearMessages()

# output project parameter values before update
logFile.write("Parameter values in original project: \n")
writeParams(logFile)

# walk through each system in the project and replace
# the geometry file (if there is a geometry Component)
for system in GetAllSystems():
    try:
        geometry = system.GetContainer(ComponentName="Geometry")
    except:
        logFile.write("No geometry to replace in system " + system.DisplayText +
"\n")
    else:
        geometry.SetFile(FilePath=newGeom)

# update the project
Update()

# if the project has been successfully updated, write out the new parameter values
# if not, write any project messages
if IsProjectUpToDate():
    logFile.write("Parameter values in revised project:\n")
    writeParams(logFile)
else:
    logFile.write("ERROR: Project not successfully updated. The following messages
were found:\n")
    for msg in GetMessages():
        msgString = "      " + msg.DateTimeStamp.ToString() + " " +
msg.MessageType + ": " + msg.Summary + "\n"
        logFile.write(msgString + "\n")

# in any case, save the modified project to the new directory
projPath = os.path.join(newDir, projFile)
Save(FilePath=projPath)

logFile.write("\n")

#end of project loop

logFile.close()

#set flag
flagger = open(AbsUserPathName("C:/t1/flag.txt"),"w")
flagger.write("Done!")
flagger.close()

```

## C# Script (Thread.Sleep):

```
//Import SDK and Framework namespaces
using Rhino;
using Rhino.Geometry;
using Rhino.Collections;

using Grasshopper;
using Grasshopper.Kernel;
using Grasshopper.Kernel.Data;
using Grasshopper.Kernel.Types;

using GH_IO;
using GH_IO.Serialization;

using System;
using System.IO;
using System.Xml;
using System.Xml.Linq;
using System.Linq;
using System.Data;
using System.Drawing;
using System.Reflection;
using System.Collections;
using System.Windows.Forms;
using System.Collections.Generic;
using System.Runtime.InteropServices;

//Code generated by Grasshopper(R) (except for RunScript() content and Additional
content)
//Copyright (C) 2012 - Robert McNeel & Associates
[System.Runtime.CompilerServices.CompilerGenerated()]
public class Script_Instance : GH_ScriptInstance //IGH_ScriptInstance
{
    #region Members
    /// <summary>List of error messages. Do not modify this list directly.</summary>
    private List<string> __err = new List<string>();

    /// <summary>List of print messages. Do not modify this list directly, use the Print() and
    Reflect() functions instead.</summary>
    private List<string> __out = new List<string>();

    /// <summary>Represents the current Rhino document.</summary>
    private RhinoDoc doc = RhinoDoc.ActiveDoc;

    /// <summary>Represents the Script component which maintains this script.</summary>
    private IGH_ActiveObject owner;
```

```

    /// <summary>Represents the number of times that RunScript has been called within this
    solution.</summary>
    private int runCount;
#endregion

#region Utility functions
    /// <summary>Print a String to the [Out] Parameter of the Script component.</summary>
    /// <param name="text">String to print.</param>
    private void Print(string text)
    {
        __out.Add(text);
    }

    /// <summary>Print a formatted String to the [Out] Parameter of the Script
    component.</summary>
    /// <param name="format">String format.</param>
    /// <param name="args">Formatting parameters.</param>
    private void Print(string format, params object[] args)
    {
        __out.Add(string.Format(format, args));
    }

    /// <summary>Print useful information about an object instance to the [Out] Parameter of
    the Script component. </summary>
    /// <param name="obj">Object instance to parse.</param>
    private void Reflect(object obj)
    {
        __out.Add(GH_ScriptComponentUtilities.ReflectType_CS(obj));
    }

    /// <summary>Print the signatures of all the overloads of a specific method to the [Out]
    Parameter of the Script component. </summary>
    /// <param name="obj">Object instance to parse.</param>
    private void Reflect(object obj, string method_name)
    {
        __out.Add(GH_ScriptComponentUtilities.ReflectType_CS(obj, method_name));
    }
#endregion

    /// <summary>
    /// This procedure contains the user code. Input parameters are provided as regular
    arguments,
    /// Output parameters as ref arguments. You don't have to assign output parameters,
    /// they will be null by default.
    /// </summary>
    private void RunScript(object x, object y, ref object A)
    {
        System.Threading.Thread.Sleep(5000);
    }

```

```
//<Custom additional code>

//</Custom additional code>

}
```

## **VB Script \*.stp File Exporter:**

```
Option Strict Off
Option Explicit On
```

```
'Import SDK and Framework namespaces
Imports RMA.OpenNURBS
Imports RMA.Rhino
```

```
Imports Grasshopper
Imports Grasshopper.Kernel
Imports Grasshopper.Kernel.Data
```

```
Imports System
Imports System.IO
Imports System.Xml
Imports System.Data
Imports System.Drawing
Imports System.Reflection
Imports System.Collections
Imports System.Windows.Forms
Imports Microsoft.VisualBasic
Imports System.Collections.Generic
Imports System.Runtime.InteropServices
```

```
'Code generated by Grasshopper(R) (except for RunScript() content and Additional
content)
```

```
'Copyright (C) 2012 - Robert McNeel & Associates
```

```
<System.Runtime.CompilerServices.CompilerGenerated()> _
```

```
Public Class Script_Instance
```

```
    Implements IGH_ScriptInstance
```

```
#Region "Members"
```

```
    "" <summary>List of error messages. Do not modify this list directly.</summary>
```

```
    Private __err As New List(Of String)
```

```
    "" <summary>List of print messages. Do not modify this list directly, use the Print() and
    Reflect() functions instead.</summary>
```

```

Private __out As New List(Of String)

''' <summary>Represents the current Rhino document.</summary>
Private doc As MRhinoDoc = RMA.Rhino.RhUtil.RhinoApp().ActiveDoc()

''' <summary>Represents the current Rhino application.</summary>
Private app As MRhinoApp = RMA.Rhino.RhUtil.RhinoApp()

''' <summary>Represents the Script component which maintains this script.</summary>
Public owner As Grasshopper.Kernel.IGH_ActiveObject
#End Region

#Region "Utility functions"
''' <summary>Print a String to the [Out] Parameter of the Script component.</summary>
''' <param name="text">String to print.</param>
Private Sub Print(ByVal text As String)
    __out.Add(text)
End Sub

''' <summary>Print a formatted String to the [Out] Parameter of the Script
component.</summary>
''' <param name="format">String format.</param>
''' <param name="args">Formatting parameters.</param>
Private Sub Print(ByVal format As String, ByVal ParamArray args As Object())
    __out.Add(String.Format(format, args))
End Sub

''' <summary>Print useful information about an object instance to the [Out] Parameter of
the Script component. </summary>
''' <param name="obj">Object instance to parse.</param>
Private Sub Reflect(ByVal obj As Object)
    __out.Add(GH_ScriptComponentUtilities.ReflectType_VB(obj))
End Sub

''' <summary>Print the signatures of all the overloads of a specific method to the [Out]
Parameter of the Script component. </summary>
''' <param name="obj">Object instance to parse.</param>
Private Sub Reflect(ByVal obj As Object, ByVal method_name As String)
    __out.Add(GH_ScriptComponentUtilities.ReflectType_VB(obj, method_name))
End Sub
#End Region

''' <summary>
''' This procedure contains the user code. Input parameters are provided as ByVal
arguments,
''' Output parameter are ByRef arguments. You don't have to assign output parameters,
''' they will be null by default.
''' </summary>
Private Sub RunScript(ByVal mesh As List(Of OnBrep), ByVal sFileName As String,
ByVal blnSave As Boolean, ByRef A As Object)

```



```

    If blnSave Then
    doc.UnselectAll

    For i As Integer = 0 To mesh.Count - 1
        Dim mBrepObj As New MRhinoBrepObject
        mBrepObj = doc.AddBrepObject(mesh(i))
        mBrepObj.Select()
    Next

    app.RunScript("_-export " & sFileName & " _Enter")
    app.RunScript("_delete")
    A = 0

End If

```

```
End Sub
```

```
'<Custom additional code>
```

```
'</Custom additional code>
```

```
End Class
```

### **VB Script Text File Writer:**

```

Option Strict Off
Option Explicit On

'Import SDK and Framework namespaces
Imports Rhino
Imports Rhino.Geometry
Imports Rhino.Collections

Imports Grasshopper
Imports Grasshopper.Kernel
Imports Grasshopper.Kernel.Data
Imports Grasshopper.Kernel.Types

Imports GH_IO
Imports GH_IO.Serialization

Imports System
Imports System.IO
Imports System.Xml
Imports System.Xml.Linq
Imports System.Linq

```

```
Imports System.Data
Imports System.Drawing
Imports System.Reflection
Imports System.Collections
Imports System.Windows.Forms
Imports Microsoft.VisualBasic
Imports System.Collections.Generic
Imports System.Runtime.InteropServices
```

'Code generated by Grasshopper(R) (except for RunScript() content and Additional content)

'Copyright (C) 2012 - Robert McNeel & Associates

<System.Runtime.CompilerServices.CompilerGenerated()> \_

Public Class Script\_Instance

Inherits GH\_ScriptInstance

Implements IGH\_ScriptInstance

#Region "Members"

''' <summary>List of error messages. Do not modify this list directly.</summary>

Private \_\_err As New List(Of String)

''' <summary>List of print messages. Do not modify this list directly, use the Print() and Reflect() functions instead.</summary>

Private \_\_out As New List(Of String)

''' <summary>Represents the current Rhino document.</summary>

Private doc As RhinoDoc = RhinoDoc.ActiveDoc

''' <summary>Represents the Script component which maintains this script.</summary>

Public owner As Grasshopper.Kernel.IGH\_ActiveObject

''' <summary>Represents the number of times that RunScript has been called within this solution.</summary>

Public runCount As Int32

#End Region

#Region "Utility functions"

''' <summary>Print a String to the [Out] Parameter of the Script component.</summary>

''' <param name="text">String to print.</param>

Private Sub Print(ByVal text As String)

\_\_out.Add(text)

End Sub

''' <summary>Print a formatted String to the [Out] Parameter of the Script component.</summary>

''' <param name="format">String format.</param>

''' <param name="args">Formatting parameters.</param>

Private Sub Print(ByVal format As String, ByVal ParamArray args As Object())

```

    __out.Add(String.Format(format, args))
End Sub

''' <summary>Print useful information about an object instance to the [Out] Parameter of
the Script component. </summary>
''' <param name="obj">Object instance to parse.</param>
Private Sub Reflect(ByVal obj As Object)
    __out.Add(GH_ScriptComponentUtilities.ReflectType_VB(obj))
End Sub

''' <summary>Print the signatures of all the overloads of a specific method to the [Out]
Parameter of the Script component. </summary>
''' <param name="obj">Object instance to parse.</param>
Private Sub Reflect(ByVal obj As Object, ByVal method_name As String)
    __out.Add(GH_ScriptComponentUtilities.ReflectType_VB(obj, method_name))
End Sub
#End Region

''' <summary>
''' This procedure contains the user code. Input parameters are provided as ByVal
arguments,
''' Output parameter are ByRef arguments. You don't have to assign output parameters,
''' they will be null by default.
''' </summary>
Private Sub RunScript(ByVal filePath As String, ByVal data As List(Of String), ByVal
append As Boolean, ByVal activate As Boolean, ByVal clearFile As Boolean, ByRef A As
Object)

    If activate Then

        Dim i As Integer
        Dim aryText(4) As String

        aryText(0) = "Mary WriteLine"
        aryText(1) = "Had"
        aryText(2) = "Another"
        aryText(3) = "Little"
        aryText(4) = "One"

        ' the data is appended to the file. If file doesnt exist, a new file is created
        Dim objWriter As New System.IO.StreamWriter(filePath, append)

        For i = 0 To data.Count - 1
            objWriter.WriteLine(data(i))
        Next

        objWriter.Close()

    End If

```

```
If clearFile Then
    Dim objWriter As New System.IO.StreamWriter(filePath, False)
    objWriter.Close()
End If

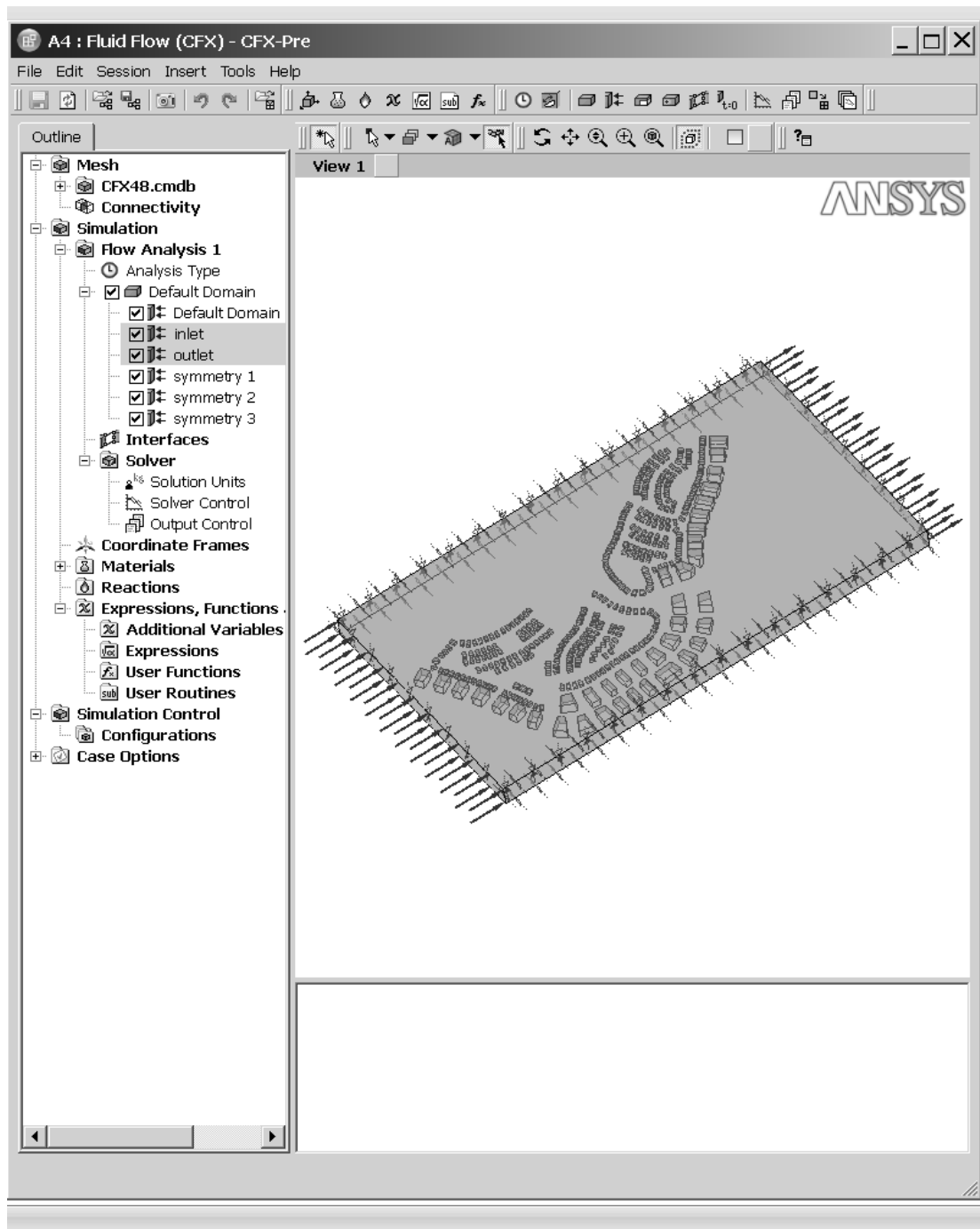
End Sub

'<Custom additional code>

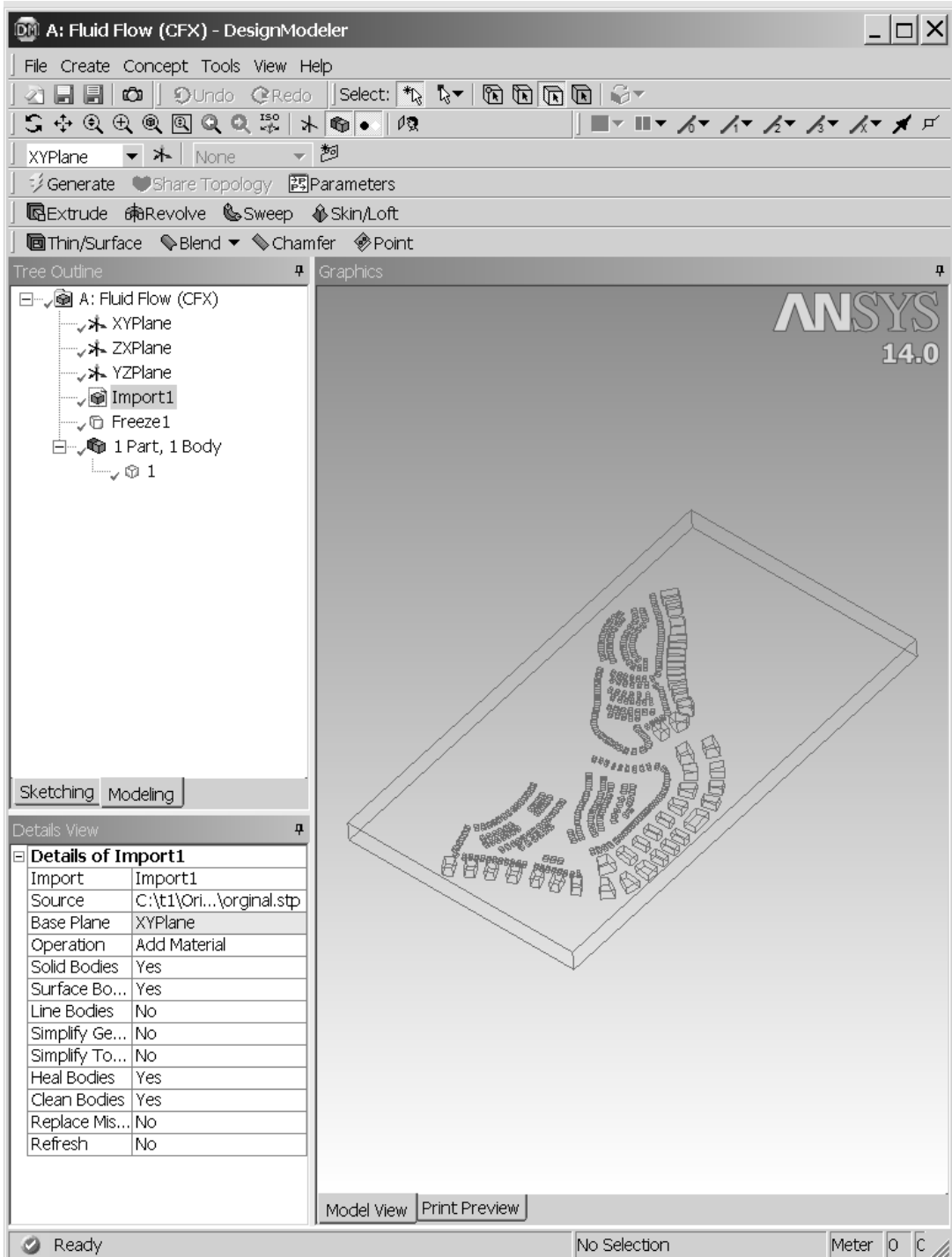
'</Custom additional code>

End Class
```

## CFX Pre and Setup:

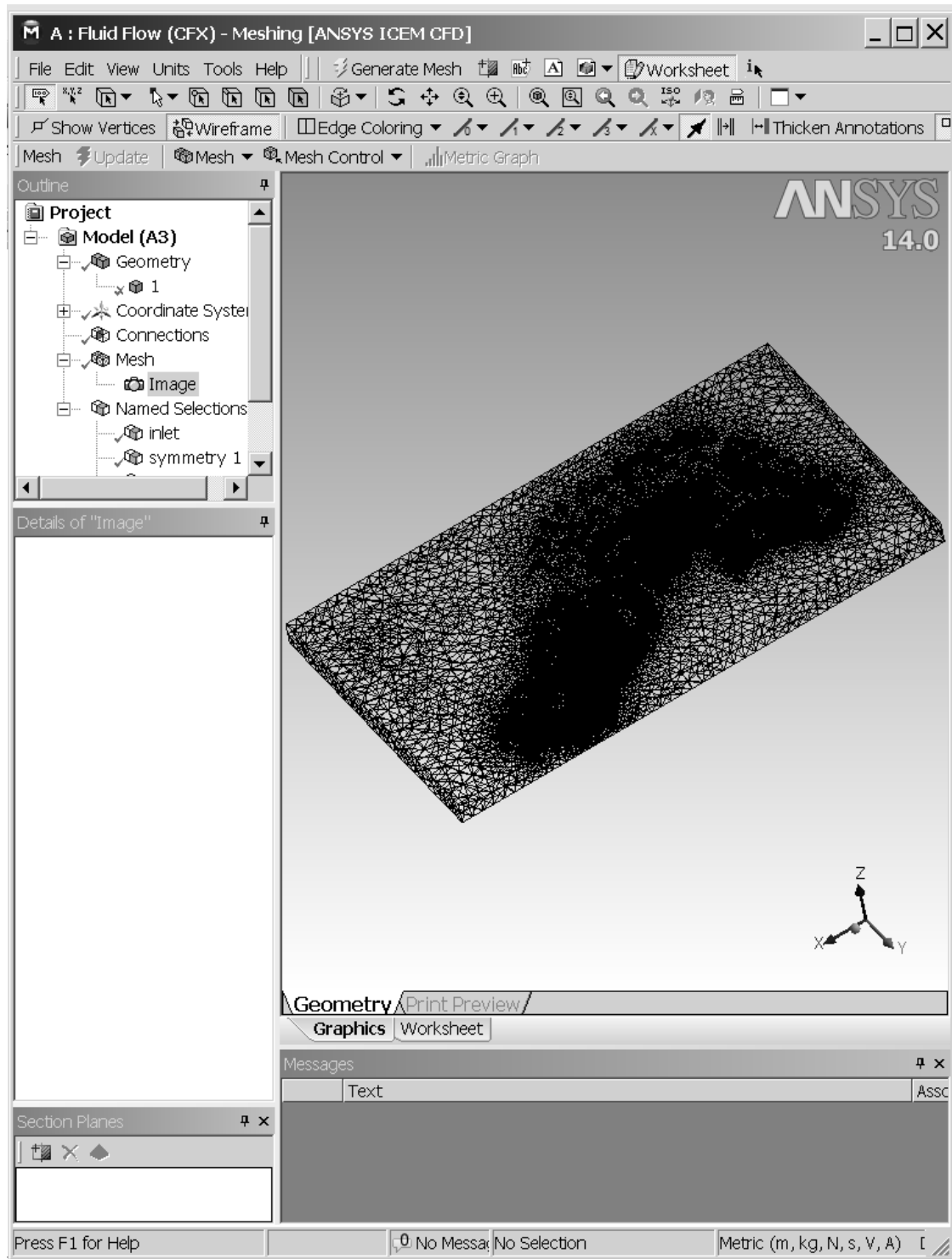


**CFX Pre Design Modeler:**

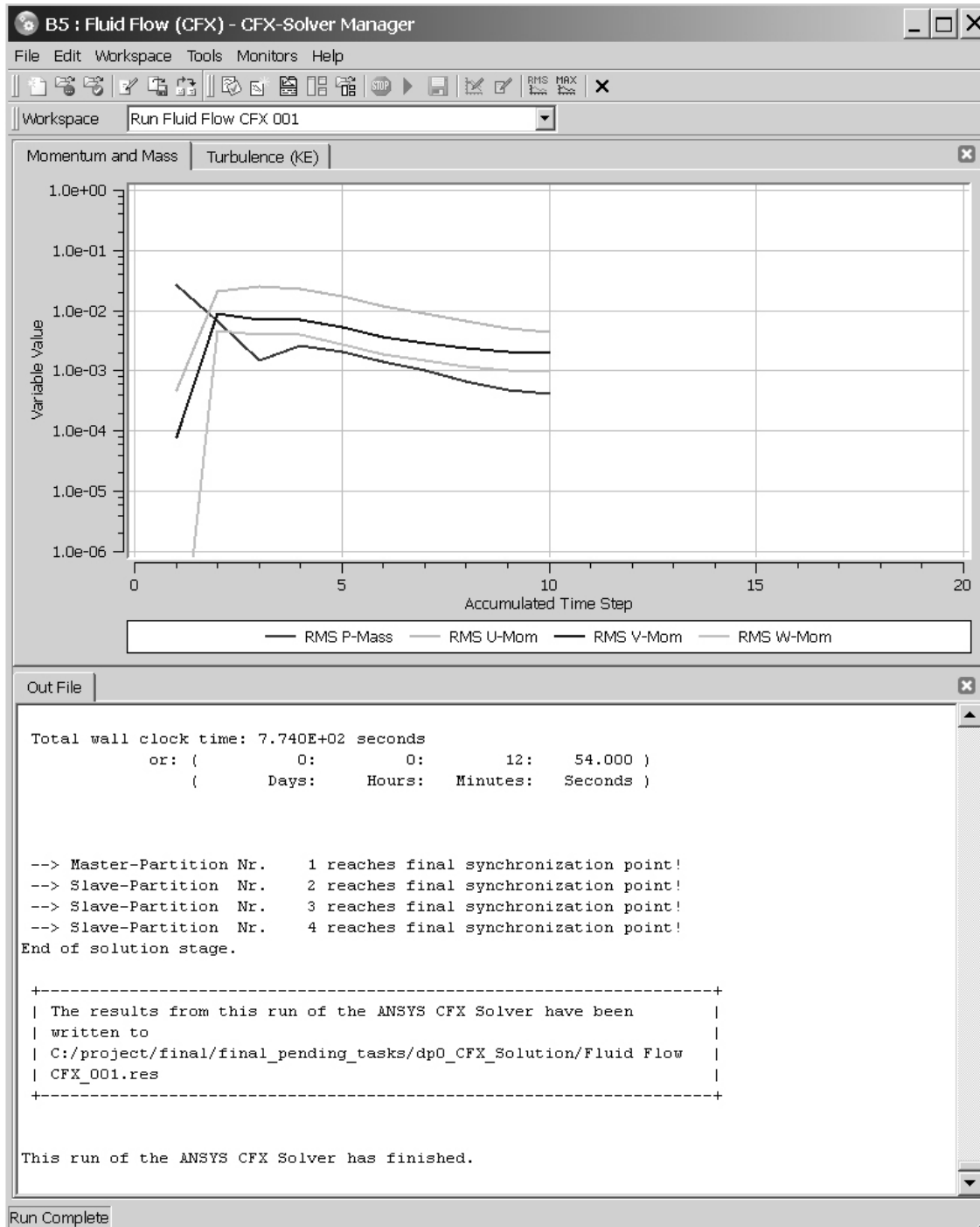




## CFX Meshing:



## CFX Solver:



## CFX Out file:

```
"C:\Program Files\ANSYS Inc\v140\CFX\bin\perl\lib\cfx5solve.pl" -batch  
-ccl runInput.ccl -fullname "Fluid Flow CFX_001"
```

Setting up CFX Solver run ...

```
+-----+  
|               |  
| CFX Command Language for Run |  
|               |  
+-----+
```

### LIBRARY:

CEL:

EXPRESSIONS:

point 1 wind speed = ave(Velocity u )@REGION:outlet  
END

END

MATERIAL: Air Ideal Gas

Material Description = Air Ideal Gas (constant Cp)

Material Group = Air Data, Calorically Perfect Ideal Gases

Option = Pure Substance

Thermodynamic State = Gas

PROPERTIES:

Option = General Material

EQUATION OF STATE:

Molar Mass = 28.96 [kg kmol<sup>-1</sup>]

Option = Ideal Gas

END

SPECIFIC HEAT CAPACITY:

Option = Value

Specific Heat Capacity = 1.0044E+03 [J kg<sup>-1</sup> K<sup>-1</sup>]

Specific Heat Type = Constant Pressure

END

REFERENCE STATE:

Option = Specified Point

Reference Pressure = 1 [atm]

Reference Specific Enthalpy = 0. [J/kg]

Reference Specific Entropy = 0. [J/kg/K]

Reference Temperature = 25 [C]

END

DYNAMIC VISCOSITY:

Dynamic Viscosity = 1.831E-05 [kg m<sup>-1</sup> s<sup>-1</sup>]

Option = Value

END

THERMAL CONDUCTIVITY:

Option = Value

Thermal Conductivity = 2.61E-2 [W m<sup>-1</sup> K<sup>-1</sup>]

END

ABSORPTION COEFFICIENT:

Absorption Coefficient = 0.01 [m<sup>-1</sup>]

Option = Value

END

SCATTERING COEFFICIENT:

Option = Value

Scattering Coefficient = 0.0 [m<sup>-1</sup>]

END

REFRACTIVE INDEX:

Option = Value

Refractive Index = 1.0 [m m<sup>-1</sup>]

END

END

END

END

FLOW: Flow Analysis 1

SOLUTION UNITS:

Angle Units = [rad]

Length Units = [m]

Mass Units = [kg]

Solid Angle Units = [sr]

Temperature Units = [K]

```

Time Units = [s]
END
ANALYSIS TYPE:
Option = Steady State
EXTERNAL SOLVER COUPLING:
Option = None
END
END
DOMAIN: Default Domain
Coord Frame = Coord 0
Domain Type = Fluid
Location = B27270
BOUNDARY: inlet
Boundary Type = INLET
Location = inlet
BOUNDARY CONDITIONS:
FLOW REGIME:
Option = Subsonic
END
MASS AND MOMENTUM:
Normal Speed = 17 [m s-1]
Option = Normal Speed
END
TURBULENCE:
Option = Medium Intensity and Eddy Viscosity Ratio
END
END
END
BOUNDARY: outlet
Boundary Type = OUTLET
Location = outlet
BOUNDARY CONDITIONS:
FLOW REGIME:
Option = Subsonic
END
MASS AND MOMENTUM:
Option = Average Static Pressure
Pressure Profile Blend = 0.05
Relative Pressure = 0 [Pa]
END
PRESSURE AVERAGING:
Option = Average Over Whole Outlet
END
END
END
BOUNDARY: symmetry1
Boundary Type = SYMMETRY
Location = symmetry1
END
BOUNDARY: symmetry2
Boundary Type = SYMMETRY
Location = symmetry2
END
BOUNDARY: symmetry3
Boundary Type = SYMMETRY
Location = symmetry3
END
BOUNDARY: wall
Boundary Type = WALL
Location = wall
BOUNDARY CONDITIONS:
MASS AND MOMENTUM:
Option = No Slip Wall
END
WALL ROUGHNESS:
Option = Smooth Wall
END
END
END
DOMAIN MODELS:
BUOYANCY MODEL:
Option = Non Buoyant
END
DOMAIN MOTION:
Option = Stationary

```

```

END
MESH DEFORMATION:
  Option = None
END
REFERENCE PRESSURE:
  Reference Pressure = 1 [atm]
END
END
FLUID DEFINITION: Fluid 1
  Material = Air Ideal Gas
  Option = Material Library
MORPHOLOGY:
  Option = Continuous Fluid
END
END
FLUID MODELS:
COMBUSTION MODEL:
  Option = None
END
HEAT TRANSFER MODEL:
  Fluid Temperature = 35 [C]
  Option = Isothermal
END
THERMAL RADIATION MODEL:
  Option = None
END
TURBULENCE MODEL:
  Option = k epsilon
END
TURBULENT WALL FUNCTIONS:
  Option = Scalable
END
END
END
OUTPUT CONTROL:
MONITOR OBJECTS:
MONITOR BALANCES:
  Option = Full
END
MONITOR FORCES:
  Option = Full
END
MONITOR PARTICLES:
  Option = Full
END
MONITOR RESIDUALS:
  Option = Full
END
MONITOR TOTALS:
  Option = Full
END
END
RESULTS:
  File Compression Level = Default
  Option = Standard
END
END
SOLVER CONTROL:
  Turbulence Numerics = First Order
ADVECTION SCHEME:
  Option = High Resolution
END
CONVERGENCE CONTROL:
  Length Scale Option = Conservative
  Maximum Number of Iterations = 10
  Minimum Number of Iterations = 1
  Timescale Control = Auto Timescale
  Timescale Factor = 1.0
END
CONVERGENCE CRITERIA:
  Residual Target = 1.E-4
  Residual Type = RMS
END
DYNAMIC MODEL CONTROL:
  Global Dynamic Model Control = On

```

```

END
END
END
COMMAND FILE:
  Version = 14.0
  Results Version = 14.0
END
SIMULATION CONTROL:
EXECUTION CONTROL:
  EXECUTABLE SELECTION:
    Double Precision = Off
  END
INTERPOLATOR STEP CONTROL:
  Runtime Priority = Standard
MEMORY CONTROL:
  Memory Allocation Factor = 1.0
END
END
PARALLEL HOST LIBRARY:
  HOST DEFINITION: pc
  Remote Host Name = -PC
  Host Architecture String = winnt-amd64
  Installation Root = C:\Program Files\ANSYS Inc\v%v\CFX
END
END
PARTITIONER STEP CONTROL:
  Multidomain Option = Independent Partitioning
  Runtime Priority = Standard
  EXECUTABLE SELECTION:
    Use Large Problem Partitioner = Off
  END
  MEMORY CONTROL:
    Memory Allocation Factor = 1.0
  END
  PARTITIONING TYPE:
    MeTiS Type = k-way
    Option = MeTiS
    Partition Size Rule = Automatic
    Partition Weight Factors = 0.25000, 0.25000, 0.25000, 0.25000
  END
END
RUN DEFINITION:
  Run Mode = Full
  Solver Input File = Fluid Flow CFX.def
END
SOLVER STEP CONTROL:
  Runtime Priority = High
  MEMORY CONTROL:
    Memory Allocation Factor = 1.0
  END
PARALLEL ENVIRONMENT:
  Number of Processes = 4
  Start Method = Platform MPI Local Parallel
  Parallel Host List = pc*4
END
END
END
END

```

```

+-----+
|                                     |
|                                     |
| Partitioning                       |
|                                     |
|                                     |
+-----+

```

```

+-----+
|                                     |
| ANSYS(R) CFX(R) Partitioner 14.0 |
|                                     |
| Version 2011.10.10-23.01          | Tue Oct 11 00:28:38 GMTDT 2011 |
|                                     |
+-----+

```

```

| Executable Attributes |
| single-int32-64bit-novc8-noifort-novc6-optimised-supfort-noprof-nos|
| (C) 2011 ANSYS, Inc. |
| All rights reserved. Unauthorized use, distribution or duplication |
| is prohibited. This product is subject to U.S. laws governing |
| export and re-export. For full Legal Notice, see documentation. |
+-----+

```

```

+-----+
| Job Information |
+-----+

```

Run mode: partitioning run

Host computer: -PC (PID:1040)

Job started: Mon Oct 22 08:04:20 2012

```

+-----+
| Memory Allocated for Run (Actual usage may be less) |
+-----+

```

Data Type	Kwords	Words/Node	Words/Elem	Kbytes	Bytes/Node
Real	4609.7	6.90	1.30	18006.7	27.60
Integer	64908.8	97.16	18.33	253549.9	388.63
Character	3533.1	5.29	1.00	3450.3	5.29
Logical	80.0	0.12	0.02	312.5	0.48
Double	600.5	0.90	0.17	4691.4	7.19

```

+-----+
| Mesh Statistics |
+-----+

```

Domain Name : Default Domain

```

Total Number of Nodes          = 668072

Total Number of Elements        = 3541111
Total Number of Tetrahedrons    = 3541111

Total Number of Faces           = 312472

```

```

+-----+
| Vertex Based Partitioning |
+-----+

```

Partitioning of domain: Default Domain

```

- Partitioning tool:  MeTiS multilevel k-way algorithm
- Number of partitions:      4
- Number of graph-nodes:    668072
- Number of graph-edges:    8730836

```

```

+-----+
| Partitioning Information |
+-----+

```

Partitioning information for domain: Default Domain

Elements		Vertices		Faces	
Part	Number	%	Number	%	%Ovlp
Full	3541111		668072		312472
1	894605	25.1	170010	25.0	1.6
					77112 24.5



	2	893782	25.0	170002	25.0	1.7	78966	25.1
	3	889247	24.9	169341	25.0	1.6	79045	25.1
	4	890583	25.0	169361	25.0	1.4	79607	25.3
+-----+-----+-----+-----+								
	Sum	3568217	100.0	678714	100.0	1.6	314730	100.0
+-----+-----+-----+-----+								

+-----+-----+	
	Partitioning CPU-Time Requirements
+-----+-----+	

```

- Preparations                      4.384E+00 seconds
- Low-level mesh partitioning        1.513E+00 seconds
- Global partitioning information    3.740E-01 seconds
- Element and face partitioning information 5.150E-01 seconds
- Vertex partitioning information    4.700E-02 seconds
- Partitioning information compression 3.100E-02 seconds
- Summed CPU-time for mesh partitioning 7.348E+00 seconds

```

+-----+-----+	
	Job Information
+-----+-----+	

Job finished: Mon Oct 22 08:04:31 2012  
Total CPU time: 1.123E+01 seconds  
or: ( 0: 0: 0: 11.232 )  
( Days: Hours: Minutes: Seconds )

Total wall clock time: 1.100E+01 seconds  
or: ( 0: 0: 0: 11.000 )  
( Days: Hours: Minutes: Seconds )

+-----+-----+	
	Solver
+-----+-----+	

+-----+-----+	
	ANSYS(R) CFX(R) Solver 14.0
	Version 2011.10.10-23.01 Tue Oct 11 00:28:38 GMTDT 2011
	Executable Attributes
	single-int32-64bit-novc8-noifort-novc6-optimised-supfort-noprof-nos
	(C) 2011 ANSYS, Inc.
	All rights reserved. Unauthorized use, distribution or duplication
	is prohibited. This product is subject to U.S. laws governing
	export and re-export. For full Legal Notice, see documentation.
+-----+-----+	

+-----+-----+	
	Job Information
+-----+-----+	

Run mode: parallel run (MPI)

Host computer: -PC (PID:1984)

Par. Process: Master running on mesh partition: 1

Solver Build: Tue Oct 11 00:28:38 GMTDT 2011

Attributes: single-int32-64bit-novc8-noifort-novc6-optimised-su...

Job started: Mon Oct 22 08:04:33 2012

Host computer: -PC (PID:5360)  
Par. Process: Slave running on mesh partition: 2  
Solver Build: Tue Oct 11 00:28:38 GMTDT 2011  
Attributes: single-int32-64bit-novc8-noifort-novc6-optimised-su...  
Job started: Mon Oct 22 08:04:33 2012

Host computer: -PC (PID:4528)  
Par. Process: Slave running on mesh partition: 3  
Solver Build: Tue Oct 11 00:28:38 GMTDT 2011  
Attributes: single-int32-64bit-novc8-noifort-novc6-optimised-su...  
Job started: Mon Oct 22 08:04:33 2012

Host computer: -PC (PID:4088)  
Par. Process: Slave running on mesh partition: 4  
Solver Build: Tue Oct 11 00:28:38 GMTDT 2011  
Attributes: single-int32-64bit-novc8-noifort-novc6-optimised-su...  
Job started: Mon Oct 22 08:04:33 2012  
License Cap: ANSYS CFX Solver (> 512K Nodes)  
License Cap: Parallel  
License ID: -PC-SYSTEM-1380-007301

+-----+  
| Memory Allocated for Run (Actual usage may be less) |  
+-----+

Allocated storage in: Kwords  
Words/Node  
Words/Elem  
Kbytes  
Bytes/Node

Partition	Real	Integer	Character	Logical	Double
1	73636.9	28414.2	3983.1	80.0	608.0
	433.13	167.13	23.43	0.47	3.58
	82.31	31.76	4.45	0.09	0.68
	287644.1	110993.1	3889.8	78.1	4750.0
	1732.53	668.53	23.43	0.47	28.61
2	73783.6	28416.1	3983.1	80.0	608.0
	434.02	167.15	23.43	0.47	3.58
	82.55	31.79	4.46	0.09	0.68
	288217.2	111000.3	3889.8	78.1	4750.0
	1736.06	668.61	23.43	0.47	28.61
3	73483.5	28315.9	3983.1	80.0	608.0
	433.94	167.21	23.52	0.47	3.59
	82.64	31.84	4.48	0.09	0.68
	287045.1	110608.8	3889.8	78.1	4750.0
	1735.75	668.85	23.52	0.47	28.72
4	73615.9	28358.5	3983.1	80.0	608.0
	434.67	167.44	23.52	0.47	3.59
	82.66	31.84	4.47	0.09	0.68
	287561.9	110775.2	3889.8	78.1	4750.0
	1738.67	669.78	23.52	0.47	28.72
Total	294519.9	113504.6	15932.5	320.0	2432.0
	440.85	169.90	23.85	0.48	3.64
	83.17	32.05	4.50	0.09	0.69
	1150468.2	443377.5	15559.1	312.5	19000.0
	1763.40	679.60	23.85	0.48	29.12

+-----+

Mesh Statistics			
Domain Name	Orthog. Angle	Exp. Factor	Aspect Ratio
Minimum [deg]   Maximum   Maximum			
Default Domain	41.9 ok	18 ok	6 OK

+-----+

```

+-----+-----+-----+
|          | %! %ok %OK | %! %ok %OK | %! %ok %OK |
+-----+-----+-----+
| Default Domain | 0 <1 100 | 0 2 98 | 0 0 100 |
+-----+-----+-----+

```

Domain Name : Default Domain

```

Total Number of Nodes          = 668072

Total Number of Elements       = 3541111
Total Number of Tetrahedrons   = 3541111

Total Number of Faces          = 312472

```

```

+-----+
| Average Scale Information |
+-----+

```

Domain Name : Default Domain

```

Global Length          = 4.8770E+02
Minimum Extent         = 5.6000E+01
Maximum Extent         = 1.6220E+03
Density                = 1.1453E+00
Dynamic Viscosity      = 1.8310E-05
Velocity               = 1.7000E+01
Advection Time         = 2.8688E+01
Reynolds Number        = 5.1860E+08
Speed of Sound         = 3.5197E+02
Mach Number            = 4.8300E-02

```

```

+-----+
| Checking for Isolated Fluid Regions |
+-----+

```

No isolated fluid regions were found.

```

+-----+
| The Equations Solved in This Calculation |
+-----+

```

Subsystem : Momentum and Mass

U-Mom  
V-Mom  
W-Mom  
P-Mass

Subsystem : TurbKE and Diss.K

K-TurbKE  
E-Diss.K

CFD Solver started: Mon Oct 22 08:06:05 2012

```

+-----+
| Convergence History |
+-----+

```

```

=====
| Timescale Information |
+-----+
| Equation | Type | Timescale |
+-----+-----+-----+
| U-Mom | Auto Timescale | 8.60654E+00 |
| V-Mom | Auto Timescale | 8.60654E+00 |
| W-Mom | Auto Timescale | 8.60654E+00 |
| P-Mass | Auto Timescale | 8.60654E+00 |
+-----+-----+-----+
| K-TurbKE | Auto Timescale | 8.60654E+00 |
| E-Diss.K | Auto Timescale | 8.60654E+00 |
+-----+-----+-----+
=====

```

OUTER LOOP ITERATION = 1 CPU SECONDS = 3.731E+02

Equation	Rate	RMS Res	Max Res	Linear Solution
U-Mom	0.00	4.9E-04	4.6E-03	1.2E+00 ok
V-Mom	0.00	7.9E-05	5.8E-04	1.2E+01 ok
W-Mom	0.00	2.5E-09	7.2E-08	3.2E+05 ok
P-Mass	0.00	2.7E-02	3.1E-01	8.6 2.9E-02 OK
K-TurbKE	0.00	1.8E+00	2.0E+00	5.5 3.2E-08 OK
E-Diss.K	0.00	1.1E+02	1.1E+02	8.6 2.7E-08 OK

OUTER LOOP ITERATION = 2 CPU SECONDS = 6.339E+02

Equation	Rate	RMS Res	Max Res	Linear Solution
U-Mom	43.52	2.1E-02	3.8E-01	3.9E-02 OK
V-Mom	99.99	8.8E-03	9.8E-02	4.4E-02 OK
W-Mom	99.99	4.7E-03	1.3E-01	6.8E-02 OK
P-Mass	0.25	6.9E-03	1.1E-01	8.6 4.1E-02 OK
K-TurbKE	0.03	5.7E-02	3.3E-01	5.5 1.9E-04 OK
E-Diss.K	0.00	1.9E-02	4.7E-01	8.6 2.9E-08 OK

OUTER LOOP ITERATION = 3 CPU SECONDS = 8.605E+02

Equation	Rate	RMS Res	Max Res	Linear Solution
U-Mom	1.22	2.6E-02	1.1E+00	2.5E-02 OK
V-Mom	0.81	7.1E-03	2.0E-01	3.5E-02 OK
W-Mom	0.86	4.0E-03	1.6E-01	5.6E-02 OK
P-Mass	0.22	1.5E-03	3.6E-02	8.6 3.3E-02 OK
K-TurbKE	0.68	3.8E-02	3.4E-01	5.5 1.7E-02 OK
E-Diss.K	0.32	5.9E-03	1.6E-01	8.6 7.8E-05 OK

OUTER LOOP ITERATION = 4 CPU SECONDS = 1.086E+03

Equation	Rate	RMS Res	Max Res	Linear Solution
U-Mom	0.91	2.3E-02	4.8E-01	8.1E-02 OK
V-Mom	0.99	7.0E-03	1.5E-01	1.3E-01 ok
W-Mom	0.99	4.0E-03	1.8E-01	1.9E-01 ok
P-Mass	1.72	2.6E-03	8.1E-02	4.8 5.8E-02 OK
K-TurbKE	0.49	1.9E-02	3.6E-01	5.6 2.7E-02 OK
E-Diss.K	0.56	3.4E-03	4.5E-02	8.6 7.1E-04 OK

OUTER LOOP ITERATION = 5 CPU SECONDS = 1.307E+03

Equation	Rate	RMS Res	Max Res	Linear Solution
U-Mom	0.73	1.7E-02	4.0E-01	1.1E-01 ok
V-Mom	0.75	5.3E-03	1.3E-01	1.7E-01 ok
W-Mom	0.70	2.8E-03	1.2E-01	2.2E-01 ok
P-Mass	0.78	2.0E-03	5.1E-02	4.8 5.3E-02 OK
K-TurbKE	0.37	7.0E-03	4.2E-01	5.5 1.8E-02 OK
E-Diss.K	0.68	2.3E-03	1.9E-01	8.6 2.9E-04 OK

Timescale Information			
Equation	Type	Timescale	
U-Mom	Auto Timescale	8.60654E+00	

V-Mom	Auto Timescale	8.60654E+00	
W-Mom	Auto Timescale	8.60654E+00	
P-Mass	Auto Timescale	8.60654E+00	
+-----+			
K-TurbKE	Auto Timescale	8.60654E+00	
E-Diss.K	Auto Timescale	8.60654E+00	
+-----+			

=====

OUTER LOOP ITERATION = 6 CPU SECONDS = 1.526E+03

Equation	Rate	RMS Res	Max Res	Linear Solution	
+-----+					
U-Mom	0.69	1.2E-02	3.1E-01	1.4E-01	ok
V-Mom	0.71	3.7E-03	1.8E-01	1.9E-01	ok
W-Mom	0.69	1.9E-03	9.3E-02	2.2E-01	ok
P-Mass	0.69	1.4E-03	3.7E-02	4.8	5.9E-02 OK
+-----+					
K-TurbKE	0.58	4.0E-03	3.4E-01	5.5	1.8E-02 OK
E-Diss.K	0.72	1.7E-03	1.3E-01	8.6	2.9E-04 OK
+-----+					

=====

OUTER LOOP ITERATION = 7 CPU SECONDS = 1.752E+03

Equation	Rate	RMS Res	Max Res	Linear Solution	
+-----+					
U-Mom	0.75	8.9E-03	3.0E-01	1.6E-01	ok
V-Mom	0.77	2.9E-03	1.1E-01	1.9E-01	ok
W-Mom	0.76	1.5E-03	4.4E-02	2.2E-01	ok
P-Mass	0.71	1.0E-03	3.7E-02	4.8	7.1E-02 OK
+-----+					
K-TurbKE	0.84	3.4E-03	2.8E-01	5.5	1.8E-02 OK
E-Diss.K	0.79	1.3E-03	9.0E-02	8.6	3.0E-04 OK
+-----+					

=====

OUTER LOOP ITERATION = 8 CPU SECONDS = 1.982E+03

Equation	Rate	RMS Res	Max Res	Linear Solution	
+-----+					
U-Mom	0.74	6.6E-03	2.0E-01	1.7E-01	ok
V-Mom	0.81	2.3E-03	9.7E-02	1.9E-01	ok
W-Mom	0.79	1.2E-03	4.8E-02	2.1E-01	ok
P-Mass	0.67	6.7E-04	3.4E-02	4.8	8.6E-02 OK
+-----+					
K-TurbKE	1.00	3.4E-03	3.0E-01	5.5	1.7E-02 OK
E-Diss.K	0.85	1.1E-03	1.0E-01	8.6	4.6E-04 OK
+-----+					

=====

OUTER LOOP ITERATION = 9 CPU SECONDS = 2.209E+03

Equation	Rate	RMS Res	Max Res	Linear Solution	
+-----+					
U-Mom	0.78	5.2E-03	1.8E-01	4.9E-02	OK
V-Mom	0.88	2.1E-03	9.6E-02	4.7E-02	OK
W-Mom	0.87	1.0E-03	4.7E-02	5.5E-02	OK
P-Mass	0.73	4.9E-04	2.7E-02	8.6	3.1E-02 OK
+-----+					
K-TurbKE	0.89	3.0E-03	3.0E-01	5.6	1.8E-02 OK
E-Diss.K	0.91	1.0E-03	1.1E-01	8.6	1.0E-03 OK
+-----+					

=====

OUTER LOOP ITERATION = 10 CPU SECONDS = 2.444E+03

Equation	Rate	RMS Res	Max Res	Linear Solution	
+-----+					
U-Mom	0.85	4.4E-03	1.8E-01	4.6E-02	OK
V-Mom	0.96	2.0E-03	1.3E-01	4.3E-02	OK
W-Mom	0.98	9.8E-04	6.3E-02	5.0E-02	OK
P-Mass	0.83	4.1E-04	1.9E-02	8.6	3.0E-02 OK
+-----+					
K-TurbKE	0.96	2.9E-03	2.8E-01	5.6	1.7E-02 OK

| E-Diss.K | 0.85 | 8.7E-04 | 7.1E-02 | 8.6 2.0E-03 OK|  
+-----+-----+-----+-----+

CFD Solver finished: Mon Oct 22 08:15:45 2012  
CFD Solver wall clock seconds: 5.8000E+02

=====  
Termination and Interrupt Condition Summary  
=====

CFD Solver: Run duration reached  
(Maximum number of outer iterations)

=====  
Boundary Flow and Total Source Term Summary  
=====

+-----+  
| U-Mom |  
+-----+  
Boundary : inlet 3.0776E+07  
Boundary : outlet -2.4412E+07  
Boundary : wall -7.0012E+06

Domain Imbalance : -6.3735E+05  
Domain Imbalance, in %: -2.0709 %

+-----+  
| V-Mom |  
+-----+  
Boundary : inlet -1.2578E-03  
Boundary : outlet 2.6086E+04  
Boundary : symmetry2 1.2506E+06  
Boundary : symmetry3 -1.4008E+06  
Boundary : wall 1.0474E+05

Domain Imbalance : -1.9406E+04  
Domain Imbalance, in %: -0.0631 %

+-----+  
| W-Mom |  
+-----+  
Boundary : inlet -1.5538E-03  
Boundary : outlet 2.1673E+04  
Boundary : symmetry1 -2.9256E+07  
Boundary : wall 2.9258E+07

Domain Imbalance : 2.4338E+04  
Domain Imbalance, in %: 0.0791 %

+-----+  
| P-Mass |  
+-----+  
Boundary : inlet 1.4171E+06  
Boundary : outlet -1.4174E+06

Domain Imbalance : -2.9800E+02  
Domain Imbalance, in %: -0.0210 %

=====  
Wall Force and Moment Summary  
=====

Notes:

1. Pressure integrals exclude the reference pressure. To include it, set the expert parameter 'include pref in forces = t'.

+-----+  
| Pressure Force On Walls |  
+-----+

X-Comp.   Y-Comp.   Z-Comp.

Domain Group: Default Domain

wall                    6.5901E+06 -1.0323E+05 -2.9261E+07  
-----

Domain Group Totals :        6.5901E+06 -1.0323E+05 -2.9261E+07

+-----+  
|                    Viscous Force On Walls                    |  
+-----+  
X-Comp.   Y-Comp.   Z-Comp.

Domain Group: Default Domain

wall                    4.1110E+05 -1.5123E+03 2.6927E+03  
-----

Domain Group Totals :        4.1110E+05 -1.5123E+03 2.6927E+03

+-----+  
|                    Pressure Moment On Walls                    |  
+-----+  
X-Comp.   Y-Comp.   Z-Comp.

Domain Group: Default Domain

wall                    -3.9340E+10 6.0303E+10 -8.6235E+09  
-----

Domain Group Totals :        -3.9340E+10 6.0303E+10 -8.6235E+09

+-----+  
|                    Viscous Moment On Walls                    |  
+-----+  
X-Comp.   Y-Comp.   Z-Comp.

Domain Group: Default Domain

wall                    3.4446E+06 -6.2872E+06 -5.4248E+08  
-----

Domain Group Totals :        3.4446E+06 -6.2872E+06 -5.4248E+08

+-----+  
|                    Locations of Maximum Residuals                    |  
+-----+  
|   Equation   | Node # | X   | Y   | Z   |  
+-----+  
U-Mom	11246	2.529E+03	1.143E+03	3.466E-16
V-Mom	9906	3.002E+03	1.624E+03	0.000E+00
W-Mom	9906	3.002E+03	1.624E+03	0.000E+00
P-Mass	154518	2.303E+03	1.085E+03	4.881E+00
K-TurbKE	350423	2.256E+03	1.205E+03	6.392E+00
E-Diss.K	161595	2.367E+03	9.882E+02	1.915E+00
+-----+

+-----+  
|                    Peak Values of Residuals                    |  
+-----+  
|   Equation   | Loop # | Peak Residual | Final Residual |  
+-----+  
U-Mom	3	2.58189E-02	4.42214E-03
V-Mom	2	8.79479E-03	1.96728E-03
W-Mom	2	4.71940E-03	9.84940E-04
P-Mass	1	2.70638E-02	4.08779E-04
K-TurbKE	1	1.79691E+00	2.89955E-03
E-Diss.K	1	1.06586E+02	8.70936E-04
+-----+

+-----+  
|                    False Transient Information                    |  
+-----+



Equation	Type	Elapsed Pseudo-Time
U-Mom	Auto	8.60654E+01
V-Mom	Auto	8.60654E+01
W-Mom	Auto	8.60654E+01
P-Mass	Auto	8.60654E+01
K-TurbKE	Auto	8.60654E+01
E-Diss.K	Auto	8.60654E+01

Average Scale Information
---------------------------

Domain Name : Default Domain

Global Length	= 4.8770E+02
Minimum Extent	= 5.6000E+01
Maximum Extent	= 1.6220E+03
Density	= 1.1453E+00
Dynamic Viscosity	= 1.8310E-05
Velocity	= 1.4836E+01
Advection Time	= 3.2872E+01
Reynolds Number	= 4.5261E+08
Speed of Sound	= 3.5197E+02
Mach Number	= 4.2152E-02

Variable Range Information
----------------------------

Domain Name : Default Domain

Variable Name	min	max
Density	1.14E+00	1.15E+00
Specific Heat Capacity at Constant Pressure	1.00E+03	1.00E+03
Dynamic Viscosity	1.83E-05	1.83E-05
Thermal Conductivity	2.61E-02	2.61E-02
Isothermal Compressibility	9.84E-06	9.91E-06
Static Entropy	3.22E+01	3.45E+01
Velocity u	-1.55E+01	2.59E+01
Velocity v	-1.82E+01	1.87E+01
Velocity w	-1.04E+01	1.85E+01
Pressure	-4.65E+02	3.35E+02
Turbulence Kinetic Energy	9.27E-09	2.58E+00
Turbulence Eddy Dissipation	1.54E-07	1.15E+01
Eddy Viscosity	4.26E-11	4.90E-01
Temperature	3.08E+02	3.08E+02

CPU Requirements of Numerical Solution - Total
--

Subsystem Name	Discretization (secs. %total)	Linear Solution (secs. %total)
Momentum and Mass	1.12E+03 36.0 %	2.82E+02 9.1 %
TurbKE and Diss.K	3.63E+02 11.7 %	2.85E+02 9.2 %
Subsystem Summary	1.48E+03 47.7 %	5.67E+02 18.3 %
Variable Updates	2.47E+02 8.0 %	
File Reading	2.72E+02 8.8 %	
File Writing	4.29E+01 1.4 %	
Miscellaneous	4.94E+02 15.9 %	
Total	3.10E+03	

Job Information
-----------------

Host computer: -PC (PID:1984)  
Par. Process: Master running on mesh partition: 1  
Job finished: Mon Oct 22 08:17:27 2012  
Total CPU time: 7.752E+02 seconds  
or: ( 0: 0: 12: 55.198 )  
( Days: Hours: Minutes: Seconds )

Host computer: -PC (PID:5360)  
Par. Process: Slave running on mesh partition: 2  
Job finished: Mon Oct 22 08:17:27 2012  
Total CPU time: 7.752E+02 seconds  
or: ( 0: 0: 12: 55.183 )  
( Days: Hours: Minutes: Seconds )

Host computer: -PC (PID:4528)  
Par. Process: Slave running on mesh partition: 3  
Job finished: Mon Oct 22 08:17:27 2012  
Total CPU time: 7.752E+02 seconds  
or: ( 0: 0: 12: 55.183 )  
( Days: Hours: Minutes: Seconds )

Host computer: -PC (PID:4088)  
Par. Process: Slave running on mesh partition: 4  
Job finished: Mon Oct 22 08:17:27 2012  
Total CPU time: 7.753E+02 seconds  
or: ( 0: 0: 12: 55.276 )  
( Days: Hours: Minutes: Seconds )

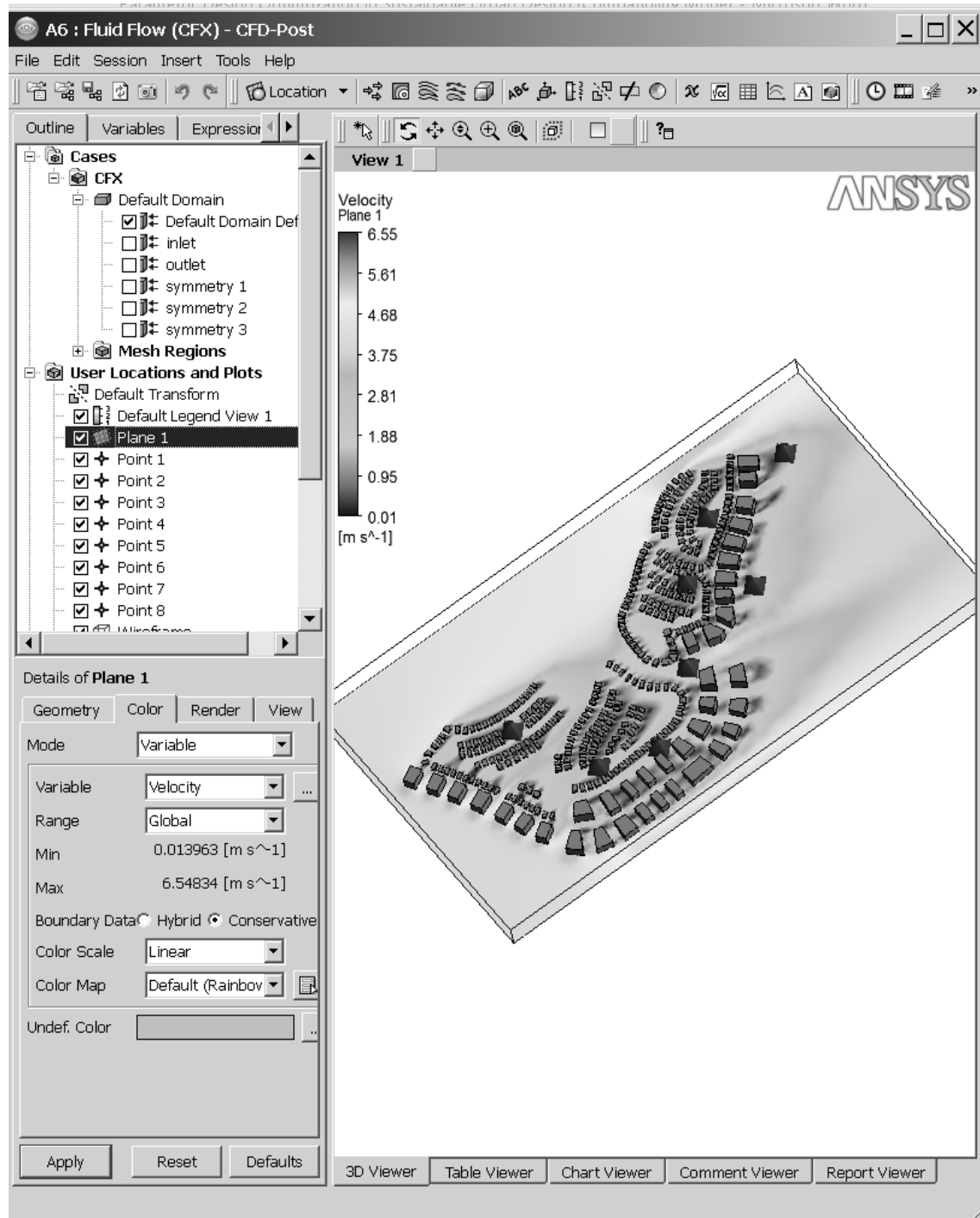
Total wall clock time: 7.740E+02 seconds  
or: ( 0: 0: 12: 54.000 )  
( Days: Hours: Minutes: Seconds )

--> Master-Partition Nr. 1 reaches final synchronization point!  
--> Slave-Partition Nr. 2 reaches final synchronization point!  
--> Slave-Partition Nr. 3 reaches final synchronization point!  
--> Slave-Partition Nr. 4 reaches final synchronization point!  
End of solution stage.

```
+-----+
| The results from this run of the ANSYS CFX Solver have been |
| written to |
| C:/project/final/final_pending_tasks/dp0_CFX_Solution/Fluid Flow |
| CFX_001.res |
+-----+
```

This run of the ANSYS CFX Solver has finished.

## CFX Post:



ANSYS Workbench with Output Parameters:

model - Workbench

FileViewToolsUnitsHelp

NewOpen...SaveSave As...Import...ReconnectRefresh ProjectUpdate Project

Toolbox

Parameter Charts

Parameters Parallel

Parameters Chart

Outline of All Parameters

	A	B	C	D
1	ID	Parameter Name	Value	Unit
2	Input Parameters			
*	New input parameter	New name	New expression	
4	Output Parameters			
5	Fluid Flow (CFX) (A1)			
6	P4	point3	2.2436	m s^-
7	P2	point1	1.391	m s^-
8	P3	point2	2.4971	m s^-
9	P5	point4	2.7487	m s^-
10	P6	point5	0.89988	m s^-
11	P7	point6	2.214	m s^-
12	P8	point7	1.3958	m s^-
13	P9	point8	1.3279	m s^-
*	New output parameter		New expression	
15	Charts			

Properties: No data

	A	B
1	Property	Value

Messages

Progress

	A	B	C
1	Status	Details	Progress

Table

	A
1	Name
2	Units
3	Current
*	

Char

view All / Customize...

Double-click to view and edit all project parameters.

Hide Progress

Hide 15 Messages

### Temp-Radiation map from Radiance for one run:

0.000000e+000	0.000000e+000	0.000000e+000
0.000000e+000	0.000000e+000	0.000000e+000
1.950633e+003	1.950633e+003	1.950633e+003
1.560335e+003	1.560335e+003	1.560335e+003
0.000000e+000	0.000000e+000	0.000000e+000
0.000000e+000	0.000000e+000	0.000000e+000
0.000000e+000	0.000000e+000	0.000000e+000
2.029889e+003	2.029889e+003	2.029889e+003
1.543054e+003	1.543054e+003	1.543054e+003
1.871541e-003	1.871541e-003	1.871541e-003
8.887276e+002	8.887276e+002	8.887276e+002
1.491463e+003	1.491463e+003	1.491463e+003
8.235314e+002	8.235314e+002	8.235314e+002
5.927195e+002	5.927195e+002	5.927195e+002
0.000000e+000	0.000000e+000	0.000000e+000
0.000000e+000	0.000000e+000	0.000000e+000
5.688380e+002	5.688380e+002	5.688380e+002
1.113450e+003	1.113450e+003	1.113450e+003
0.000000e+000	0.000000e+000	0.000000e+000
0.000000e+000	0.000000e+000	0.000000e+000
7.554254e+002	7.554254e+002	7.554254e+002
9.667570e+002	9.667570e+002	9.667570e+002
1.967858e+003	1.967858e+003	1.967858e+003
1.591266e+003	1.591266e+003	1.591266e+003
0.000000e+000	0.000000e+000	0.000000e+000
0.000000e+000	0.000000e+000	0.000000e+000
0.000000e+000	0.000000e+000	0.000000e+000
6.779356e+002	6.779356e+002	6.779356e+002
0.000000e+000	0.000000e+000	0.000000e+000
2.043714e+003	2.043714e+003	2.043714e+003
1.517125e+003	1.517125e+003	1.517125e+003
6.699795e+002	6.699795e+002	6.699795e+002
1.780272e+003	1.780272e+003	1.780272e+003
0.000000e+000	0.000000e+000	0.000000e+000
6.024389e+002	6.024389e+002	6.024389e+002
9.772266e+002	9.772266e+002	9.772266e+002
0.000000e+000	0.000000e+000	0.000000e+000
0.000000e+000	0.000000e+000	0.000000e+000
6.581157e+002	6.581157e+002	6.581157e+002
1.228397e+003	1.228397e+003	1.228397e+003
0.000000e+000	0.000000e+000	0.000000e+000
0.000000e+000	0.000000e+000	0.000000e+000
0.000000e+000	0.000000e+000	0.000000e+000
0.000000e+000	0.000000e+000	0.000000e+000
0.000000e+000	0.000000e+000	0.000000e+000
0.000000e+000	0.000000e+000	0.000000e+000
0.000000e+000	0.000000e+000	0.000000e+000
0.000000e+000	0.000000e+000	0.000000e+000
0.000000e+000	0.000000e+000	0.000000e+000
6.523770e+002	6.523770e+002	6.523770e+002
1.216459e+003	1.216459e+003	1.216459e+003
1.848961e+002	1.848961e+002	1.848961e+002
0.000000e+000	0.000000e+000	0.000000e+000
2.022179e+003	2.022179e+003	2.022179e+003
2.082003e+003	2.082003e+003	2.082003e+003
0.000000e+000	0.000000e+000	0.000000e+000
6.341915e+002	6.341915e+002	6.341915e+002
1.003655e+003	1.003655e+003	1.003655e+003
1.224968e+003	1.224968e+003	1.224968e+003
1.804865e+003	1.804865e+003	1.804865e+003

8.419942e+002	8.419942e+002	8.419942e+002
0.000000e+000	0.000000e+000	0.000000e+000
0.000000e+000	0.000000e+000	0.000000e+000
0.000000e+000	0.000000e+000	0.000000e+000
1.173329e+003	1.173329e+003	1.173329e+003
2.004495e+003	2.004495e+003	2.004495e+003
1.635612e+003	1.635612e+003	1.635612e+003
8.154104e+002	8.154104e+002	8.154104e+002
0.000000e+000	0.000000e+000	0.000000e+000
1.815051e+003	1.815051e+003	1.815051e+003
0.000000e+000	0.000000e+000	0.000000e+000
2.068656e+003	2.068656e+003	2.068656e+003
6.881228e+002	6.881228e+002	6.881228e+002
6.214031e+002	6.214031e+002	6.214031e+002
0.000000e+000	0.000000e+000	0.000000e+000
0.000000e+000	0.000000e+000	0.000000e+000
5.850231e+002	5.850231e+002	5.850231e+002
0.000000e+000	0.000000e+000	0.000000e+000
6.363525e+002	6.363525e+002	6.363525e+002
0.000000e+000	0.000000e+000	0.000000e+000
1.991231e+003	1.991231e+003	1.991231e+003
1.599727e+003	1.599727e+003	1.599727e+003
2.054093e+003	2.054093e+003	2.054093e+003
1.285513e+003	1.285513e+003	1.285513e+003
0.000000e+000	0.000000e+000	0.000000e+000
0.000000e+000	0.000000e+000	0.000000e+000
0.000000e+000	0.000000e+000	0.000000e+000
5.871295e+002	5.871295e+002	5.871295e+002
1.109670e+003	1.109670e+003	1.109670e+003
0.000000e+000	0.000000e+000	0.000000e+000
0.000000e+000	0.000000e+000	0.000000e+000
6.055737e+002	6.055737e+002	6.055737e+002
0.000000e+000	0.000000e+000	0.000000e+000
0.000000e+000	0.000000e+000	0.000000e+000
1.246605e+003	1.246605e+003	1.246605e+003
0.000000e+000	0.000000e+000	0.000000e+000
1.523581e+003	1.523581e+003	1.523581e+003
0.000000e+000	0.000000e+000	0.000000e+000
0.000000e+000	0.000000e+000	0.000000e+000
5.071624e+002	5.071624e+002	5.071624e+002
1.202125e+002	1.202125e+002	1.202125e+002
1.244571e+003	1.244571e+003	1.244571e+003
1.705656e+003	1.705656e+003	1.705656e+003
1.536369e+003	1.536369e+003	1.536369e+003
6.484730e+002	6.484730e+002	6.484730e+002
1.376231e+003	1.376231e+003	1.376231e+003
8.142202e+002	8.142202e+002	8.142202e+002
0.000000e+000	0.000000e+000	0.000000e+000
1.063052e+003	1.063052e+003	1.063052e+003
0.000000e+000	0.000000e+000	0.000000e+000
1.407272e+003	1.407272e+003	1.407272e+003
4.963174e+002	4.963174e+002	4.963174e+002
5.498652e+002	5.498652e+002	5.498652e+002
1.351081e+003	1.351081e+003	1.351081e+003
4.783632e+002	4.783632e+002	4.783632e+002
1.226338e+003	1.226338e+003	1.226338e+003
0.000000e+000	0.000000e+000	0.000000e+000
1.305809e+003	1.305809e+003	1.305809e+003
1.400187e+003	1.400187e+003	1.400187e+003
6.008931e+002	6.008931e+002	6.008931e+002

0.000000e+000	0.000000e+000	0.000000e+000
1.485844e+003	1.485844e+003	1.485844e+003
3.882441e+002	3.882441e+002	3.882441e+002
8.312285e+002	8.312285e+002	8.312285e+002
0.000000e+000	0.000000e+000	0.000000e+000
0.000000e+000	0.000000e+000	0.000000e+000
1.096645e+003	1.096645e+003	1.096645e+003
2.050070e+002	2.050070e+002	2.050070e+002
0.000000e+000	0.000000e+000	0.000000e+000
1.910158e+003	1.910158e+003	1.910158e+003
0.000000e+000	0.000000e+000	0.000000e+000
1.030860e+003	1.030860e+003	1.030860e+003
0.000000e+000	0.000000e+000	0.000000e+000
6.092772e+002	6.092772e+002	6.092772e+002
0.000000e+000	0.000000e+000	0.000000e+000
1.571741e+003	1.571741e+003	1.571741e+003
0.000000e+000	0.000000e+000	0.000000e+000
0.000000e+000	0.000000e+000	0.000000e+000
7.503145e+002	7.503145e+002	7.503145e+002
3.809247e+002	3.809247e+002	3.809247e+002
8.185218e+002	8.185218e+002	8.185218e+002
0.000000e+000	0.000000e+000	0.000000e+000
1.548845e+003	1.548845e+003	1.548845e+003
0.000000e+000	0.000000e+000	0.000000e+000
0.000000e+000	0.000000e+000	0.000000e+000
1.362781e+003	1.362781e+003	1.362781e+003
1.607165e+001	1.607165e+001	1.607165e+001
5.341156e+002	5.341156e+002	5.341156e+002
2.057125e+000	2.057125e+000	2.057125e+000
1.248457e+003	1.248457e+003	1.248457e+003
3.886062e+002	3.886062e+002	3.886062e+002
0.000000e+000	0.000000e+000	0.000000e+000
1.048338e+003	1.048338e+003	1.048338e+003
6.248920e+002	6.248920e+002	6.248920e+002
1.301183e+003	1.301183e+003	1.301183e+003
8.152486e+002	8.152486e+002	8.152486e+002
4.498708e+002	4.498708e+002	4.498708e+002
6.457482e+002	6.457482e+002	6.457482e+002
0.000000e+000	0.000000e+000	0.000000e+000
0.000000e+000	0.000000e+000	0.000000e+000
0.000000e+000	0.000000e+000	0.000000e+000
8.404991e+002	8.404991e+002	8.404991e+002
0.000000e+000	0.000000e+000	0.000000e+000
0.000000e+000	0.000000e+000	0.000000e+000
6.523262e+002	6.523262e+002	6.523262e+002
1.271078e+003	1.271078e+003	1.271078e+003
1.954488e+003	1.954488e+003	1.954488e+003
1.168565e+003	1.168565e+003	1.168565e+003
6.148008e+002	6.148008e+002	6.148008e+002
6.191113e+002	6.191113e+002	6.191113e+002
1.396081e+003	1.396081e+003	1.396081e+003
5.522722e+002	5.522722e+002	5.522722e+002
8.861056e+002	8.861056e+002	8.861056e+002
1.486028e+003	1.486028e+003	1.486028e+003
0.000000e+000	0.000000e+000	0.000000e+000
1.437756e+003	1.437756e+003	1.437756e+003
0.000000e+000	0.000000e+000	0.000000e+000
0.000000e+000	0.000000e+000	0.000000e+000
8.854752e+002	8.854752e+002	8.854752e+002
0.000000e+000	0.000000e+000	0.000000e+000



2.444273e+001	2.444273e+001	2.444273e+001
2.001687e+003	2.001687e+003	2.001687e+003
7.643881e+002	7.643881e+002	7.643881e+002
0.000000e+000	0.000000e+000	0.000000e+000
0.000000e+000	0.000000e+000	0.000000e+000
9.337425e+002	9.337425e+002	9.337425e+002
1.329655e+003	1.329655e+003	1.329655e+003
0.000000e+000	0.000000e+000	0.000000e+000
4.420292e-002	4.420292e-002	4.420292e-002
6.592261e+002	6.592261e+002	6.592261e+002
1.513291e+003	1.513291e+003	1.513291e+003
8.204970e+002	8.204970e+002	8.204970e+002
0.000000e+000	0.000000e+000	0.000000e+000
1.692665e+003	1.692665e+003	1.692665e+003
1.426220e+003	1.426220e+003	1.426220e+003
0.000000e+000	0.000000e+000	0.000000e+000
5.883542e+002	5.883542e+002	5.883542e+002
4.214167e+002	4.214167e+002	4.214167e+002
1.203188e+003	1.203188e+003	1.203188e+003
3.021596e+001	3.021596e+001	3.021596e+001
2.717446e+002	2.717446e+002	2.717446e+002
0.000000e+000	0.000000e+000	0.000000e+000
0.000000e+000	0.000000e+000	0.000000e+000
9.321583e+002	9.321583e+002	9.321583e+002
6.445471e+002	6.445471e+002	6.445471e+002
1.584177e+003	1.584177e+003	1.584177e+003
0.000000e+000	0.000000e+000	0.000000e+000
1.319638e+003	1.319638e+003	1.319638e+003
1.021581e+003	1.021581e+003	1.021581e+003
0.000000e+000	0.000000e+000	0.000000e+000
5.970106e+002	5.970106e+002	5.970106e+002
1.318669e+003	1.318669e+003	1.318669e+003
2.060180e+003	2.060180e+003	2.060180e+003
0.000000e+000	0.000000e+000	0.000000e+000
8.519059e+002	8.519059e+002	8.519059e+002
1.519493e+003	1.519493e+003	1.519493e+003
1.935254e+003	1.935254e+003	1.935254e+003
1.074577e+003	1.074577e+003	1.074577e+003
2.042394e+003	2.042394e+003	2.042394e+003
1.264433e+003	1.264433e+003	1.264433e+003
5.744325e+002	5.744325e+002	5.744325e+002
1.333805e-004	1.333805e-004	1.333805e-004
1.998587e+003	1.998587e+003	1.998587e+003
1.390765e+003	1.390765e+003	1.390765e+003
1.269989e-003	1.269989e-003	1.269989e-003
1.381673e+003	1.381673e+003	1.381673e+003
2.012093e+003	2.012093e+003	2.012093e+003
3.827531e+002	3.827531e+002	3.827531e+002
2.227995e+002	2.227995e+002	2.227995e+002
0.000000e+000	0.000000e+000	0.000000e+000
1.048711e+003	1.048711e+003	1.048711e+003
1.970798e+003	1.970798e+003	1.970798e+003
9.213449e+002	9.213449e+002	9.213449e+002
0.000000e+000	0.000000e+000	0.000000e+000
9.157723e+002	9.157723e+002	9.157723e+002
1.962008e+003	1.962008e+003	1.962008e+003
1.565768e+003	1.565768e+003	1.565768e+003
0.000000e+000	0.000000e+000	0.000000e+000
1.329013e+003	1.329013e+003	1.329013e+003
0.000000e+000	0.000000e+000	0.000000e+000

7.881107e+002	7.881107e+002	7.881107e+002
6.663141e+002	6.663141e+002	6.663141e+002
0.000000e+000	0.000000e+000	0.000000e+000
0.000000e+000	0.000000e+000	0.000000e+000
5.851509e-003	5.851509e-003	5.851509e-003
2.740541e+002	2.740541e+002	2.740541e+002
1.363345e+003	1.363345e+003	1.363345e+003
0.000000e+000	0.000000e+000	0.000000e+000
0.000000e+000	0.000000e+000	0.000000e+000
0.000000e+000	0.000000e+000	0.000000e+000
7.491198e+002	7.491198e+002	7.491198e+002
0.000000e+000	0.000000e+000	0.000000e+000
0.000000e+000	0.000000e+000	0.000000e+000
1.187008e+003	1.187008e+003	1.187008e+003
5.697299e+002	5.697299e+002	5.697299e+002
1.177021e+003	1.177021e+003	1.177021e+003
1.113777e+003	1.113777e+003	1.113777e+003
1.635879e+003	1.635879e+003	1.635879e+003
6.140696e+002	6.140696e+002	6.140696e+002
3.529554e+002	3.529554e+002	3.529554e+002
1.924733e+003	1.924733e+003	1.924733e+003
0.000000e+000	0.000000e+000	0.000000e+000
0.000000e+000	0.000000e+000	0.000000e+000
6.094405e+002	6.094405e+002	6.094405e+002
1.299658e+003	1.299658e+003	1.299658e+003
1.838173e+003	1.838173e+003	1.838173e+003
1.626968e+003	1.626968e+003	1.626968e+003
9.966550e+002	9.966550e+002	9.966550e+002
2.615193e+002	2.615193e+002	2.615193e+002
0.000000e+000	0.000000e+000	0.000000e+000
2.835554e+002	2.835554e+002	2.835554e+002
1.640933e+003	1.640933e+003	1.640933e+003
2.748366e+002	2.748366e+002	2.748366e+002
1.631095e+002	1.631095e+002	1.631095e+002
8.108099e+002	8.108099e+002	8.108099e+002
0.000000e+000	0.000000e+000	0.000000e+000
1.153255e+003	1.153255e+003	1.153255e+003
3.146714e+002	3.146714e+002	3.146714e+002
1.136242e+003	1.136242e+003	1.136242e+003
0.000000e+000	0.000000e+000	0.000000e+000
0.000000e+000	0.000000e+000	0.000000e+000
8.487566e+002	8.487566e+002	8.487566e+002
0.000000e+000	0.000000e+000	0.000000e+000
0.000000e+000	0.000000e+000	0.000000e+000
1.027766e+003	1.027766e+003	1.027766e+003
0.000000e+000	0.000000e+000	0.000000e+000
9.348381e+002	9.348381e+002	9.348381e+002
3.931806e+002	3.931806e+002	3.931806e+002
1.554922e-004	1.554922e-004	1.554922e-004
4.197500e+002	4.197500e+002	4.197500e+002
1.029779e+003	1.029779e+003	1.029779e+003
2.862678e+002	2.862678e+002	2.862678e+002
1.335406e+003	1.335406e+003	1.335406e+003
0.000000e+000	0.000000e+000	0.000000e+000
9.769332e+002	9.769332e+002	9.769332e+002
2.129113e+002	2.129113e+002	2.129113e+002
0.000000e+000	0.000000e+000	0.000000e+000
1.776635e+003	1.776635e+003	1.776635e+003
1.645510e+003	1.645510e+003	1.645510e+003
1.360657e+003	1.360657e+003	1.360657e+003

0.000000e+000	0.000000e+000	0.000000e+000
1.889702e+002	1.889702e+002	1.889702e+002
0.000000e+000	0.000000e+000	0.000000e+000
0.000000e+000	0.000000e+000	0.000000e+000
1.381614e+003	1.381614e+003	1.381614e+003
5.704794e-004	5.704794e-004	5.704794e-004
1.194680e+003	1.194680e+003	1.194680e+003
1.678920e+003	1.678920e+003	1.678920e+003
1.642844e+003	1.642844e+003	1.642844e+003
2.012833e+003	2.012833e+003	2.012833e+003
0.000000e+000	0.000000e+000	0.000000e+000
1.219382e+003	1.219382e+003	1.219382e+003
1.483434e+003	1.483434e+003	1.483434e+003
1.614565e+003	1.614565e+003	1.614565e+003
1.084363e+003	1.084363e+003	1.084363e+003
0.000000e+000	0.000000e+000	0.000000e+000
0.000000e+000	0.000000e+000	0.000000e+000
0.000000e+000	0.000000e+000	0.000000e+000
1.904817e+003	1.904817e+003	1.904817e+003
1.470279e+003	1.470279e+003	1.470279e+003
6.464911e+002	6.464911e+002	6.464911e+002
1.492648e+003	1.492648e+003	1.492648e+003
1.021742e+003	1.021742e+003	1.021742e+003
0.000000e+000	0.000000e+000	0.000000e+000
1.421792e+003	1.421792e+003	1.421792e+003
0.000000e+000	0.000000e+000	0.000000e+000
0.000000e+000	0.000000e+000	0.000000e+000
0.000000e+000	0.000000e+000	0.000000e+000
6.912249e+002	6.912249e+002	6.912249e+002
0.000000e+000	0.000000e+000	0.000000e+000
0.000000e+000	0.000000e+000	0.000000e+000
1.685108e+003	1.685108e+003	1.685108e+003
5.083416e-001	5.083416e-001	5.083416e-001
1.203338e+003	1.203338e+003	1.203338e+003
1.083261e+003	1.083261e+003	1.083261e+003
1.649136e+003	1.649136e+003	1.649136e+003
8.298475e+001	8.298475e+001	8.298475e+001
3.517675e-003	3.517675e-003	3.517675e-003
1.273071e+003	1.273071e+003	1.273071e+003
0.000000e+000	0.000000e+000	0.000000e+000
0.000000e+000	0.000000e+000	0.000000e+000
6.610828e+002	6.610828e+002	6.610828e+002
1.421893e+003	1.421893e+003	1.421893e+003
0.000000e+000	0.000000e+000	0.000000e+000
1.006297e+003	1.006297e+003	1.006297e+003
0.000000e+000	0.000000e+000	0.000000e+000
0.000000e+000	0.000000e+000	0.000000e+000
0.000000e+000	0.000000e+000	0.000000e+000
0.000000e+000	0.000000e+000	0.000000e+000
5.107524e+002	5.107524e+002	5.107524e+002
0.000000e+000	0.000000e+000	0.000000e+000
1.593991e+003	1.593991e+003	1.593991e+003
0.000000e+000	0.000000e+000	0.000000e+000
7.422610e+002	7.422610e+002	7.422610e+002
1.550782e+003	1.550782e+003	1.550782e+003
1.648753e+003	1.648753e+003	1.648753e+003
1.857758e-003	1.857758e-003	1.857758e-003
9.939058e-004	9.939058e-004	9.939058e-004
0.000000e+000	0.000000e+000	0.000000e+000
1.367538e+003	1.367538e+003	1.367538e+003

5.807582e+002	5.807582e+002	5.807582e+002
4.115827e+002	4.115827e+002	4.115827e+002
1.509257e+003	1.509257e+003	1.509257e+003
0.000000e+000	0.000000e+000	0.000000e+000
5.608281e+002	5.608281e+002	5.608281e+002
0.000000e+000	0.000000e+000	0.000000e+000
1.798537e+003	1.798537e+003	1.798537e+003
0.000000e+000	0.000000e+000	0.000000e+000
0.000000e+000	0.000000e+000	0.000000e+000
1.027702e+003	1.027702e+003	1.027702e+003
0.000000e+000	0.000000e+000	0.000000e+000
1.627521e+003	1.627521e+003	1.627521e+003
0.000000e+000	0.000000e+000	0.000000e+000
5.170258e+002	5.170258e+002	5.170258e+002
0.000000e+000	0.000000e+000	0.000000e+000
0.000000e+000	0.000000e+000	0.000000e+000
0.000000e+000	0.000000e+000	0.000000e+000
1.075235e+003	1.075235e+003	1.075235e+003
1.602222e+003	1.602222e+003	1.602222e+003
1.230317e+003	1.230317e+003	1.230317e+003
6.737585e+002	6.737585e+002	6.737585e+002
0.000000e+000	0.000000e+000	0.000000e+000

## Input Verification and Results Summary EnergyPlus for one run:

### Table of Contents

Program Version: **EnergyPlus-32 7.0.0.036**

Tabular Output Report in Format: **HTML**

Building: **BUILDING**

Environment: **ABU DHABI - ARE IVEC Data WMO#=412170**

Simulation Timestamp: **00:44:41**

---

### Table of Contents

Top

Input Verification and Results Summary

**ZoneCoolingSummaryMonthly**

| Environment |

**ZoneHeatingSummaryMonthly**

| Environment |

**SpaceGainsMonthly**

| ZONE1 |

**WindowReportMonthly**

| ZONE1 FACE 2 WINDOW 1 | ZONE1 FACE 3 WINDOW 1 | ZONE1 FACE 4 WINDOW 1 |  
ZONE1 FACE 5 WINDOW 1 |

---

### Table of Contents

Report: **InputVerificationandResultsSummary**

For: **Entire Facility**

Timestamp: **00:44:41**

### General

	Value
Program Version and Build	EnergyPlus-32 7.0.0.036, 11/26/2012 12:44 AM
Weather	ABU DHABI - ARE IVEC Data WMO#=412170
Latitude [deg]	24.43
Longitude [deg]	54.65

Elevation [m]	27.00
Time Zone	4.00
North Axis Angle [deg]	0.00
Rotation for Appendix G [deg]	0.00
Hours Simulated [hrs]	8760.00

## ENVELOPE

### Window-Wall Ratio

	Total	North (315 to 45 deg)	East (45 to 135 deg)	South (135 to 225 deg)	West (225 to 315 deg)
Gross Wall Area [m2]	4875.46	1431.89	1039.75	1437.22	966.60
Window Opening Area [m2]	1194.61	350.85	254.77	352.15	236.84
Window-Wall Ratio [%]	24.50	24.50	24.50	24.50	24.50

### Conditioned Window-Wall Ratio

	Total	North (315 to 45 deg)	East (45 to 135 deg)	South (135 to 225 deg)	West (225 to 315 deg)
Gross Wall Area [m2]	4875.46	1431.89	1039.75	1437.22	966.60
Window Opening Area [m2]	1194.61	350.85	254.77	352.15	236.84
Window-Wall Ratio [%]	24.50	24.50	24.50	24.50	24.50

### Skylight-Roof Ratio

	Total
Gross Roof Area [m2]	1404.92
Skylight Area [m2]	0.00
Skylight-Roof Ratio [%]	0.00

## PERFORMANCE

### Zone Summary

	Area [m2]	Conditioned (Y/N)	Volume [m3]	Multipliers	Gross Wall Area [m2]	Window Glass Area [m2]	Lighting [W/m2]	People [m2] per person	Plug and Process [W/m2]
ZONE1	1404.92	Yes	44957.41	1.00	4875.46	1194.61	11.7400	10.00	4.0000
Total	1404.92		44957.41		4875.46	1194.61	11.7400	10.00	4.0000
Conditioned Total	1404.92		44957.41		4875.46	1194.61	11.7400	10.00	4.0000
Unconditioned Total	0.00		0.00		0.00	0.00			

## Table of Contents

Report: **ZoneCoolingSummaryMonthly**

For: **Environment**

Timestamp: **00:44:41**

	ZONE/ SYS SENSI BLE COOLI NG ENER GY [kWh]	ZONE/SY S SENSIBL E COOLING RATE {Maximu m}[W]	ZONE/SY S SENSIBL E COOLING RATE {TIMEST AMP}	OUTD OOR DRY BULB {AT MAX/ MIN} [C]	OUTD OOR WET BULB {AT MAX/ MIN} [C]	ZONE TOTAL INTER NAL LATEN T GAIN [kWh]	ZONE TOTAL INTERNA L LATENT GAIN {Maximu m}[W]	ZONE TOTAL INTERNA L LATENT GAIN {TIMEST AMP}	OUTD OOR DRY BULB {AT MAX/ MIN} [C]	OUTD OOR WET BULB {AT MAX/ MIN} [C]
Januar y	29426.4 6	226720.34	15-JAN- 14:00	27.00	16.60	3252.52	7764.95	16-JAN- 21:15	21.12	15.40
Februa ry	39984.1 9	295303.36	28-FEB- 15:15	33.50	18.86	3054.92	7764.95	19-FEB- 21:15	23.68	19.54
March	48449.9 5	321881.56	24-MAR- 14:00	39.00	23.74	3537.84	7764.95	24-MAR- 23:45	27.25	22.83
April	76762.7 5	371989.06	12-APR- 16:15	39.42	19.52	3673.52	7764.95	12-APR- 23:15	28.38	16.73
May	122532. 95	419013.50	04-MAY- 16:30	42.10	23.80	3944.47	7764.95	05-MAY- 22:00	32.00	21.13
June	138026. 85	431289.76	20-JUN- 16:30	42.75	23.82	3825.02	7764.95	21-JUN- 21:45	31.95	26.68
July	157943. 86	446808.24	24-JUL- 15:00	46.20	23.81	3952.52	7764.95	09-JUL- 21:15	32.75	27.04
August	161945. 32	435796.71	05-AUG- 16:30	43.30	24.53	3952.52	7764.95	01-AUG- 21:30	32.50	29.68
Septe mber	135884. 26	382945.20	02-SEP- 15:00	41.70	24.33	3825.02	7764.95	05-SEP- 21:15	32.83	27.12
Octobe r	102347. 72	351574.54	07-OCT- 14:00	39.00	22.26	3903.53	7764.95	06-OCT- 22:45	29.27	26.70
Nove mber	62162.7 4	320220.12	03-NOV- 13:00	35.00	23.21	3550.69	7764.95	11-NOV- 21:15	24.75	21.51
Decem ber	35864.0 5	265760.34	23-DEC- 13:45	28.95	20.10	3336.99	7764.95	27-DEC- 21:15	21.77	19.18
Annua l Sum or Avera ge	111133 1.10					43809.5 5				
Minim um of Month s	29426.4 6	226720.34		27.00	16.60	3054.92	7764.95		21.12	15.40
Maxim um of	161945. 32	446808.24		46.20	24.53	3952.52	7764.95		32.83	29.68



Months										
--------	--	--	--	--	--	--	--	--	--	--

## Table of Contents

Report: **ZoneHeatingSummaryMonthly**

For: **Environment**

	ZONE/SYS SENSIBLE HEATING ENERGY [kWh]	ZONE/SYS SENSIBLE HEATING RATE {Maximum}[W]	ZONE/SYS SENSIBLE HEATING RATE {TIMESTAMP}	OUTDOOR DRY BULB {AT MAX/MIN} [C]
January	21908.11	142345.61	29-JAN-06:00	9.90
February	13154.69	150646.56	02-FEB-07:00	5.00
March	6493.17	124228.35	10-MAR-06:30	10.80
April	199.22	26170.99	03-APR-06:30	17.75
May	0.00	0.00	01-MAY-00:15	25.10
June	0.00	0.00	01-JUN-00:15	28.72
July	0.00	0.00	01-JUL-00:15	28.85
August	0.00	0.00	01-AUG-00:15	31.82
September	0.00	0.00	01-SEP-00:15	30.50
October	2.94	7506.81	29-OCT-06:30	18.85
November	1408.71	48751.84	24-NOV-06:45	16.10
December	12402.05	149084.39	10-DEC-06:45	9.32
Annual Sum or Average	55568.90			
Minimum of Months	0.00	0.00		5.00
Maximum of Months	21908.11	150646.56		31.82

## Table of Contents

Report: **SpaceGainsMonthly**

For: **ZONE1**

Timestamp: **00:44:41**

	ZONE PEOP LE TOTA	ZONE E LIGH TS	ZONE ELECTR IC EQUIP	ZONE GAS EQUIPMEN T TOTAL HEAT	ZONE HOT WATER EQUIPMEN T TOTAL	ZONE STEAM EQUIPMEN T TOTAL	ZONE OTHER EQUIPMEN T TOTAL	ZONE INFILTRA TION SENSIBL	ZONE INFILTRA TION SENSIBL
--	----------------------------	-------------------------	-------------------------------	---	--	--------------------------------------	--------------------------------------	-------------------------------------	-------------------------------------

	L HEAT GAIN [kWh]	TOT AL HEA T GAI N [kWh]	MENT TOTAL HEAT GAIN [kWh]	GAIN [Invalid/Und efined]	HEAT GAIN [Invalid/Und efined]	HEAT GAIN [Invalid/Und efined]	HEAT GAIN [Invalid/Und efined]	E HEAT GAIN [kWh]	E HEAT LOSS [kWh]
January	8581.58	4029.09	2750.78	0.00	0.00	0.00	0.00	188.96	31164.99
February	7751.11	3639.18	2484.57	0.00	0.00	0.00	0.00	2226.50	22212.94
March	8581.58	4029.09	2750.78	0.00	0.00	0.00	0.00	4875.43	15920.89
April	8304.76	3899.12	2662.04	0.00	0.00	0.00	0.00	14061.00	5070.85
May	8581.58	4029.09	2750.78	0.00	0.00	0.00	0.00	31646.37	1213.34
June	8304.76	3899.12	2662.04	0.00	0.00	0.00	0.00	39377.65	86.55
July	8581.58	4029.09	2750.78	0.00	0.00	0.00	0.00	49021.94	0.00
August	8581.58	4029.09	2750.78	0.00	0.00	0.00	0.00	50995.44	0.00
September	8304.76	3899.12	2662.04	0.00	0.00	0.00	0.00	38337.71	33.69
October	8581.58	4029.09	2750.78	0.00	0.00	0.00	0.00	21564.25	2360.28
November	8304.76	3899.12	2662.04	0.00	0.00	0.00	0.00	7038.59	7891.27
December	8581.58	4029.09	2750.78	0.00	0.00	0.00	0.00	1128.99	21519.46
Annual Sum or Average	101041.21	47439.32	32388.16	0.00	0.00	0.00	0.00	260462.82	107474.25
Minimum of Months	7751.11	3639.18	2484.57	0.00	0.00	0.00	0.00	188.96	0.00
Maximum of Months	8581.58	4029.09	2750.78	0.00	0.00	0.00	0.00	50995.44	31164.99

---

Table of Contents

Report: **WindowReportMonthly**

For: **ZONE1\_FACE\_2\_WINDOW\_1**

Timestamp: **00:44:41**

	WINDOW TRANSMITT ED SOLAR [W]	WINDOW TRANSMITT ED BEAM SOLAR [W]	WINDOW TRANSMITT ED DIFFUSE SOLAR [W]	WINDO W HEAT GAIN [W]	WINDO W HEAT LOSS [W]	INSIDE GLASS CONDENSATI ON FLAG {HOURS NON-ZERO} [HOURS]	FRACTI ON OF TIME SHADIN G DEVICE IS ON {HOURS NON- ZERO} [HOURS]	STORM WINDO W ON/OFF FLAG {HOUR S NON- ZERO} [HOUR S]
January	41629.29	28251.23	13378.06	43309.7 9	4000.62	0.00	0.00	744.00
Februar y	41030.07	27236.27	13793.80	43110.5 4	3682.69	0.00	0.00	672.00
March	28507.89	13350.38	15157.51	29719.3 4	2800.09	0.00	0.00	744.00
April	22007.88	7018.65	14989.23	23952.5 3	1915.45	0.00	0.00	720.00
May	16584.54	2561.29	14023.25	19648.0 5	1070.40	0.00	0.00	744.00
June	14374.04	1023.12	13350.92	17880.3 2	476.16	0.00	0.00	720.00
July	15516.93	1510.97	14005.96	20357.0 3	164.90	0.00	0.00	744.00
August	19488.52	5311.74	14176.78	25264.1 0	108.87	0.00	0.00	744.00
Septemb er	27510.78	13344.27	14166.51	32838.0 4	339.85	0.00	0.00	720.00
October	37695.33	23719.92	13975.41	42389.9 2	1436.67	0.00	0.00	744.00
Novemb er	42546.16	29409.30	13136.85	46176.4 3	2386.58	0.00	0.00	720.00
Decemb er	42156.86	29049.45	13107.41	44400.6 7	3361.68	0.00	0.00	744.00
Annual Sum or Average	29016.35	15076.39	13939.97	32356.9 1	1802.46	0.00	0.00	8760.00
Minimu m of Months	14374.04	1023.12	13107.41	17880.3 2	108.87	0.00	0.00	672.00
Maximu m of Months	42546.16	29409.30	15157.51	46176.4 3	4000.62	0.00	0.00	744.00

---

Table of Contents

Report: **WindowReportMonthly**

For: **ZONE1\_FACE\_3\_WINDOW\_1**

Timestamp: **00:44:41**

	WINDOW TRANSMITT ED SOLAR [W]	WINDOW TRANSMITT ED BEAM SOLAR [W]	WINDOW TRANSMITT ED DIFFUSE SOLAR [W]	WINDO W HEAT GAIN [W]	WINDO W HEAT LOSS [W]	INSIDE GLASS CONDENSATI ON FLAG {HOURS NON-ZERO} [HOURS]	FRACTI ON OF TIME SHADIN G DEVICE IS ON {HOURS NON- ZERO} [HOURS]	STORM WINDO W ON/OFF FLAG {HOUR S NON- ZERO} [HOUR S]
January	9355.96	2374.81	6981.15	7950.45	2924.72	0.00	0.00	744.00
Februar y	12827.81	4667.07	8160.74	12064.2 1	2667.37	0.00	0.00	672.00
March	15197.32	5265.14	9932.18	15187.4 5	2027.45	0.00	0.00	744.00
April	18839.80	7635.59	11204.21	20352.8 0	1381.15	0.00	0.00	720.00
May	21978.59	10128.83	11849.76	25277.3 1	762.56	0.00	0.00	744.00
June	22686.07	10816.09	11869.98	26743.6 4	339.53	0.00	0.00	720.00
July	21027.63	8970.32	12057.31	25699.9 7	117.25	0.00	0.00	744.00
August	19421.27	8226.82	11194.45	24038.4 9	78.87	0.00	0.00	744.00
Septemb er	16643.10	6669.03	9974.07	19756.9 0	248.20	0.00	0.00	720.00
October	13559.31	4966.21	8593.11	14950.3 2	1040.60	0.00	0.00	744.00
Novemb er	10644.36	3463.26	7181.10	10622.2 0	1732.47	0.00	0.00	720.00
Decemb er	8852.85	2215.95	6636.90	7792.95	2460.07	0.00	0.00	744.00
Annual Sum or Average	15930.85	6287.09	9643.76	17561.2 9	1308.17	0.00	0.00	8760.00
Minimu m of Months	8852.85	2215.95	6636.90	7792.95	78.87	0.00	0.00	672.00
Maximu m of Months	22686.07	10816.09	12057.31	26743.6 4	2924.72	0.00	0.00	744.00

---

Table of Contents

Report: **WindowReportMonthly**

For: **ZONE1\_FACE\_4\_WINDOW\_1**

Timestamp: **00:44:41**

	WINDOW TRANSMITT ED SOLAR [W]	WINDOW TRANSMITT ED BEAM SOLAR [W]	WINDOW TRANSMITT ED DIFFUSE SOLAR [W]	WINDO W HEAT GAIN [W]	WINDO W HEAT LOSS [W]	INSIDE GLASS CONDENSATI ON FLAG {HOURS NON-ZERO} [HOURS]	FRACTI ON OF TIME SHADIN G DEVICE IS ON {HOURS NON- ZERO} [HOURS]	STORM WINDO W ON/OFF FLAG {HOUR S NON- ZERO} [HOUR S]
January	8469.10	0.72	8468.38	5866.43	4100.01	0.00	0.00	744.00
Februar y	9767.15	55.67	9711.48	7537.86	3681.52	0.00	0.00	672.00
March	12507.08	594.83	11912.26	11318.0 4	2770.30	0.00	0.00	744.00
April	15765.21	2236.71	13528.50	16474.6 2	1902.60	0.00	0.00	720.00
May	19992.01	5746.54	14245.47	23283.7 0	1059.31	0.00	0.00	744.00
June	21810.28	7283.95	14526.32	26263.0 2	469.16	0.00	0.00	720.00
July	20146.27	5353.03	14793.24	25483.8 7	157.73	0.00	0.00	744.00
August	16706.81	3227.41	13479.40	21753.9 9	104.85	0.00	0.00	744.00
Septemb er	12901.43	1049.30	11852.13	15794.3 8	337.57	0.00	0.00	720.00
October	10169.02	119.97	10049.06	10774.4 7	1430.17	0.00	0.00	744.00
Novemb er	8548.95	2.24	8546.71	7517.44	2397.41	0.00	0.00	720.00
Decemb er	8095.21	0.00	8095.21	5996.53	3446.03	0.00	0.00	744.00
Annual Sum or Average	13761.39	2150.80	11610.59	14880.3 6	1812.07	0.00	0.00	8760.00
Minimu m of Months	8095.21	0.00	8095.21	5866.43	104.85	0.00	0.00	672.00
Maximu m of Months	21810.28	7283.95	14793.24	26263.0 2	4100.01	0.00	0.00	744.00

Table of Contents

Report: **WindowReportMonthly**

For: **ZONE1\_FACE\_5\_WINDOW\_1**

Timestamp: **00:44:41**

	WINDOW TRANSMITT ED SOLAR [W]	WINDOW TRANSMITT ED BEAM SOLAR [W]	WINDOW TRANSMITT ED DIFFUSE SOLAR [W]	WINDO W HEAT GAIN [W]	WINDO W HEAT LOSS [W]	INSIDE GLASS CONDENSATI ON FLAG {HOURS NON-ZERO} [HOURS]	FRACTI ON OF TIME SHADIN G DEVICE IS ON {HOURS NON- ZERO} [HOURS]	STORM WINDO W ON/OFF FLAG {HOUR S NON- ZERO} [HOUR S]
January	20631.54	12759.08	7872.46	20725.5 2	2694.14	0.00	0.00	744.00
Februar y	23569.78	14910.50	8659.28	24218.5 5	2472.69	0.00	0.00	672.00
March	21119.69	10986.82	10132.87	21862.8 1	1867.41	0.00	0.00	744.00
April	20316.97	9569.78	10747.19	21972.3 7	1282.57	0.00	0.00	720.00
May	20865.64	10283.55	10582.09	23977.3 6	716.15	0.00	0.00	744.00
June	19428.15	9093.42	10334.73	23000.4 1	317.33	0.00	0.00	720.00
July	18929.73	8136.02	10793.71	23211.5 0	107.96	0.00	0.00	744.00
August	20635.90	10165.15	10470.75	25247.4 3	70.46	0.00	0.00	744.00
Septemb er	21817.49	11899.65	9917.83	25512.4 8	223.95	0.00	0.00	720.00
October	22247.36	13286.89	8960.47	24686.5 6	961.87	0.00	0.00	744.00
Novemb er	20758.80	12837.83	7920.97	22025.8 1	1607.88	0.00	0.00	720.00
Decemb er	19455.63	11838.41	7617.22	19796.3 8	2280.05	0.00	0.00	744.00
Annual Sum or Average	20794.65	11289.45	9505.20	23008.7 3	1210.48	0.00	0.00	8760.00
Minimu m of Months	18929.73	8136.02	7617.22	19796.3 8	70.46	0.00	0.00	672.00
Maximu m of Months	23569.78	14910.50	10793.71	25512.4 8	2694.14	0.00	0.00	744.00