DEPARTMENT OF MECHANICAL & AEROSPACE ENGINEERING

University of Strathclyde Engineering

Design, Modelling and Analysis of Natural Ventilation Systems for a dwelling located in the Maltese Islands

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ABSTRACT

***Keywords**: ESP-r, Natural Ventilation, Night purge Ventilation, Network air flow model, Air change rate, Thermal Comfort.*

The focus of this individual project was the study of Natural Ventilation in a building located in Malta, a country subjected to a warm Mediterranean climate. The designed and analysed model is a representation of a typical Maltese dwelling having distinguishable Maltese housing characteristics. Ventilation can occur via different modes and operations, and this project explored a variety of them.

The energy modelling software package ESP-r along with various ventilation theories were applied to complete the simulations. The generated data was analysed and compared to numerous studies and existing data as a form of validation. This, along with a careful selection of ESP-r parameters were essential in strengthening the results.

The results from various analysed models showed the potential benefits associated with the application of Natural Ventilation in a building located in a warm environment. Natural Ventilation is an essential system required to improve both the energy efficiency as well as the thermal comfort in a building zone. Having a better ventilation system will result in superior air change rates, leading to an improved indoor air quality as well as lower temperatures. The potential, as well as the benefits of Night purge ventilation were also considered. This individual project also analysed an improved system in which natural ventilation was enhanced. A main modified design included the addition of a wind catcher which can improve ventilation through an added inlet, and having an outlet fully exposed to the atmosphere.

The Ambient temperatures in Malta reach highs of over 35ºC during the summer period, with these high temepratures being synomous with the simulated results. Following a simulation having no ventilation, the kitchen zone in the model registered a highest temperature of over 37 ºC, this being a result to the high ambient temperature, operational gains mainly associated with kitchen appliances and solar gains. Improving the ventilation by opening two apertures in this zone, resulted in a drastic drops of up to 18%. This result confirms the benefits that ventilation bring into a building. The simulation of an added opening with an in-built net resulted in the zone reistering a higher temepratture when compared to an aperture having no net. The results, however, showed a temperature drop by 1.5ºC from the maximum ambient of 31ºC, which implies the need of a lower cooling load to reach thermal comfort, therefroe siggesting higher energy efficnency whilst also eliminating drawbacks associated with natural ventilation . Night purge simulations also resulted in a higher energy efficiency. The analysed zones registered a temperatures drop of circa 0.8 ºC when the apertures were modelled as closed during the day and open during the night.

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The completion of this dissertation would not have been possible without the help and constant support of a numerous number of people. In particular I would like to thank my supervisor, Dr Daniel C Cóstola, for his endless support, patience and guidance throughout the entire scholastic year and the individual project period. I would also like to thank all the lecturing professors that make part of Strathclyde University for providing their support and knowledge with regards to the course material. Their comments and suggestions were of great help and were highly appreciated.

Lastly, my gratitude extends to my parents Patrick and Helen for their continuous support and encouragement throughout this year I spent at the University.

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NOMENCLATURE

A

a	Terrain roughness coefficient [-]
A	Surface area of opening [m^2]
ACH	Air change rate per hour [m^3/hr]
A_{eff}	Surface area of inlet opening [m^2]
A_i	Surface area of inlet opening [m^2]
A_l	Total effective leakage area [m^2]
A_O	Surface area of outlet opening [m^2]

B

b	Stack coefficient [$m^6h^{-2}cm^{-4}k^{-1}$]

C

c	Wind coefficient [$m^4a^2h^{-2}cm^{-4}$]
C1, C2, C3	Fitting Parameters
Cd	Coefficient of Discharge [-]
C_P	Coefficient of Pressure [-]

D

d	Length displacement [m]

E

F

F_r	Radiation factor [-]
F_u	Usage factor [-]

G

g	Acceleration due to gravity [m/s^2]

H

h	Building height [m]
H_{eff}	Effective height of window [m]

I

J

K

k	Flow coefficient [-]
K	Terrain roughness coefficient [-]

L

M

N

n	Flow exponent [-]

P

P	Pressure imposed on building [Pa]
P_{in}	Pressure at inlet [Pa]
P_0	Static reference pressure [Pa]
P_{out}	Pressure at outlet [Pa]
Ps_{tag}	Stagnation pressure [Pa]
P_s	Pressure due to stack effect [Pa]
P_{stat}	Static pressure [Pa]
P_{stack}	Pressure due to stack effect [Pa]
P_X	Static pressure on a given point on façade [Pa]
P_W	Wind induced pressure [Pa]

Q

Q	Air flowrate [m^3/s]

Q_b	Bulk air flowrate [m^3/s]
Q_{vent}	Air flowrate due to ventilation [m^3/s]
Q_w	Air flowrate caused by wind effect [m^3/s]

R

S

T

T	Temperature [K]
Tabs	Absolute temperature [K]
Te	Exterior temperature [K]
Ti	Interior temperature [K]
Tref	Temperature at reference point [K]

U

U	Wind velocity [ms^{-1}]
U*	Atmospheric friction speed [ms^{-1}]
U10	Wind velocity measured in open countryside at a height of 10 m [ms^{-1}]
U_{eff}	Effective wind velocity [m/s]
U_h	Wind velocity at height h m [ms^{-1}]
U_l	Wind speed according to a logarithmic wind profile [ms^{-1}]
U_{in}	Wind velocity at inlet [ms^{-1}]
U_{met}	Meteorological wind velocity [ms^{-1}]
U_{out}	Wind velocity at outlet [ms^{-1}]

V

V	Zone volume [m^3]

W

W	Zone width [m]

X

Y

Z

Z_0	Terrain roughness [-]

Greek Symbols

α	Terrain dependant constant [-]
β	Terrain dependant constant [-]
ρ	Density [kg/m^3]
ρ_{air}	Air density [kg/m^3]
ρ_i	Air Density at inlet [kg/m^3]
P_{int}	Pressure at interior opening [Pa]
P_{ext}	Pressure at exterior opening [Pa]
ρ_o	Air Density at outlet [kg/m^3]
ρ_{ref}	Reference density [kg/m^3]
Φ_h	Sensible heat rate [W]
Φ_i	Input rating [W]

ACRONYMS

A

ACH	Air Changes per Hour

C

CAD	Computer Aided Drawing
CFD	Computational Fluid Dynamics

D

DBT	Dry Bulb Temperature

H

HVAC	Heating Ventilation and Air Conditioning

I

IAQ	Indoor Air Quality

M

MV	Mechanical Ventilation
MVS	Mechanical Ventilation System

N

NV	Natural Ventilation
NVS	Natural Ventilation System
NZEB	Nearly Zero Energy Building

O

OHS	Occupational Health and Safety

P

PMV	Predicted Mean Vote

S

S-TSV	Seasonal Thermal Sensation Votes

W

WBT	Wet Bulb Temperature

1. INTRODUCTION

1.1 Problem Background

The Maltese Islands are characterised by a Mediterranean Climate – they are exposed to warm and dry Summer days and nights whilst the winter days and nights can be cool, wet and humid. Such conditions result in uninhabitable houses without any cooling mechanism due to dry weather conditions and elevated temperatures. This results in the necessity of a well-designed Heating, Ventilation and Air Conditioning (HVAC) system to improve the thermal comfort within any space.

A well-designed natural ventilation system (NV) will aid in not only promoting a good indoor air quality, whilst keeping under control the temperatures in warm summer conditions but it will prevent overheating when implemented. This project will aim to analyse the design of an existing building in terms of Natural Ventilation whilst also designing and analysing an improved NV system. Chapter 3, section 3.1 gives a thorough discussion on the climatic conditions of Malta and Gozo.

> ***"Ventilation itself is essential to human health, comfort, and well-being. Natural Ventilation, if done right, can achieve all the above with much less energy than mechanical ventilation systems" –*** *Passe, U. et al. in* [7]

1.2 Problem Definition

Natural ventilation is an energy saving, sustainable design strategy which is based on the idea of having a continuous supply of fresh air inside an area. Apart from this, the concentration of the indoor pollution is diminished, resulting in a better indoor air quality. The reasons for air flow control can therefore be summarised into; Moisture control, Energy Savings and Comfort & Health [1]–[8].

Ventilation research in the building engineering sector took off in the second half of the 19th century to reduce the sources containing toxic carbon monoxide. Today the need for ventilation has shifted to accommodate for thermal comfort, indoor air quality and energy savings. The potential of NV in building design has since then become increasingly popular as this provides robust means to improve all of the above-mentioned conditions. NV can be widely used on numerous stock types, such as dwellings, schools, offices, public buildings, recreational buildings, in both moderate and mild climatic conditions [1], [7].

1.2.1 Energy Use

Since 1971, the world's energy use has drastically increased by more than 50 per-cent as a result to an increase in population, economic growth and technological improvements. A rise in non-renewable energy consumption leads to numerous negative environmental impacts, such as greenhouse gases emissions, global warming and even climate change. Apart from this, energy generation by these means can result in being costly. Currently, the building environment accounts for 40 per-cent of the world's primary energy consumption, and as a result to this, the building environment is also responsible for over a third of global CO_2 emissions. Figure 1.1 shows the distribution of end energy within the European Union (EU). Until 2020, the EU is expected to reduce energy usage by 20 per-cent [6], [9]–[11].

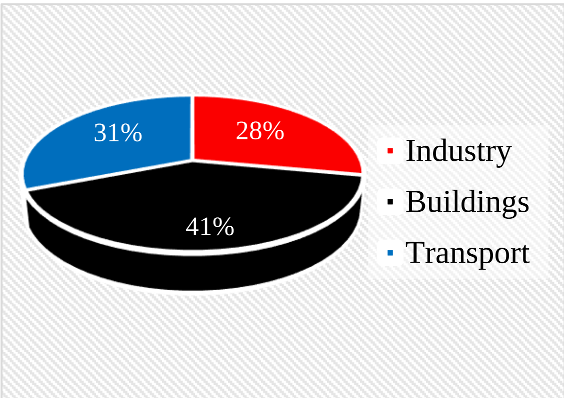


Figure 1.1. End Energy Consumption Distribution within the EU. Source:[10]

1.2.2 Energy Efficiency

According to the Energy Performance of Buildings Directive (2010/31/EU) and the Renewable Energy Contribution Directive (2009/28/EC), domestic premises such as houses, energy efficiency measures can be easily implemented with a positive result in economic benefits. Such an area is given major priority as it can result in achieving the "20-20-20" target. The Europe 2020, which is a European growth strategy for the current decade has put forward the importance of research and implementation of NZEB, or Nearly Zero Energy Buildings [7], [12], [13].

As discussed by Allard et. al in [1], a proper building design with a given importance to a highly energy efficient building will require a balance between two things. Firstly, an adequate technique should be designed for heating, cooling and daylight provision, this along with a good thermal performance of the building envelope. Secondly, the indoor climate should be of a more than acceptable quality, providing thermal comfort, ventilation effectiveness and decent indoor air quality.

Following a study carried out with Maltese occupants, which is discussed in Chapter 3, it resulted that for a Maltese house to live in comfortable way electricity bills can be considerably expensive. The results of this questionnaire also showed how the Maltese and Gozitans can be sceptical with regards to the implementation of a Solar Water Heater (SWH) or Solar Panels to decrease these costs. This gives rise to the importance of a well-designed ventilation system to promote energy efficiency.

1.2.3 Heating Ventilation and Air Conditioning

HVAC systems are becoming more widely available due to increase in wages, and with technology improvements, decrease in system cost to achieve a better standard of living. These systems are wildly found in developed countries, and even more popularly found in countries with warm climatic conditions. Figure 1.2 gives a graphical representation of the expected energy usage in the European countries to provide means of cooling in their buildings [14].

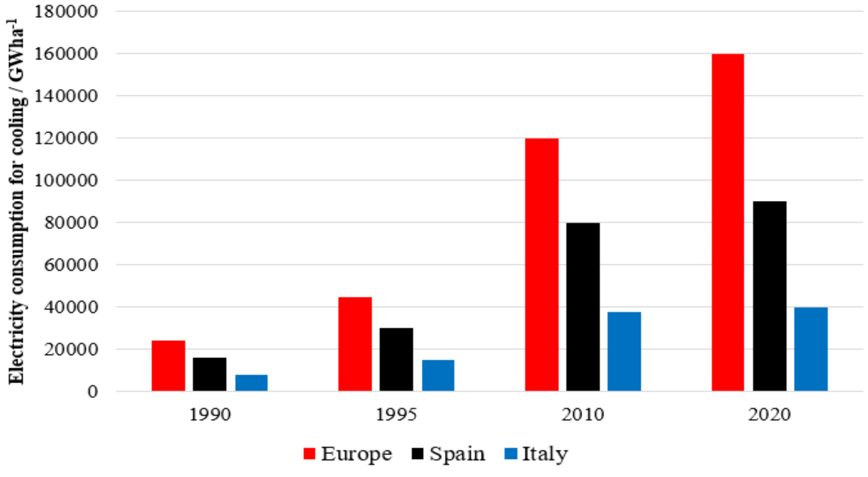


Figure 1.2. Projected Electricity consumption for cooling in Europe with the two main consumers, Italy and Spain. Source: [45]

1.2.4 Benefits of Natural Ventilation

Air can be described as a classical element fundamental for human life. This gives a valid reason for adequate ventilation in any space that will be inhabited. Natural ventilation is also beneficial in improving the indoor air quality, which amongst others includes Odour, Carbon Dioxide, Volatile Organic Compounds (VOCs) and water vapor/humidity. Ventilation is also useful to offer both adequate breathing conditions and to remove internally produced pollution. Building ventilation is essential to preserve an acceptable level of oxygen in the air and prevent the rise in CO_2 levels. It is desired to keep the CO_2 concentration less than 5000 ppm to avoid deficiency in oxygen [6], [7].

NV in a space is significant during night time. A building can be cooled down during the overnight by the removal heat from thermal masses. This in return, will provide additional energy storage for the following day. NV will not only aid in cooling down a space, but also aid in cooling down the human body. The air velocity provide means by cooling the human body by evaporation, thus affecting the human's thermal comfort perception. The human body would also build up a tolerance for higher air temperatures with a higher air velocity [7].

1.3 Aim and Objectives

1.3.1 Aim

Supplying fresh air into a space with minimal energy requirement can be a problematic endeavour. The aim of this project is to analyse the natural ventilation of an existing typical Maltese house, giving particular attention to apertures such as doors and window. An improved design will also be analysed with the sole aim of improving the current design and also possibly eliminating concerns associated with Natural Ventilation. The simulations will be conducted using the software package ESP-r and the data will be exported to and analysed via Microsoft Excel.

1.3.2 Objectives

- To analyse and compare the NV Systems adopted by a typical Maltese house subjected to the Maltese climate which was built during a specific era and later modified using the software package ESP-r

- To design, develop and analyse an improved and implemented NV system to increase energy efficiency and thermal comfort using the software package ESP-r
- To analyse and compare different aperture parameters and study their effect on the NV and Thermal Comfort within the building
- To create a design for an improved thermal comfort during warm days/nights at low energy

1.4 Outline for Methodology

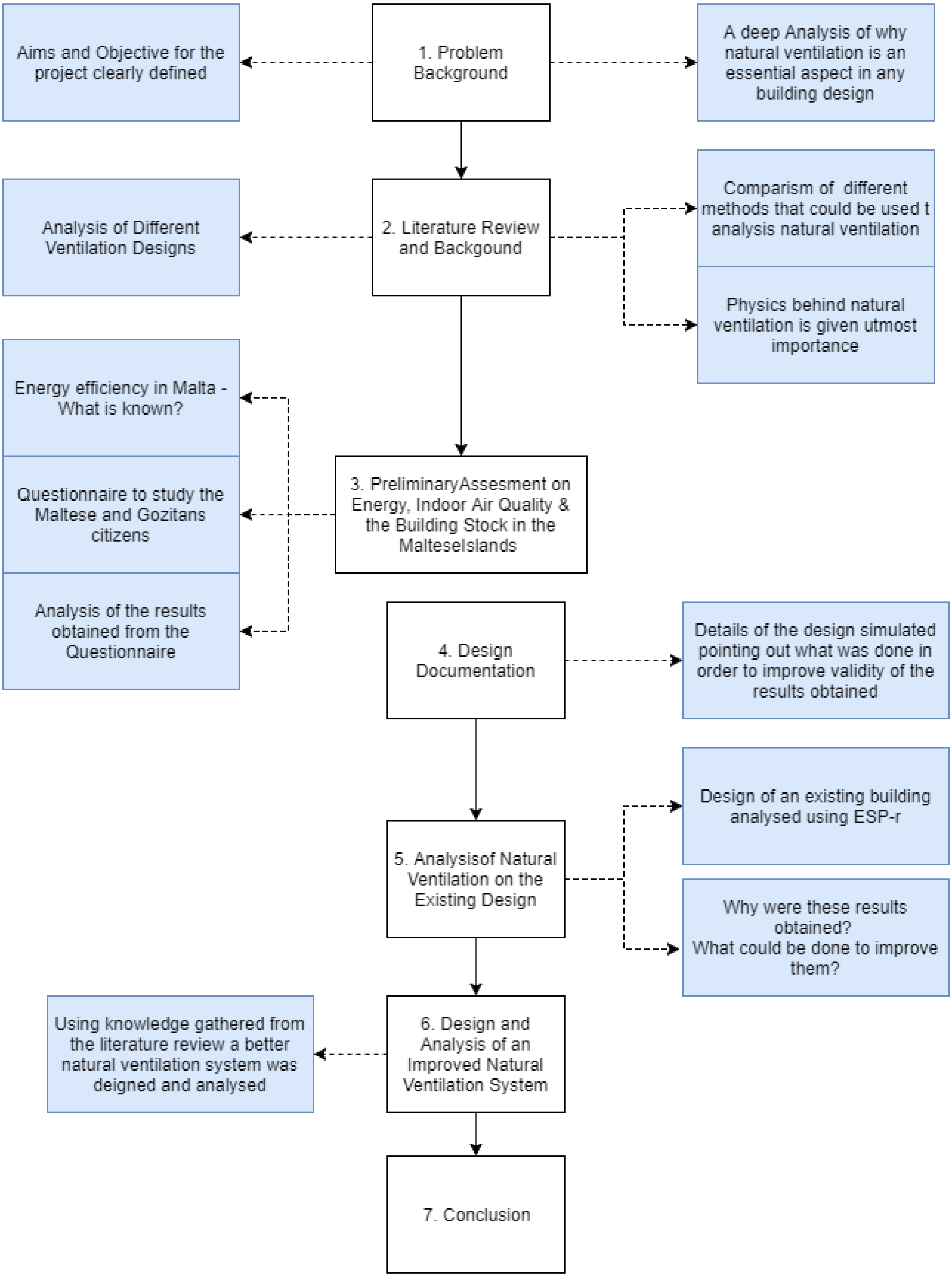
The Literature review considers different Natural Ventilation techniques and applications which are widely in use. The physics behind NV was thoroughly investigated, and the possibility to apply these theories to the results of the analysed designs to further improve their validity. Mechanical Ventilation systems were considered whilst carrying out the literature review to better improve the knowledge associated with the importance of having an adequate ventilation system, whilst also including the advantages and dis-advantages of each.

An electronic questionnaire was created and distributed amongst Maltese citizens to better understand the problem associated with energy efficiency and thermal comfort of buildings in the Maltese Islands. The results obtained were investigated and compared to previously conducted studies, census and other findings.

Following a thorough literature review, an ideal design to improve NV of a space was conducted carried out. This will be conducted using the software package ESP-r whilst also making use of analytical methods were possible to verify the findings from the software results. Different Parameters and variable will be altered to obtain a vast selection of results.

All simulations on the current house design were carried out using ESP-r. Theories and Analytical models were also used during the analysis of the designs and results. The simulated data was exported and analysed in the spreadsheet software Microsoft Excel.

1.5 Structure of Dissertation



2. LITEREATURE REVIEW AND BACKGROUND

2.1 Introduction

Air exchange in a building can be divided into two distinct classifications: Ventilation and Infiltration. Ventilation, which can occur both Naturally and/or Mechanically, is the intentional introduction of the outside air. It is used to provide acceptable indoor air quality (IAQ) whilst also improving the thermal comfort inside the building.

Natural ventilation is the flow of air through openings such as doors, windows, grilles or any planned building penetration, and it is driven through the openings due to a resultant pressure differences. Forced/Mechanical ventilation, as the name itself suggests, is the intentional movement of air, many of the times using systems such as fans or intake/exhaust vents.

Infiltration, or air leakage, is the flow of air which occurs into the building through unintentional openings such as cracks. Exfiltration is the term used for air leakage to the outside of the building. Both infiltration and exfiltration use the same mechanism of pressure difference as NV (later explained in section 2.4). Figure 2.1 shows a schematic representation of mechanical ventilation, infiltration and exfiltration [1], [15].

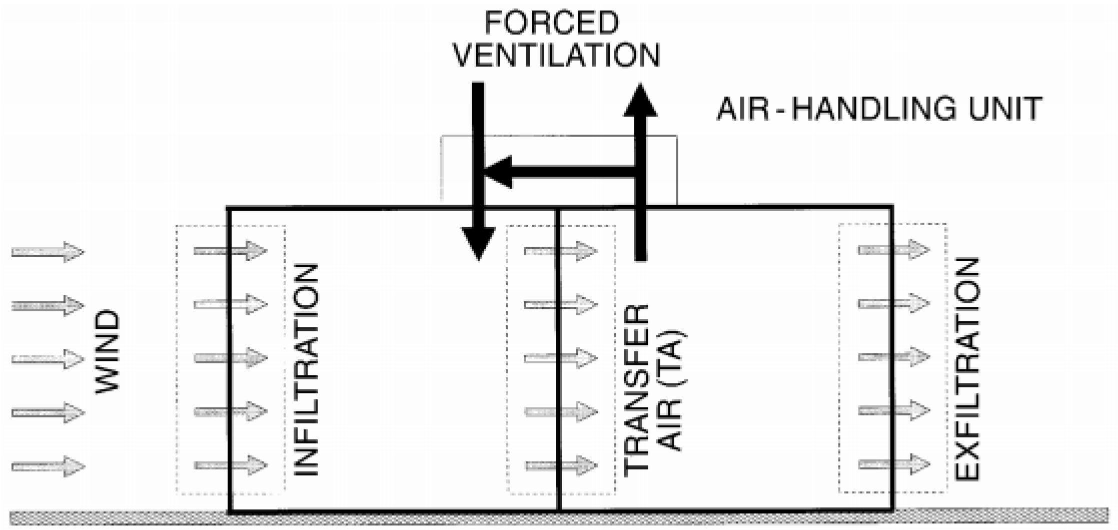


Figure 2.1. Schematic diagram for forced ventilation, infiltration and exfiltration. Source: [34]

The physics behind NV is a complex and a problematic issue to interpret. Classical fluid dynamics theories describe the phenomena associated with air flow in satisfactory means, however, having an in-depth knowledge of both the boundary and initial conditions a nearly impossible task [14].

The requirement of knowledge of specific airflow characteristics will vary depending on its use. Designers require the airflow rate through large openings so the sizing of the windows and doors could be done efficiently. Engineers will make use of the distribution of air velocity, to efficiently size ventilation inlets and/or outlets. Air velocity will be used by comfort experts with the aim to calculate heat convection from the human body to maximise the comfort in a space. Finally, air quality experts will make use of the flow rate, dispersion of contaminant and also the ventilation efficiency to better improve IAQ [14].

Natural ventilation can be modelled using four distinguishable methods:

- Empirical Models
- Network Models
- Zonal Models
- Computational Fluid Dynamics (CFD) Models

Each of these models, are based on a number of assumptions, and much of the time fail to represent the actual conditions within any space. The results may be inaccurate, however, they give a good representation of what is happening. Figure 2.2 shows typical wind movement caused by NV in a house. A deeper analysis of these techniques is discussed in sections 2.6-2.8 [14].

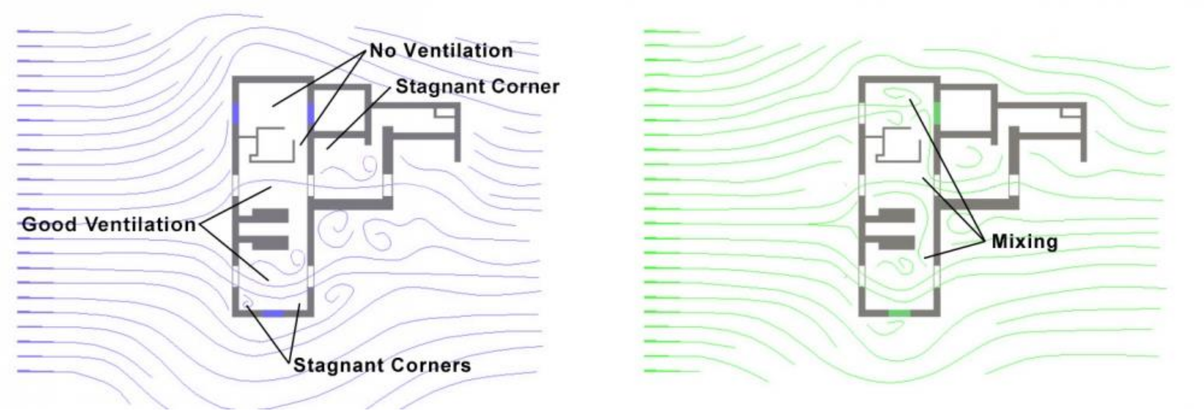


Figure 2.2. Results of Natural Ventilation. Source: [46]

2.2 Barriers to Natural Ventilation Systems

Implementation of Natural Ventilation is not always a feasible operation, either financially and/or design-wise. During the design stage, all possible drawbacks associated with NV systems should be carefully analysed. This being said, the benefits should also be considered, and the designers should make the client aware of all the pros and cons. Figure 2.3 gives a brief overview of all the potential barriers associated with the application of NV [1].

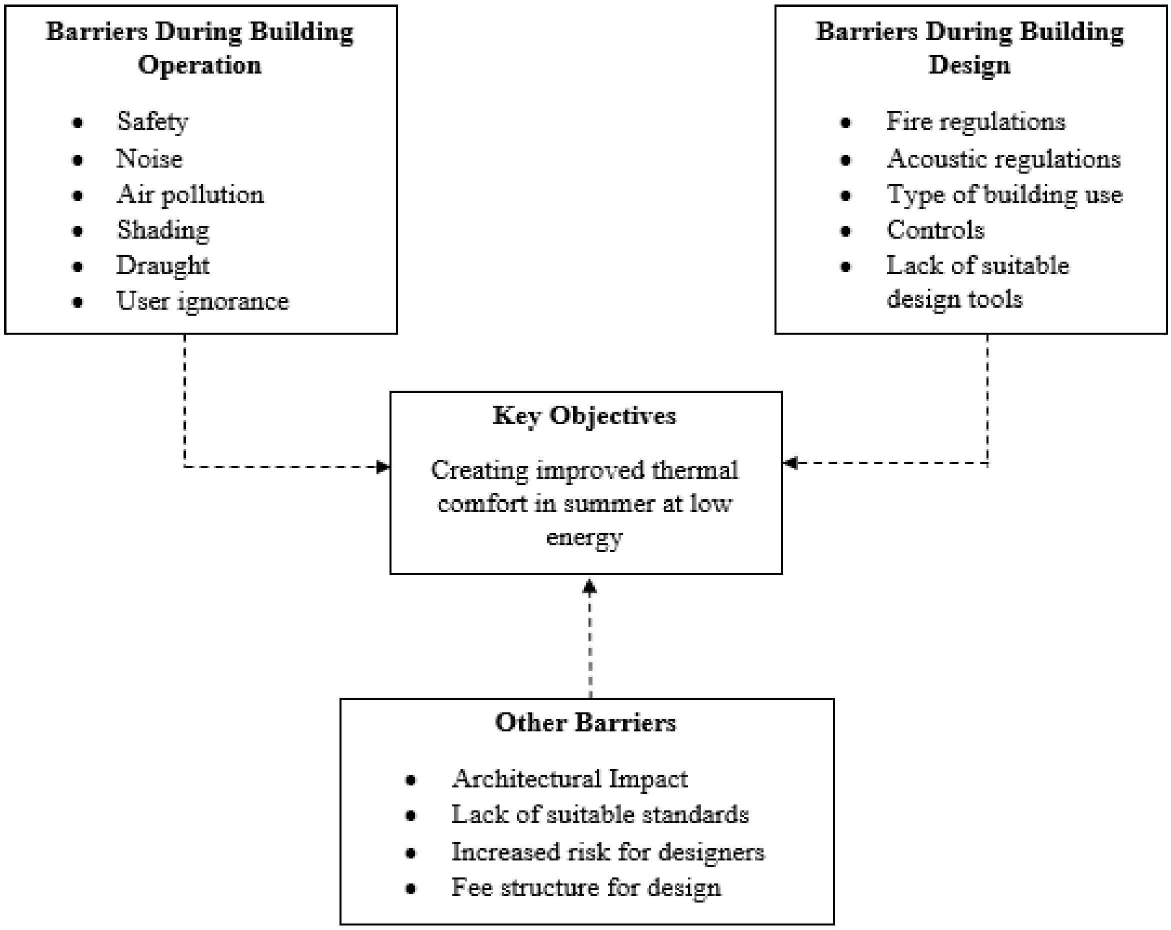


Figure 2.3. Barriers to Natural Ventilation Overview. Source: [1]

2.2.1 Barriers during Building Operations

The occupants might have issues in accepting or implements NV systems due to safety concerns. These concerns are mainly associated with the possibility of unauthorised or undesired entry from people, animals or insects. To avoid any possible intrusions, all inlets and outlets should be well thought, giving special attention to lower level floor entries which facilitate access to unauthorised personnel. One option to avoid intrusions is by limiting the entry size. The openings can also be bars fixed onto them as shown in Figure 2.4. This, however, will not solve the issue associated with animals, insects or even birds. Insects are commonly associated with a Maltese summer, and such an issue can prevent the implication of a NV system. These can be limited by including a screen or net with an adequate mesh size. Manually operated openings can be implemented to avoid any rain entering the house, which can damage the furniture or appliances [1].

Figure 2.4. Steel bars limiting entrance through the windows. Source: Author

Another issue associated with NV systems is noise pollution. This is a major concern for people that live close to a main road or night operating establishments. Noise is much of the time attenuated by including physical boundaries in the building itself, such as walls or doors. With regards to a highly designed NV building, the idea behind physical boundaries is to keep these to a minimum to guarantee better air flow and therefore better ventilation. Openings can be designed including noise-reducing baffles. Mechanical ventilation might not always be the better option with this regard, since they themselves generate noise from fans or the internal mechanical systems [1].

Draughts could result in a problem, especially when NV is employed in an office, resulting in the movement of papers from working desks. Provision of air flow should be always existent whatever the conditions, even if these are unfavourable, e.g. low wind speeds or minimal temperature differences, to promote a satisfactory level of IAQ. This can be tackled by applying large openings, which in turn would have a negative effect when the wind speeds are much higher, as with high wind speeds, high air flow velocity results. Applying windows with several opening options can be one option to avoid lack of air flow or abundant airflow. Section 2.9 discusses window designs more thoroughly [1].

Air pollution can be a major issue associated with NV drawbacks. Pollutants concentration can be considered as being a minor issue in suburbs and rural areas, but this is not the case for Urban areas, particularly for buildings close to roads susceptible to traffic. Pollutants in urban areas reach higher levels during daytime, and as a result to this, air entering the building might lead to poor indoor air quality, which is harmful to the occupants and the furniture [1].

Figure 2.5 shows graphical results for a study carried out on SO_2 content in the Acropolis Museum which was calculated on a typical day. The concentration trend is similar in all cases, which lowers during night time. The maximum limit proposed by ASHRAE is 365µm^{-3}, in an hour, and this was never exceeded.

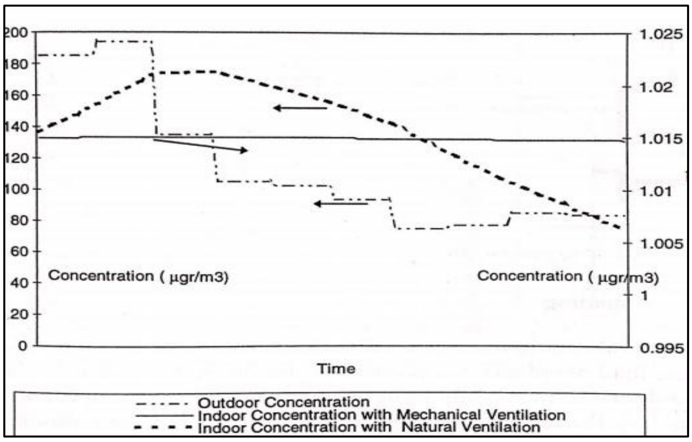


Figure 2.5. Outdoor and Indoor SO2 variation study for the Acropolysis, Museum. Source: [1]

2.2.2 Barriers during Building Design

Laws and regulations might be a limiting actor when it comes to NV implementation. Some laws can for example imply design limitations which can be fundamental in improving ventilation naturally. Fire regulations can also play a role in NV design as these could be set in a way to prevent free flow of air, smoke or odour in the event of a fire. Acoustic regulations may also be set with the aim to minimise noise pollution in urban areas.

The requirement to provide shading, privacy or daylight might have major influence on NV design openings design. Also, lack of suitable and reliable design tools might lead to inefficiently designing the building and not exploiting the area's full potential.

2.2.3 Other Barriers

The implementation of a NV system might affect the overall aesthetic design of a building, which in turn might influence the architect and opt to disregard NV. Overall results with such systems are very depending on weather conditions, and thus the designer might not have full control over the indoor conditions. Customer's dissatisfaction may result which can even harm the architect's/designer's reputation. For this reason, designer's might prefer the application of a mechanically ventilated system, where the user under total control of the indoor condition. When compared to the design of a building with implemented mechanical ventilation system, a naturally ventilated one requires much more work resulting in a costlier design. Even though the payback of systems making use of NV is shorter, people may still avoid this.

2.3 Night Flush Cooling

In humid countries, such as Malta, night air can be significantly cooler than daytime air. This could be used as a means to flush out the heat which accumulates inside a building during the day. The cooled mass acts as a heat sink or as a means to keep the house cooler for a longer time the following day. Night-flush cooling acts in two distinctive stages. The initial stage is the introduction of the outside air inside the building during night time. This can be carried out either via a natural or a mechanical ventilation system. The second stage is to then close the windows during the day. This will prevent the heating of the building caused by the outside air. Later on, the thermal comfort within tends to decrease, and mechanical ventilation would then be required to be introduced in order to circulate the internal air and keep high comfort levels for longer times. This will lead to a lower cooling load and therefore a higher energy efficiency. Figure 2.6 shows a schematic of a house with the night flushing effect [16] [17].

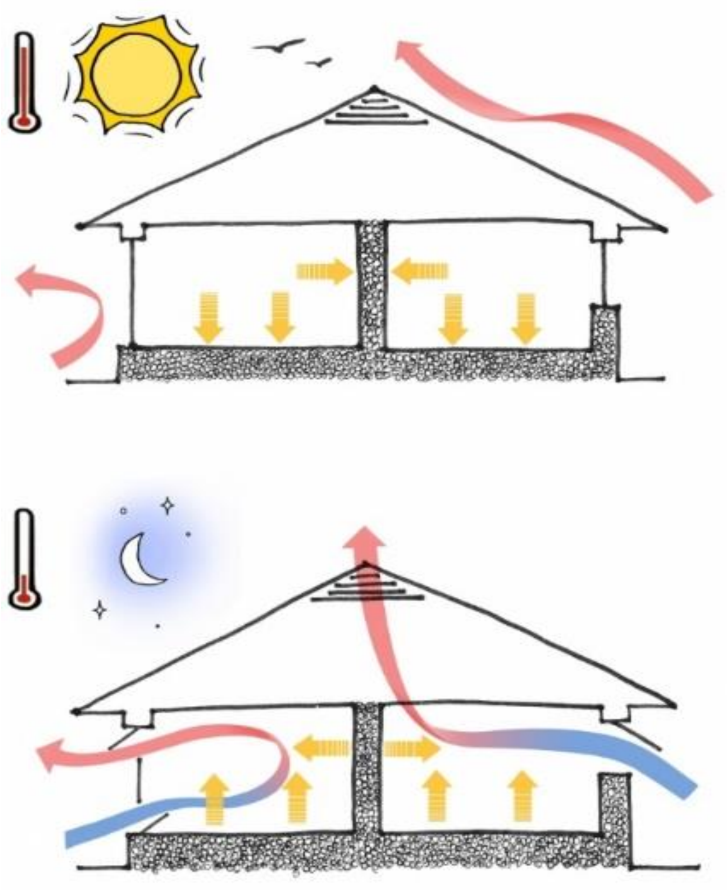


Figure 2.6. Schematic showing effect of Night Flush Cooling. Source: [17]

Use of night purge ventilation would be ideal in an ambient which will not be occupied by anyone due to the higher air change rates which are synonymous with night time. Performance of night ventilation system will depend on a set of different criteria;

- Building's inertia capability in conserving the night coolness,
- Relative difference between day and night temperature, and
- Airflow during night time

2.4 Driving Forces

Airflow control is essential to guarantee occupant's health and safety (OHS) through improved IAQ, ensure comfort, increase energy efficiency and provide moisture damage control. Airflow inside a building is controlled by wind pressure, stack handling and mechanical systems such as fans or furnaces. For airflow to occur, there must exist a pressure difference between two points, and an opening which connects them guaranteeing a continuous flow path. For an air flow to occur, any of the three primary mechanisms is required. The Three mechanisms, which are shown schematically in Figure 2.7 are:

- Wind
- Stack effect or Buoyancy
- Mechanical air handling equipment and appliances

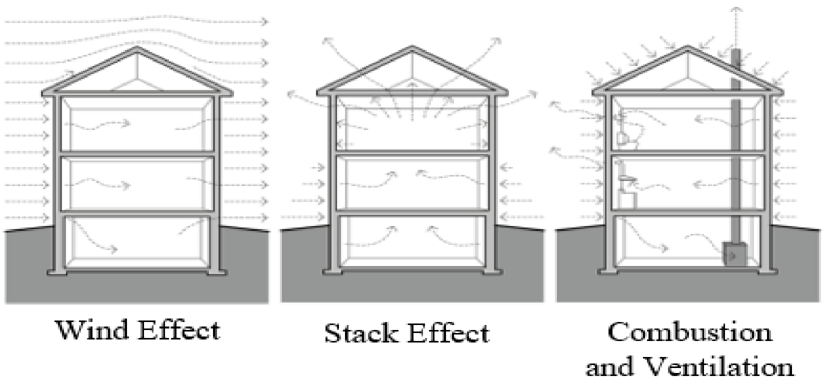


Figure 2.7. Driving forces for Air Flow. Source: [8]

2.4.1 Wind Effect

A positive pressure is created on the windward face (the side that faces the wind) whilst a negative or suction pressure results on the leeward face (the opposite side) walls caused by the wind forces which act on any building. These resultant wind pressure effects can be seen in

Figure 2.8, with the schematic on the right being more representative of a building in Malta due to its flat designed roof.

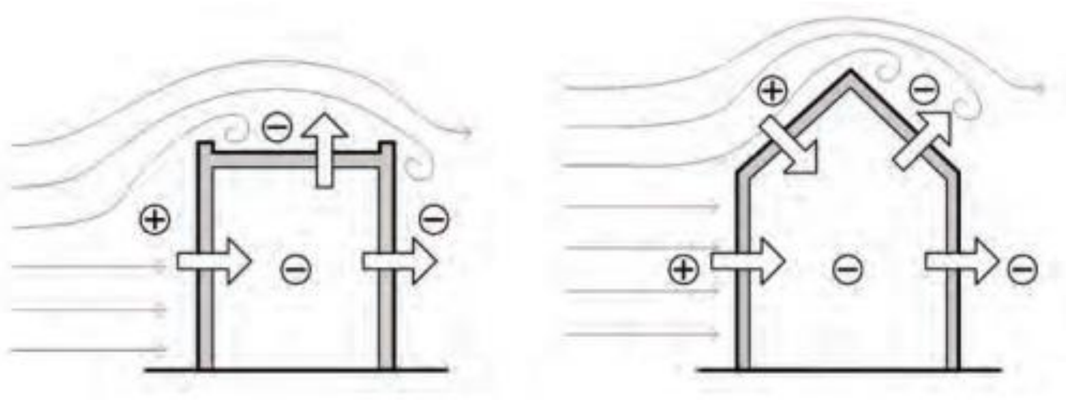


Figure 2.8. Pressure difference due to wind effect. Source: [8]

The pressure resulting from wind effects can be calculated using Bernoulli's principle as a function of wind speed given by equation 2.1. The stagnation pressure, given by equation 2.2 is defined as the pressure which is resulted after a flow decelerates to zero. In these equations ρ_{air} is the air density in kg/m^3 and U is the velocity of the wind in m/s. A pressure coefficient, C_P is introduced, given by equation 2.3, to account for errors in the calculated stagnation pressure and calculate the pressure imposed on the building [1], [4].

$$P_{out} + \frac{1}{2}\rho U_{out}^2 + \rho gh = P_{in} + \frac{1}{2}\rho U_{in}^2 + \rho gh \quad (2.1)$$

$$P_{stag} = \frac{1}{2} \times \rho_{air} \times U^2 \times 0.65 \times U^2 \quad (2.2)$$

$$P = C_P \times P_{stag} \quad (2.3)$$

Equations 2.2 and 2.3 can be combined and simplified to equation 2.4 where ΔP_w is the wind induced pressure in Pa.

$$\Delta P_w = 0.5 C_p \rho_{air} U^2 \quad (2.4)$$

The wind pressure coefficient acting on a building varies according to different paramets which include the building geometry, façade detail, location of the building and also the degree to which the building is exposed, wind speed and wind direction. The exposure level and location have a major influence on this value. The data could be obtianed from literature, by modelling of the actual building in wind tunnels or by simulation using Computational Fluid Dynamics

(CFD). Obtaining highly accurate results without the use of expensive wind-tunnel testing can be a nearly, if not, an impossible task.

The Pressure Coefficient can be defined by equation 2.5 where P_x is the static pressure at a given point on the building façade in Pa, P_o is the static reference pressure also in Pa. P_d can be calculated using equation 2.6 where U_h is the wind velocity at the building's height in m/s [18], [19].

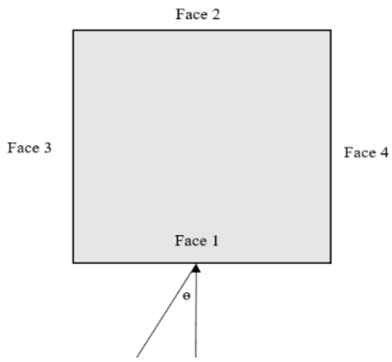


Figure 2.9. Building Schematic having a length to width ratio of 1:1

$$C_P = \frac{P_X - P_o}{P_d} \quad (2.5)$$

$$P_d = \frac{\rho_{air} \cdot U_h^2}{2} \quad (2.6)$$

Table 2.1 gives a summary of pressure coefficients from literature associated with a shielded building (obstructions of equal height). Figure 2.9 shows a schematic of a building with a wind acting towards face 1 and having an dngle of incidence of ɵ⁰ [18], [19].

Table 2.1. Coefficient of pressure on building having a shielded condition in an urban environment. Source: [19]

Location	**Wind Angle**							
	0	**45**	**90**	**135**	**180**	**225**	**270**	**315**
Face 1	0.2	0.05	-0.25	-0.3	-0.25	-0.3	-0.25	0.05
Face 2	-0.25	-0.3	-0.25	0.05	0.2	0.05	-0.25	-0.3
Face 3	-0.25	0.05	0.2	0.05	-0.25	-0.3	-0.25	-0.3
Face 4	-0.25	-0.3	-0.25	-0.3	-0.25	0.05	0.2	0.05

As can be observed in Figure 2.10, wind speed varies with height, this being many of the time available from typical metrological data at fixed height. A more accurate wind speed at a specific height could then be found using a correlation between both wind speed and height. Equations 2.7 – 2.9 represent three wind profiles which can be used to calculate the wind velocity [1], [19].

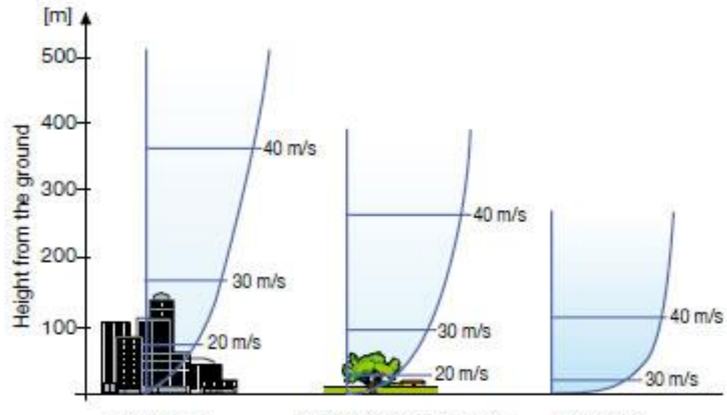


Figure 2.10. Wind Profile. Source [47]

2.4.1.1 The power law wind profile

The wind speed at a height h, U_h can be calculated using equation 2.7 where the coefficients a and K depend on the terrain roughness with typical values given in Table 2.2. U_{10} is the wind speed measured in an open country side at a height above ground of 10m. [1], [19].

$$\frac{U_h}{U_{10}} = Kz^a \quad (2.7)$$

2.4.1.2 The logarithmic wind profile

According to the logarithmic wind profile, the wind speed U_l is a logarithmic function of the height. In equation 2.8 U_{met} is the wind speed acquired from metrological data in ms^{-1}, U_* is the atmospheric friction speed also in ms^{-1}, Z_o and d are the terrain roughness and length displacement in m respectively. Values for the constants Zo and d are given in Table 2.2 [1], [19].

$$\frac{U_l}{U_{met}} = \frac{U_{*,l}}{U_{*,met}} \left[\frac{\ln \frac{Z_{ll} - d_l}{Z_{0,l}}}{\ln \frac{Z_m - d_m}{Z_{0,m}}} \right] \quad (2.8)$$

Where;

$$\frac{U_{*,l}}{U_{*,m}} = \left[\frac{Z_{0,l}}{Z_{0,m}} \right]^{0.1}$$

2.4.1.3 Power-law wind profile developed at the Laurence Berkeley Laboratory

As with previous model, U_l is the logarithmic wind velocity required at a height z and U_m is the wind speed acquired from meteorological data at a height z_m. In equation 2.9, both α and β are terrain dependent constants and are given in Table 2.2.

$$\frac{U_l}{U_m} = \frac{\alpha(z/10)^{\beta}}{\alpha_m(z_m/10)^{\beta}} \quad (2.9)$$

Table 2.2. Ttypical values for terrain dependant constants where h is the height of the building. Source: [1], [19]

Terrain	K	A	Z_0	D	α	β
Open flat country	0.68	0.17	0.03	0.0	1.00	0.15
Country with scattered wind breaks	0.52	0.20	0.1	0.0	1.00	0.15
Rural	-	-	0.5	0.7h	0.85	0.20
Urban	0.35	0.25	1.0	0.8h	0.67	0.25
City	0.21	0.33	>2.0	0.8h	0.47	0.35

2.4.1.4 Wind Velocity Effect on Temperature Rise

Wind velocities can have a major influence on the ventilation effects of a building, improving thermal comfort by reducing air temperatures. Interior temperatures can be reduced about 5ºC if the wind velocity reaches a speed of 0.8m/s. Figure 2.11 shows the effect that wind speed has on the temperature rise [20].

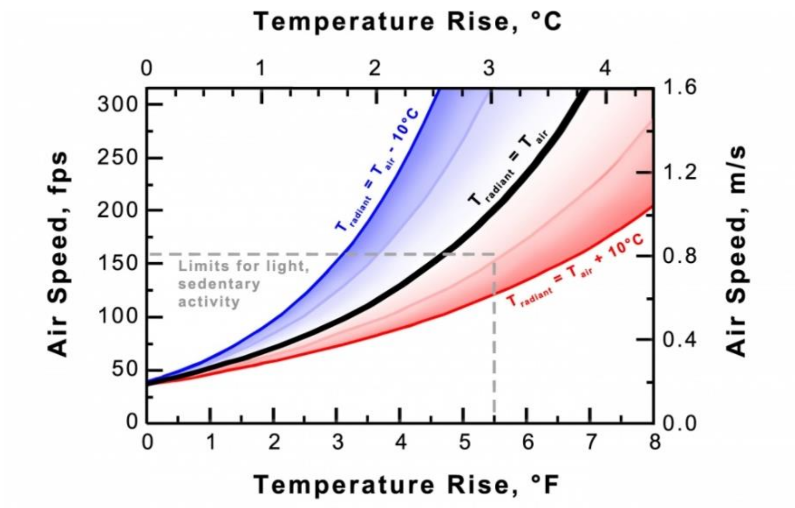


Figure 2.11. Moving Air and Temperature relationship for different radiant temperature. Source: [17]

2.4.2 Stack Effect

The stack effect pressure is the result of air density difference which is caused by a temperature difference. In simple terms, warm air will rise and replace the cooler air due to a lower density. The density of dry air, ρ_{dry} vary with temperature and a higher potential difference will occur within a larger column height. The stack effect is more common in high rise buildings, especially in places with vertical passages such as shafts and lifts.

Equation 2.10 gives the pressure due to stack effect, P_s, P_o is the static pressure, h is the height of the opening in m, g is the acceleration due to gravity in m/s^2 and ρ_{air} is the air density equivalent to a temperature Ti, the temperature inside the building.

$$P_S = P_O - \rho g h \quad (2.10)$$

If it assumed that the air behaves as an ideal gas, then equation 2.11 can be used to calculate the respective density where T_{abs} is the absolute temperature in K and the subscript ref refers to the reference condition of the air. Equation 2.10 shows that as the height increases, the stack pressure decreases.

$$\rho = \rho_{ref} \ \frac{T_{ref}}{T_{abs}} \quad (2.11)$$

If two isothermal zones are assumed, i.e. temperature within the zone do not change by height, equation 2.12 can be used to calculate the pressure difference at a height of z m. in equation 2.12, $P_{stat,1}$ and $P_{stat,2}$ are the static pressure at the two different zones and ρ_1 and ρ_2 are the densities of zone 1 and zone 2 respectively. Figure 2.12 shows a schematic for the stack effect for a typical building.

$$\Delta P_s = P_{stat,1} - P_{stat,2} + (\rho_1 - \rho_2) g z \quad (2.12)$$

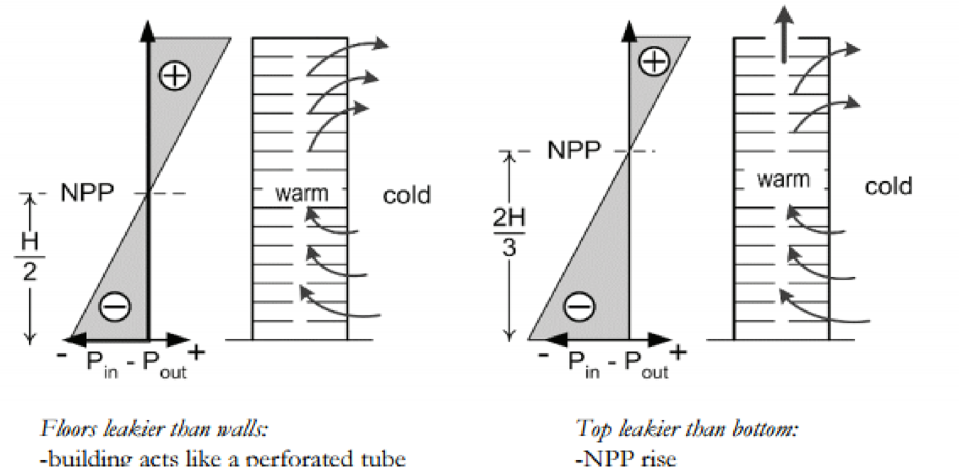


Figure 2.12. Stack effect in real buildings showing the neutral pressure point (NPP). Source: [8]

2.4.3 Combination of the Wind effect and the Stack effect

Equation 2.13, which is used to calculate the overall pressure difference across an opening is the result of combining equations 2.4 and 2.12. U_1 and U_2 are the wind speeds at the two sides of the openings and ρ_1 and ρ_2 are the densities of interconnected zones.

$$\Delta P = \mathrm{P}_{\mathrm{stat,1}} - P_{stat,2} + \frac{\rho_1 C_p U_1^2}{2} - \frac{\rho_2 C_p U_2^2}{2} - (\rho_1 - \rho_2)gh \quad (2.13)$$

Equation 2.13 can be modified to calculate the pressure difference for exterior opening, interior openings as seen in equations 2.14 and 2.15 respectively. For exterior openings, U_2=0 and U_1 is equal to the wind speed U, ρ_i is the interior air density and ρ_o is the outdoor density. P_o is the reference pressure of the zone where the opening is. For interior openings, U_1=U_2=0.

$$\Delta P_{ext} = P_O - \frac{\rho_i C_p U^2}{2} + (\rho_i - \rho_O)gh \quad (2.14)$$

$$\Delta P_{int} = P_{1,0} - P_{2,0} + \left(\rho_{i,1} - \rho_{i,2}\right)gh$$

2.4.4 Airflow through large openings and cracks

Large and small openings are defined according to their size. An opening will be considered as large if its dimension is larger than 10mm, and therefore windows and doors are defined as large openings. The air flow rate through an opening is given by equation 2.15 where k is the flow coefficient and n is the flow exponent which is typically 0.67 for cracks which form around a close window. Table 2.3 tabulates typical flow coefficients. The flow exponent n depends on the flow characteristics and lies in between the range of 0.5 and 1.0. For turbulent flow, n is equal to 0.5 whilst n is equal to 1.0 for completely laminar flow [1].

$$Q = k(\Delta P)^n \quad (2.15)$$

Table 2.3. Typical flow coefficient, K. Source: [1]

Window type	Average	Range
Sliding	8	2-30
Pivoted	21	6-80
Pivoted (weather-stripped)	8	0.5-20

For large openings, the common orifice equation can be given by Equation 2.16 (Bernoulli equation) can be applied for point 1 and point 2 which are seen in Figure 2.13. If an assumptions whereby the velocity profiles at sections 1 and 2 are uniform, equation 2.16 results in equation 2.17, where A_2 is the smaller area when compared to A_1 [1].

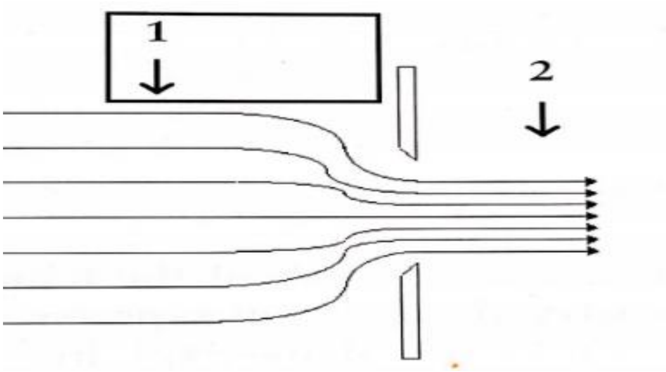


Figure 2.13. Flow modification though an opening

$$p_1 + \frac{1}{2}\rho U_1^2 = p_2 + \frac{1}{2}\rho U_2^2 \quad (2.16)$$

$$Q = A_1 U_1 = A_2 U_2 \quad (2.17)$$

Combining equations 2.16 and 2.17 result in equation 2.18, and since for openings in buildings $A_2 << A_1$, the term A_2/A_1 cancels out forming equation 2.19, which is however the ideal situation. The coefficient of discharge, C_d is added to account for the real world resulting from turbulent flow.

$$U = \sqrt{\frac{2(p_1 - p_2)}{\rho\left[1 - \left(\frac{A_2}{A_1}\right)^2\right]}} \quad (2.18)$$

$$U = C_d \sqrt{\frac{2(p_1 - p_2)}{\rho}} \quad (2.19)$$

C_d is a function of the temperature difference, wind speed and opening geometry. For internal openings C_d can be calculated using equation 2.20 and for steady state and buoyancy driven flow equation 2.21 can be used.

$$C_d = 0.0835 \left(\frac{\Delta T}{T}\right)^{-0.3} \quad (2.20)$$

$$C_d = 0.4 + 0.0075\Delta T \quad (2.21)$$

Equation 2.22 gives the airflow rate dQ through a small area dA, where W is the width of the opening and z is the height. Replacing the velocity U in equation 2.22 by equation 2.19 results in equation 2.23.

$$dQ = UdA = VWdz \quad (2.22)$$

$$dQ = C_d \sqrt{\frac{2(p_1 - p_2)}{\rho}} Wdz \quad (2.23)$$

2.5 Single sided and Cross-Ventilated Buildings

Both single-sided and cross ventilation are wind induced. This means that the strategy depends on a pressure difference between the inlet and the outlet as explained in section 2.3.1. Figure 2.14 gives an overview of the two types of ventilations.

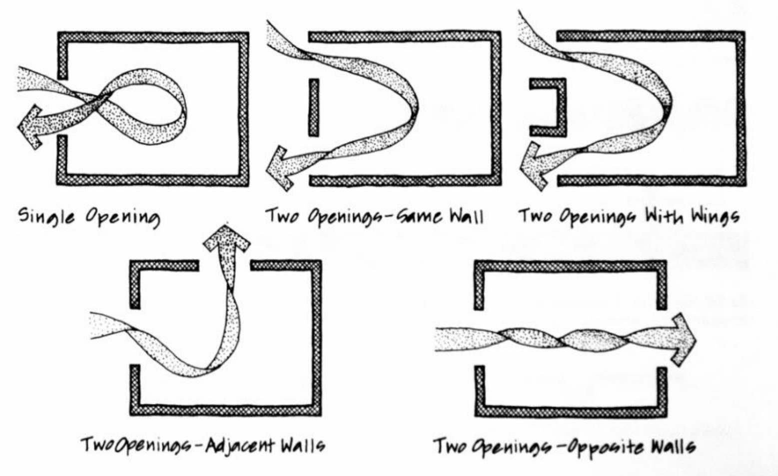


Figure 2.14. Different ventilation resulting from different openings. Source: [46]

2.5.1 Single-Sided Ventilation

The schematic in Figure 2.15 shows a single-sided ventilation system, where ventilation occurs through one opening on one side of the building. This type of ventilation system is mostly common in Maltese houses. Single-sided ventilation is effective to the double of a space height of a building. Prediction for the ventilation rate for a single sided ventilation system is hard to predict due to the turbulent nature and bi-directional flow associated with wind entering such apertures. It is however very easily implemented in buildings and has little restrictions [21].

2.5.2 Cross Ventilation

A cross ventilation schematic can be seen in shown in **Error! Reference source not found.**. When compared to single-sided ventilation, it is more effective in terms of creating flow paths within the building. Cross ventilation can provide a higher ventilation rate when compared to single-sided, however it requires for the buildings to be thin and obstacles in the path flow should be kept to a minimum. It is effective up to a maximum depth of five times the building's height. Openings in opposite directions are more efficient when compared with openings in adjacent walls. An inlet placed in the lower section of a wall is more ideal to provide cooling, as opposed to heating, where an inlet higher on the wool is desired[4], [21].

As suggested by Smith in [8] the minimum window area should be 5per-cent of the floor area, in order to secure the minimum flow area. Table 2.4 summarises the ideal inlet to outlet area for a desired outcome, where A_i is the inlet area and A_o is the outlet area.[4]

Table 2.4. Ideal inlet and outlet area ratio. Source:[1]

	Observation	Design Target
$A_i = A_o$	Maximum air change created	Building cooling
$A_i < A_o$	Maximum interior air speed	Users cooling
$A_i > A_o$	Air speed reduced inside, and accelerated outside	Outdoor spaces cooling

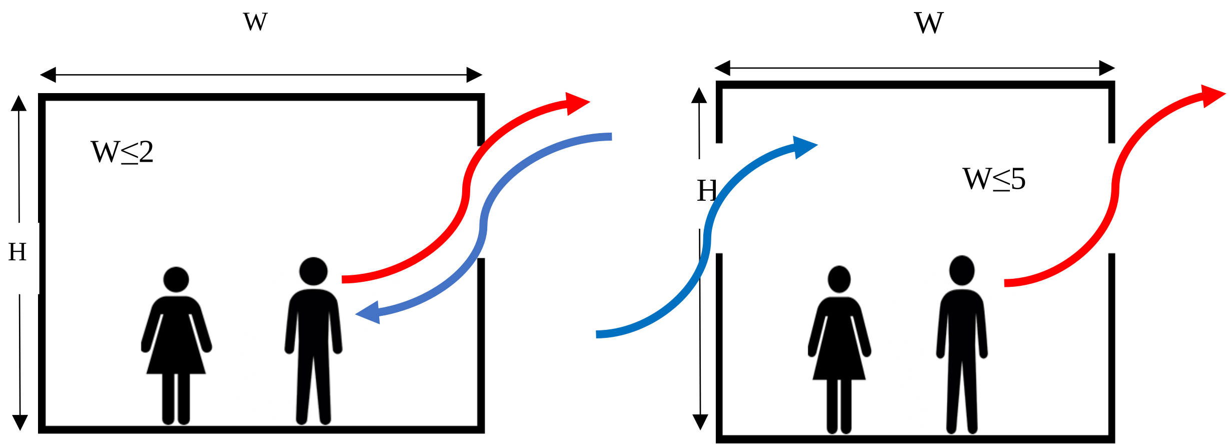


Figure 2.15 (Left). Single-Sided Ventilation schematic diagram. (Right) Cross Ventilation schematic diagram. Source: Author

2.6 Empirical Models

Empirical models are used to calculate an airflow rate, or the mean velocity within a zone. These models include a correlation between the airflow and temperature difference and wind velocity. Such models are ideal to produce a preliminary estimation.

Empirical models can be distinguished in two methodologies. The first can be used in order to predict the airflow rates whilst the second set can be used to predict the air velocity within a space.

2.6.1 The British Standards Method

The British Standard Method is a simplified method used to predict and estimate the airflow rate within naturally ventilated buildings. Such models should be used within the limits as these were derived from theories and/or experimental data and their validity is limited. This method can be used to calculate air infiltration and ventilation in either single-sided or cross-ventilation configurations.

Assumptions made during this method include:

- Two-directional flow through the building
- Internal partitions are ignored

Single-Sided Ventilation

For single sided ventilation, Q represents the flow rate in m^3/s, A is the opening surface in m^2, U is the wind velocity in m/s and C_d is the coefficient of discharge.

Ventilation due to wind

Figure 2.16 shows a cross section for s single-sided ventilation caused by the wind. The flowrate for this situation is calculated by equation 2.23 [1], [19].

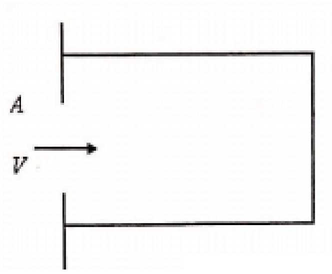


Figure 2.16. Cross-section for ventilation due to wind in single-sided Ventilation. Source: [1]

$$Q = 0.025AU \quad (2.23)$$

Ventilation due to temperature difference with two openings

Figure 2.17 shows a cross-section of a zone with two inlets on one wall with a distance between them of H_1 and an aperture area of A_1 and A_2 respectively. T_e is the external temperature whilst the internal temperature is equal to $\Delta T+T_e$[1], [19].

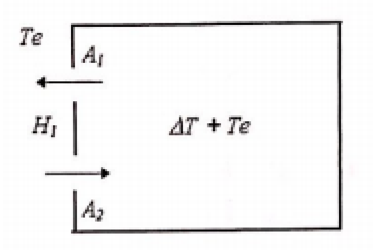


Figure 2.17. Cross-section for ventilation due to temperature differences with two openings in single-sided Ventilation. Source: [1]

$$Q = c_d A[\frac{\varepsilon\sqrt{2}}{(1+\varepsilon)(1+\varepsilon^2)^{0.5}a}\left(\frac{\Delta T H_1}{\bar{T}}\right) \quad (2.24)$$

Where; $\varepsilon = \frac{A1}{A2}, A = A1 + A2$

Ventilation due to temperature difference with one opening

This is a modification to equation 2.24 having the two apertures shown in Figure 2.17 replaced by a larger aperture having height H m. Figure 2.18 shows a cross section for when the opening area is large and has a height of H_2 m [1], [19].

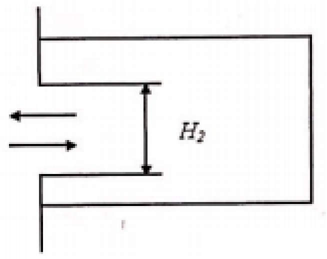


Figure 2.18. Cross-section for ventilation due to temperature difference with one opening in single-sided Ventilation. Source:[1]

$$Q = C_d \frac{A}{3}\sqrt{\frac{\Delta T_g H}{\bar{T}}} \quad (2.25)$$

Cross Ventilation

Ventilation due to wind only

For cross ventilation, the flow rate caused by a wind flow can be calculated using equation 2.26. the schematic shown in Figure 2.19 shows the cross section of a building making use of a cross ventilation with apertures having areas A1, A2, A3 and A4 [1], [19]

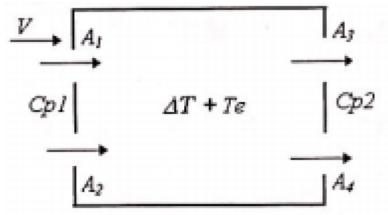


Figure 2.19 Cross-section for ventilation due to wind in cross Ventilation. Source: [1]

$$Q_w = C_d A_w U\sqrt{\Delta C_p} \quad (2.26)$$

Where;

$$\frac{1}{A_w^2} = \frac{1}{(A_1+A_2)^2} + \frac{1}{(A_3+A_4)^2}$$

$$T = \frac{T_e+T_i}{2}$$

Ventilation due to temperature difference only

the air flowrate caused by a temperature difference between the external and zone temperature can be calculated by equation 2.27, with the schematic representing this condition shown in Figure 2.20 [1], [19].

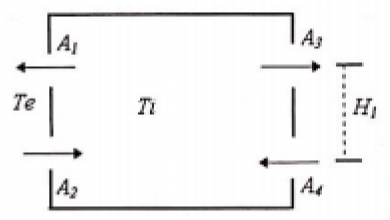


Figure 2.20. Cross-section for ventilation due to temperature difference in cross Ventilation. Source: [1]

$$Q_T = C_d A_b \left(\frac{2\Delta T_g H_1}{T}\right)^{0.5} \quad (2.27)$$

Where;

$\frac{1}{A_b^2} = \frac{1}{(A_1+A_3)^2} + \frac{1}{(A_2+A_4)^2}$

$T = \frac{T_e+T_i}{2}$

<u>Ventilation due to wind and temperature difference</u>

Equations 2.28 and 2.29 can be used in conjunction to find the total air flow rate which is caused by both wind and temperature difference effects [1], [19].

$$Q = Q_b \; when \frac{V}{\sqrt{\Delta T}} < 0.26 \sqrt{\frac{A_b}{A_w}\frac{H_1}{\Delta C_p}} \quad (2.28)$$

$$Q = Q_T \; when \frac{V}{\sqrt{\Delta T}} > 0.26 \sqrt{\frac{A_b}{A_w}\frac{H_1}{\Delta C_p}} \quad (2.29)$$

Where;

$\Delta T = Ti - Te$

2.6.2 The ASHRAE Method

In order to apply this method, knowledge regarding the total effective leakage area should be available. This data can be either determined using a pressurization/depressurization techniques or else use from evaluated tables. Typical air leakage paths are shown in the schematic of Figure 2.21 [1] [8].

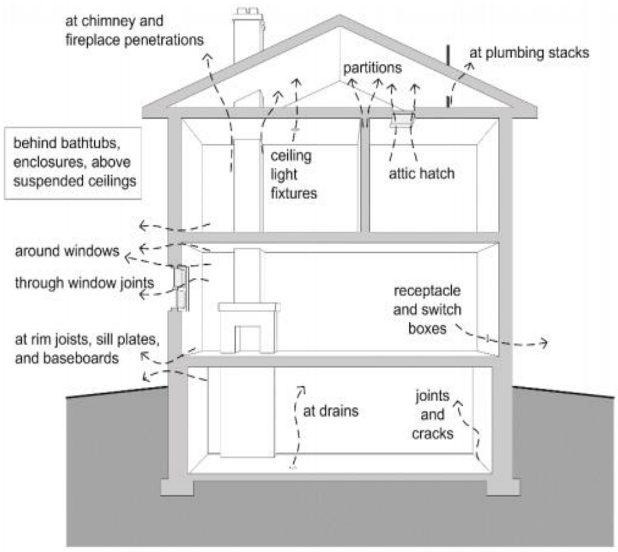


Figure 2.21. Possible leakage paths. Source: [8]

Equation 2.30 can be used to calculate the bulk airflow rate Q_b. A_l is the total effective leakage are of the building in cm^2, ΔT is the average temperature difference between inside and outside, U_{met} is the meteorological wind speed. The coefficients b and c represent the stack coefficient in $m^6h^{-2}cm^{-4}K^{-1}$ and wind coefficient in $m^4a^2h^{-2}cm^{-4}$ respectively. The value for coefficient a depends on the number of storeys of b building whilst coefficient c takes account for the local shielding class of the building rather than just the number of storeys. Some of these values are found in Table 2.5and Table 2.6 [1], [8], [14], [15].

$$Q_b = A_l\sqrt{b\Delta T + cU_{met}^2} \quad (2.30)$$

Table 2.5. Values for Coefficient b. Source:[1]

One-storey building	0.00188
Two-storey building	0.00376
Three-storey building	0.00564

Table 2.6. Values for Coefficient c

	Number of Storeys		
Shielding Class	**1**	**2**	**3**
No obstructions	0.00413	0.00544	0.00640
Light Local Shielding	0.00319	0.00421	0.00495
Moderate local Shielding	0.00226	0.00299	0.00351
Heavy Shielding	0.00135	0.00178	0.00209

Very Heavy Shielding	0.00041	0.00054	0.00063

2.6.3 The De Gidds and Phaff Method

Results from experimental data show that for the case of single-sided ventilation or in the case of the direction of the wind is parallel to openings in two parallel facades, airflow is resultant of fluctuating effects. The incoming wind has a turbulence effect, which is an attribute of fluctuating winds and positive and negative pressure fluctuations occur in inside air.

The Gidds and Phaff method allows the calculation of the ventilation rate, Q_{vent} through an open window as a result of temperature difference, wind velocity and fluctuating terms. Equation 2.31, which is derived from equation 2.30, defines the effective wind velocity, U_{eff} in terms of half a window opening. Table 2.7 tabulates the dimensionless coefficient C which depends on the wind. H is the vertical size of the opening and U_{met} is the methodological wind velocity.

$$U_{eff} = \frac{2Q}{A} = \sqrt{\frac{2}{g}(\Delta p_{wind} + \Delta p_{stack} + \Delta p_{turb})} \quad (2.30)$$

$$U_{eff} = \frac{2Q}{A} = \sqrt{C_1 U_{met}^2 + C_2 H \Delta T + C_3} \quad (2.31)$$

Table 2.7. Values for the fitting parameters

C_1	0.001
C_2	0.0035
C_3	0.01

2.6.4 Givonni's Method

Givonni's method is ideal to calculate an estimate of the air velocity inside a naturally ventilated building. The wind velocities within a building aid in improving the body's convective and evaporative heat losses. This in turn would improve the thermal comfort.

Based on experimental data, Givonni's method is given by equation 2.32 where U_i is the average indoor velocity, Uo is the reference external velocity and x is opening's area to wall area ratio. For this correlation to be applicable, the floor plan should have a square geometry, and the upwind and downwind openings should be identical and located in opposite walls.

$$U_i = 0.45(1 - e^{-3.48x})U_o \quad (2.32)$$

2.7 Network Models

Network models have a number of advantage over empirical models as the latter are based on simple formulae and a number of assumptions should be applied, thus only providing simple estimated for of the bulk airflow rates within a building, nonetheless these can still be useful.

Network modelling is based on the following assumptions; [1]

- Airflow through an opening is inviscid and incompressible
- Temperature within the zones does not change

Multizone airflow networks analysis is useful when analysing a building, since various openings to various zone will require a more realistic analysis. In network modelling, a building is represented by a grid formed by a number of nodes. Flow paths, which represent the openings link respective nodes which represent the rooms. Each and every node is attributed to a pressure value. As explained in section 2.4, there exists a direct relation between the airflow rate through a building and the pressure difference across the openings.

2.7.1 The Neutral Level

In network modelling, the airflow is bi-directional when it passes through large openings. When no wind is present, the lighter airflow will pass through the upper part of an opening due to density effects as explained in section 2.3.1. as a result to this, cooler, more dense air will pass through the lower part in the opposite direction. As a result, to this, a particular point, where no flow is presents, known as the neutral level, results. The neutral level is located at a distance H_{NL} from the ground. The location of this point, as seen in Figure 2.22, can be;

- H_{NL} > Top of opening (results in one-directional flow)
- H_{NL} < Bottom of opening (results in one-directional flow)
- H_{NL} between top and bottom of opening (results in bi-directional flow) [1]

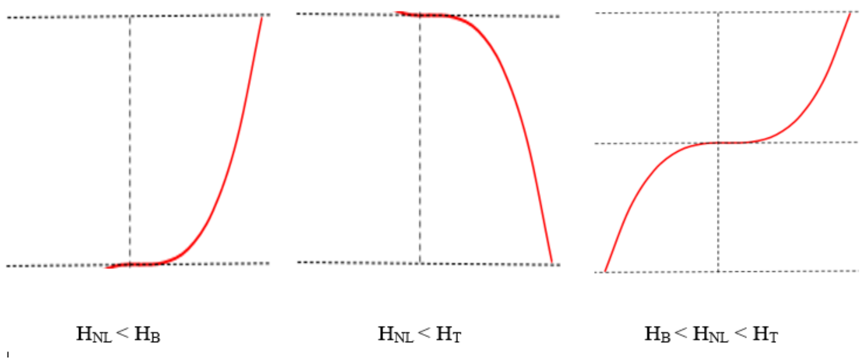


Figure 2.22. Flow direction and profile according to the Neutral Level position. Source: [1]

Following the knowledge of the neutral level, H_{NL}, the flow rates can be calculated accordingly by the integration of equations 2.33, 2.34, 2.35 [1].

$$Q_{lower} = \int_{HB}^{H_{NL_1}} C_d \sqrt{\frac{2(p_1 - p_2)}{\rho}} W\, dz \quad (2.33)$$

$$Q_{lower} = \int_{H_{NL_1}}^{H_{NL_2}} C_d \sqrt{\frac{2(p_1 - p_2)}{\rho}} W\, dz \quad (2.34)$$

$$Q_{lower} = \int_{H_{NL_2}}^{HT} C_d \sqrt{\frac{2(p_1 - p_2)}{\rho}} W\, dz \quad (2.35)$$

2.7.2 Mathematical approach to Network modelling

In network modelling, each building zone is represented by a pressure node and the outside environment is represented by boundary nodes. These nodes, as previously explained in section 2.6 are connected via flow paths such as windows, doors, shafts and even cracks.

According to this modelling approach, a building with N zones will have a network of N nodes. Applying the mass balance equation, equation 2.36, to a zone i with j flow paths results in the calculation of the unknown pressures. Q_{ik} is the volumetric flow rate from zone I to zone k and ρ_{air} is the density of the air in the flow direction [1].

$$\sum_{k=1}^{j} \rho_{air} Q_{ik} = 0 \quad (2.36)$$

Applying equation 2.36 to all the zones will result in a set of non-linear equations which calculate the internal node pressures. This system can be solved using the Newton-Raphson iterative method. For convergence to take place, a new set of pressure is derived by applying equation 2.38, with the pressure corrections [X] is defined for each iteration by equation 2.39. In equation 2.37, [J]is the Jacobian matrix (N X N) for the building under simulation and [F] is an N X 1 matrix with the residuals from the application of equation 2.36.

$$P_n^{k+1} P_n^k - X_n^k \quad (2.37)$$

$$[J][X] = [F] \quad (2.38)$$

The elements of the matrix are then calculated according to a modification of equation 2.37, given by equation 2.40 where Q_{nm} is the flow as a function of the pressure difference ΔP_{nm}.

$$f(P_n) = \sum_{m=1}^{N} \rho_{nm} Q_{nm} \quad (2.39)$$

$$\Delta P_{nm} = P_n - P_m \quad (2.40)$$

If $\Delta P_{nm} > 0$, then $Q_{nm} > 0$ and $\rho_{nm} = \rho_n$. This means that the air flow occurs from node n in a direction to node m, or outflow. On the other hand, if $\Delta P_{nm} < 0$, then $Q_{nm} < 0$ and $\rho_{nm} = \rho_m$ and the air flows in the direction to node n from node m, or inflow [1].

2.8 Zonal Modelling and CFD

Zonal Modelling and Computation Fluid Dynamics (CFD) modelling were developed with the idea of further subdividing the building volumes, applying equations associated with conservation of mass, energy and momentum to each sub volume to achieve temperature and velocity fields.

Zonal modelling is the intermediate approach between network modelling and CFD modelling. It is able to provide more detailed temperature and air velocity field results, but with a less complicated approach when compared to CFD. The basic principles associated with zonal modelling and the prediction of temperature and air velocity are:

- Dividing the are to be studied into several macroscopic subzones

- Establishing both mass and energy conservation equations or the identification of the main flows.

In Zonal modelling, both mass and energy conservation equations (section 2.8.2) are formulated per subzone. The approach to solving these equations can be either through a pressure model or through a temperature model. For the temperature model, an air movement model within the building is imposed. With regards to the pressure model, Bernoulli-like airflow equations can be introduced to account for the missing momentum equations [1], [22]

2.9 Opening Designs: Windows

Both window size and window design will have major effect on the air movement and in turn NV. Window designs can be classified in three distinctive types, which are most commonly incorporated into walls, these being;[1]

- Single opening windows (Figure 2.23)

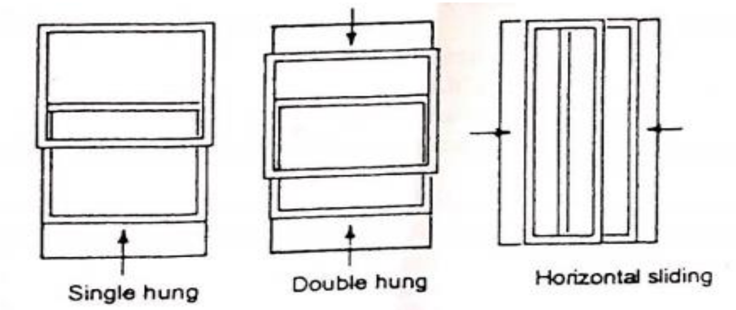


Figure 2.23. Single Openings window Types, Source. [1]

- Vertical-vane opening windows (Figure 2.24)

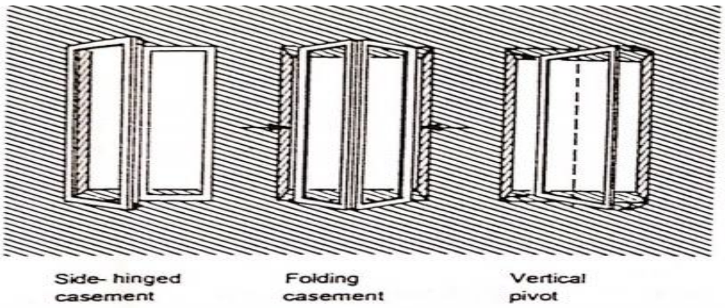


Figure 2.24. Vertical-vane opening Windows. Source: [1]

- Horizontal-vane opening windows (Figure 2.25)

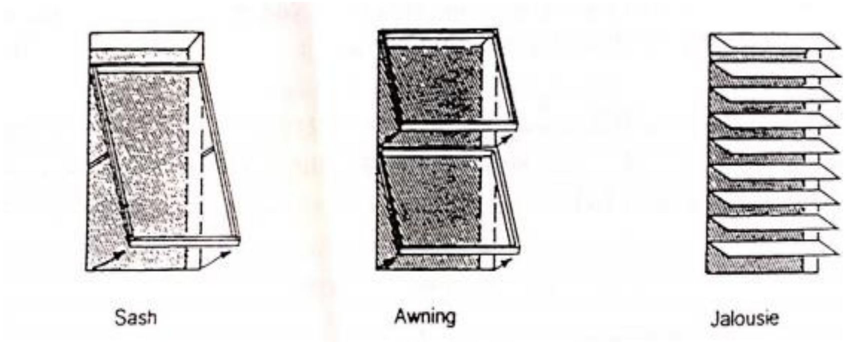


Figure 2.25. Horizontal-vane opening windows. Source: [1]

2.9.1 Airflow pattern through windows on walls

2.9.1.1 Simple Openings

Simple openings, much of the time, have no effect on the air flow's speed or pattern, expect when the airflow is close to the window. A double-hung window will allow the designer to select the airflow's height, whilst a horizontal sliding window will reflect the airflow placement within the rooms.

2.9.1.2 Vertical-vane openings

Vertical-vane designs play a role in both the pattern and velocity of the air flow entering a building. The most common window design of this type is the side-hinged casement, with such design having a wide variety for airflow control. The airflow pattern will depend on the unit type, operational position of the sashes and the opening type. Figure 2.26, schematically show an example of an airflow pattern through an in-swinging double side-hinged design for both a fully opened and partially opened condition [1].

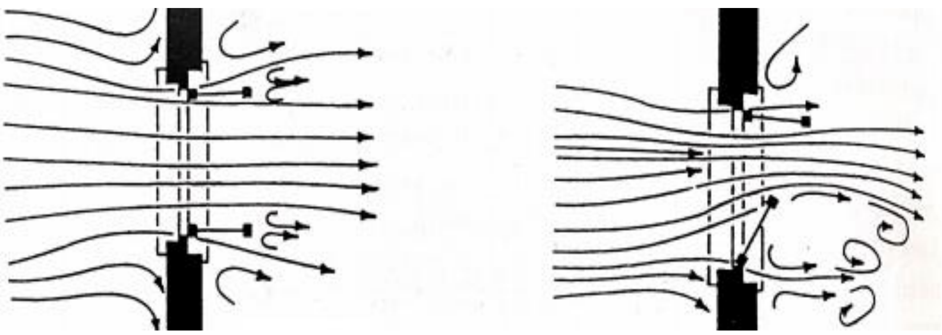


Figure 2.26. Airflow pattern though a fully open window (Left) and partially open (Right) in swinging double casement. Source: [1]

2.9.1.3 Horizontal-vane openings

With a horizontal-vane opening design, the influence on both the velocity and pattern air flow movement is mainly on the vertical direction. With both a projected sash and horizontal-pivot window the airflow is directed upwards. With regards to a Jalouise design, the airflow direction can be directed both upwards and downwards depending on the sashes' positions.

2.9.2 Natural ventilation airflow calculations for different window configurations

The airway flow-rate configuration will depend on the opening area, the discharge coefficient of the opening/s and the pressure differences. The most common opening types for natural ventilation are the bottom-hung or the side-hung windows.

Geometry for such openings tends to be complicated, and therefore simple analytical calculations were derived to have an estimate of the desired parameter which are given by equations 2.47 and 2.49. the coefficient of discharge, C_d can be assigned the value of a sharp-edged orifice, between 0.60-0.65 according to BS 5925 [23].

For bottom hung windows, equation 2.47 can be used to calculate the flow effective, A_{eff}. The effective height, H_2 is given by equation 2.49. For a side hung window, equation 2.49 can be used where as before, A_{eff} is the effective window cross-sectional area and the effective height H_2 is equal to h. For both calculations, α gives the tilt angle [23].

$$A_{eff} = \sqrt{\frac{1}{\frac{1}{(w \cdot h)^2} + \frac{1}{\left(2 \cdot w \cdot h \cdot sin\left(\frac{\alpha}{2}\right) + h^2 \cdot sin(\alpha)\right)^2}}} \quad (2.41)$$

$$H_{eff} = \frac{A_{eff}}{w} \quad (2.42)$$

$$A_{eff} = \sqrt{\frac{1}{\frac{1}{(w \cdot h)^2} + \frac{1}{\left(2 \cdot w \cdot h \cdot sin\left(\frac{\alpha}{2}\right) + w^2 \cdot sin(\alpha)\right)^2}}} \quad (2.43)$$

2.10 Wind Catcher

The use and purpose of a wind catchers have been the same for a long time, that to provide comfort inside a building. The main idea behind a wind catcher is to provide cool air into the building, whilst exhausting the warmer air. In warm countries, wind catchers were used in conjunction to courtyards to provide fresh air inside the building promoting cooler air, and NV. Several modern designs are nowadays wildly used, and with the inclusion of a mechanical component can even provide air temperatures 4-5º. [20], [24]

Wind catchers are ideal when it is required to move a copious quantity of air inside large buildings, and this can be done by providing an inlet to air in all directions. Figure 2.27 shows an example of a wind tower design and installation in Dubai, UAE. [20]

Both tower and internal walls are constructed from a material able to absorb the heat during the day whilst releasing it over the night. This would in turn warm the cool night air in the tower. By convection, the warmer air will rise and this creates a draft which is exhausted through the openings at the top. The pressure difference will then ‘pull’ the cooler air down and into the building. When no wind acts on the tower, this can act as a chimney when the cool night air enters the tower in no wind presence whilst also forcing it down into the structure.[20]

Figure 2.27. Wind towers design in Dubai, UAE. Source: [20]

2.11 Indoor Air Quality and Thermal Comfort- Directives and Legislations Associated with Buildings

2.11.1 Energy Performance of Building Directives 2010/31/EU

The Energy Performance of Building Directives (2010/31/EU), highlights the importance of achieving a target of reducing the overall greenhouse gases by 20 per-cent by the year 2020. In this directive, amongst others, there is a mention of how the buildings account for 40per-cent of the total energy consumption in the EU. An increase in use of renewable energies would aid in achieving this goal. The European council of 2007 highlighted the importance of increasing the energy efficiency to reach the 2020 target. Nonetheless, whilst carrying out energy efficiency improvements, the location and climatic conditions should be always kept in mind. The necessity of heating and cooling systems in particular locations in order to achieve thermal comfort should never be ignored [25].

2.11.2 Energy Efficiency Policies in Malta

Table 2.8 gives an overview of the energy efficiency policies in Malta with the aim of improving the energy efficiency. The two highlighted campaigns would make use of NV systems study as means to which energy efficiency can be improved.

Table 2.8. Energy Efficiencies Policies in Malta. Source: [26]

Title	Status	Type	Starting Year
Information Campaigns	Ongoing	Information/Education	2008
Definition of Energy Prices	Ongoing	Legislative/Normative	2009
Energy saving measure in social housing	Ongoing	Financial, Information/Education	2010
MRA Solar Water Heaters	Ongoing	Financial	2011
MRA Roof Insulation and Double Glazing	Ongoing	Financial	2012
Energy Audits for households	Proposed (medium/long-term)	Financial, Information/Education	2013
MRA PV scheme for Domestic Sector	Ongoing	Financial	2013
EU-related: Energy Performance of Buildings (Directive 2002/91/EC) – Energy Efficiency in Low Income Housing in the Mediterranean	Ongoing	Financial	2013
Domestic wells/cisterna restoration scheme	Ongoing	Financial	2013
Feed in Tariff Scheme	Ongoing	Financial	2013

Catch the Drop Campaign	Ongoing	Information/Education	2014
MIP PV Panels Scheme	Ongoing	Fiscal/Tariffs	2014
GRTU PV Panel for Domestic Sector by Soft Loans	Ongoing	Financial	2014
Rebates on investments in energy efficiency by domestic consumers	Completed	Financial	2006
Provision of advisory services for domestic customers	Completed	Information/Education	2007
Promotion of Compact Fluorescent Lamps	Completed	Financial	2009
Support Scheme to Promote the Domestic Use of Compact Fluorescent Lamps	Completed	Financial	2009
Soft Loans from Banks	Completed	Financial	2012

2.12 Chapter Conclusion

Sections 2.7, 2.8 and 2.9 explored different methods, both analytical and numerical in which NV problems could be tackled. This study was beneficial in order to better understand the potential that ventilation, along with wind flow or wind velocity has. Different designs, such as windows or the wind catcher were briefly discussed in section 2.10. These components, or anything similar, are an essential aspect in any building which aims at improved energy efficiency through NV.

This individual project will be mainly looking at one modelling method, Network Airflow Models by the use of the ESP-r software package. As can be seen by the summary given in Table 2.9, this method could be accurate, highly cost effective, could be used to model complex geometries and time saving. It does however lack result detail. The analysis to be carried out on the results will mainly discuss the zone dry bulb temperature and in some instances the PMV. By comparing different results achieved from different parameters, the importance of NV should be clearly highlighted.

Table 2.9. Ovrview of Methods that can be applied to estimate Natural Ventilation in building. Source:[1], [22]

Method	Accuracy	Cost	Complex Geometries	Result Detail	Time
Analytical and Empirical	×	✓	×	×	✓
Network airflow models	✓	✓	✓	×	✓

CFD	✓	✓	✓	✓	✕
Small-scale experiments	✓	✕	✓	✕	✕
Full-scale experiments	✓	✕	✓	✕	✕

Summative Points

- A number of barriers could limit the use of Natural ventilation.
- Natural Ventilation can occur via two driving forces: Wind effect and Stack effect
- Natural Ventilation can be either Single-sided or Cross-Ventilated depending on the location of inlets and outlets in the zone.
- Natural Ventilation can be modelled using 4 distinctive Models: Empirical, Network, Zonal Modelling and CFD.
- Night flush cooling can be an effective way to reduce energy usage during the day to keep thermal comfort at an adequate level.

3. PRELIMINARY ASSESMENT ON ENERGY, INDOOR AIR QUALITY & THE BUILDING STOCK IN THE MALTESE ISLANDS

3.1 Introduction

This chapter gives a brief overview of the Maltese Islands and also includes a study carried out by the author in order to analyse the housing situation along with energy consumption. The scope for this study was to highlight the importance of implementing natural ventilation to meet targets set by the law, such as improving the energy efficiency in buildings.

3.2 The Maltese Islands

Having a co-ordinate location of 35.9375° N, 14.3754° E, the Maltese Island can be described as being located in the centre of the Mediterranean. The location can be seen in Figure 3.1. The Maltese Islands are subjected to Mediterranean climate characterized by warm summer days and chilly winter nights. As show in Figure 3.2 Malta is divided into six different regions and have a population of circa. 430 thousand [27].

Figure 3.2 Districts of Malta. Source: [49]

Figure 3.1. Location of the Maltese Island. Source [48]

3.1.1 The Maltese Climate

Malta is subjected to a climate characterised by warm summers and cooler winters. Spring and Autumn days are characterised by cool breezes and with lower temperatures and high humidity levels. The high humidity will result in very cold buildings during the winter season, and in return very high temperatures during the summer period. These conditions create a major thermal performance problem in the Maltese households and buildings. Table 3.1 tabulates the Average Outdoor Temperature per Month in Malta in ºC [26], [27].

Table 3.1. Average temperatures per Month in Malta and Gozo. Source: [26]

Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
12.2ºC	12.4ºC	13.4ºC	15.5ºC	19.1ºC	23.0ºC	25.9ºC	26.3ºC	24.1ºC	20.7ºC	17.0ºC	13.8ºC

3.3 Maltese housing and occupants Study

An electronic questionnaire was set up and distributed amongst Maltese residents with the purpose of achieving a greater understanding of the climatic problems and thermal performance associated with buildings in Malta and Gozo. The results were also useful to get a better understanding on the issues that should be tackled in this dissertation and set up a project definition.

3.2.1 Questionnaire Results: House Type

Figure 3.3 shows a bar chart comparing the results from the questionnaire with regards to the house type. This bar chart also shows the results which were obtained by a census carried out by the Maltese government during the year 2011. These results show that the sample collected can be trusted and gives a good representation of the housings in Malta.

The results from the Census can be seen tabulated in Appendix A, Table A.1 which tabulates a number of dwelling types, stock and quantity as per the census carried out in 2011. One fifth of the vacant properties being holiday houses and the rest unoccupied. Being only used during the warm summer months, investment in improving energy efficiency in summer houses may be not as common [26], [28].

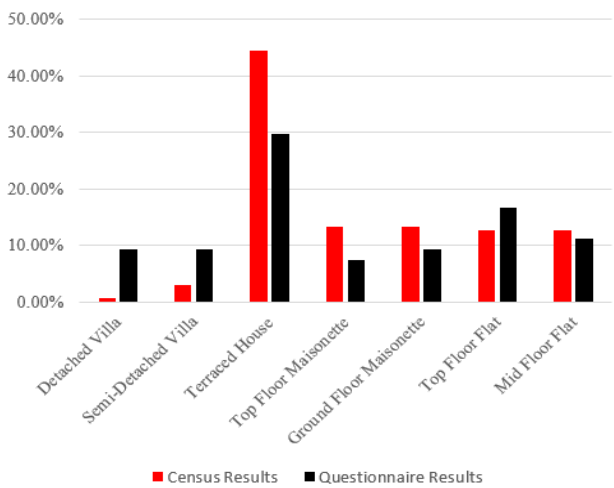


Figure 3.3. House Stock in the Maltese Islands. Source: Author, [28]

Over a quarter of these reside in a Terraced house. The second most common house type resulting from this questionnaire was a flat, followed by a semi-detached. There is a large discrepancy between Ground floor maisonette and 1st floor maisonette, as these should be either equal or the ground floor maisonettes should be higher in number. This discrepancy shows that the questionnaire, although useful in some means is not highly reliable as the sample was not vast enough.

The building regulations office give better overview of the Maltese Building Stock. Houses built in the 17th Century commonly occupy the Maltese Islands. These are more likely to be used as offices, museum or cultural centres, rather than as a residential home. These were fashionably build around a courtyard with rooms surrounding this. The most common households were built between during the British colonial period (1800-1964). These occupy around 40per-cent of the building stock in Malta. The construction industry got a boost thanks to the rapid economic growth, with the 70s and 80s seeing a construction in a number of separate house units. The most common house type is the terraced house, with a range between 150-200 square metres. The houses are very often un-insulated, even though they are characterised by a high thermal mass and cavity external walls. The 90s saw a rise in sustainable multi-swelling houses due to the limited development area available, giving a boost to flats. The early 2000s were a result to a construction boom, since housing was being seen as an investment [26].

3.2.2 Questionnaire Results: Energy Performance of a Maltese Building

To my surprise, being the perfect location to make use of solar panels, only 41per-cent of the respondents make use of these. Reasons for not having set up solar panels vary, with the most common reason being their uncertainty of pay back. With regards to solar water heaters (SWH), only 33 per-cent make use of these. Once again reasons for not installing SWH vary with the main reason being that warm water will be 'useless' during warm summer days. Figure 3.4 show graphically the results achieved.

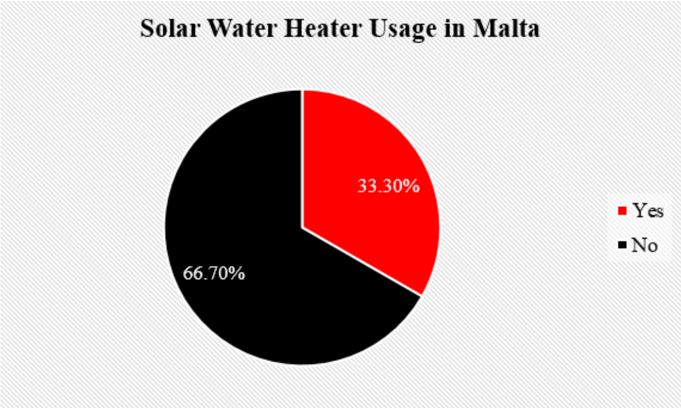


Figure 3.4. Result from questionnaire: SWH usage in Maltese Dwellings.

Figure 3.5 gives an overview of the respondent's monthly electricity bill. The majority pay between €50.00 - €100.00 per month. Unexpectedly, a low percentage pay €200.00 which is extremely high, and this shows that some people are not educated enough with regards to energy efficiency and the benefits of installing renewable energy generation sources, such as a solar panel or a SWH.

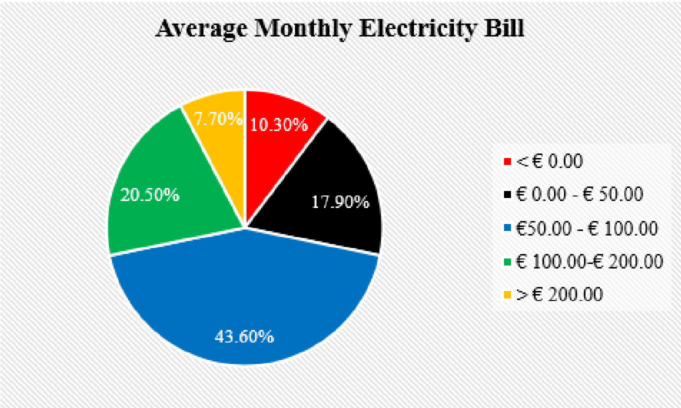


Figure 3.5. Results from questionnaire showing the average monthly electricity bill

Following a study by Sandro et al, the line graph in Figure 3.6 shows the unit consumption of electricity of a household in Malta per dwelling in kwh/dwelling. A clear trend can be observed where there is an increase in consumption from the year 1990.

Energy performance in Buildings was discussed by the Building Regulation Office in 'Nearly-Zero Energy Building in Malta. Table 3.2 and **Error! Reference source not found.** give a brief overview of the energy requirement per house/office characteristics in Malta and Gozo. It is important to point out that the stock of buildings increased from 137,000 in 2007 to

Figure 3.6. Electricity usage of households per dwelling in kwh/dw. Source [28]

167,000 in 2013 [26].

Table 3.2. Energy Requirement per house in Malta according to [26]

Reference Building	Building according to Current minimum requirements (kWh/m²yr)	Cost-optimal level without Solar Renewable sources (kWh/m²yr)	Gap between current requirement & cost-optimal level without solar renewable sources (kWh/m²yr)	Difference per-cent
Detached Villa	94	68	26	28
Semi-Detached Villa	84	64	20	24
Terraced House	82	63	19	23
Top floor maisonette	97	102	-5	-5
Ground floor maisonette	127	115	12	9
Top floor flat	125	92	33	26
Mid-floor flat	117	84	33	28
Average	103.7	84.2	19.7	19

3.2.3 Comparism of Malta with other EU Countries

Over 66 per-cent of consumption in the EU is generated in Residential buildings as opposed to Tertiary buildings. This is visualised in the bar chart in Figure 3.8. this data shows that importance should be given to the building industry if the aim is to achieve an overall higher energy efficiency, and reach the set targets in terms of energy consumption. As seen clearly in Figure 3.7, energy usage was reduced after the year 2008, showing that energy efficiency was being given more importance since this time – with Malta registering the highest energy reduction per dwelling compared to all the EU countries.

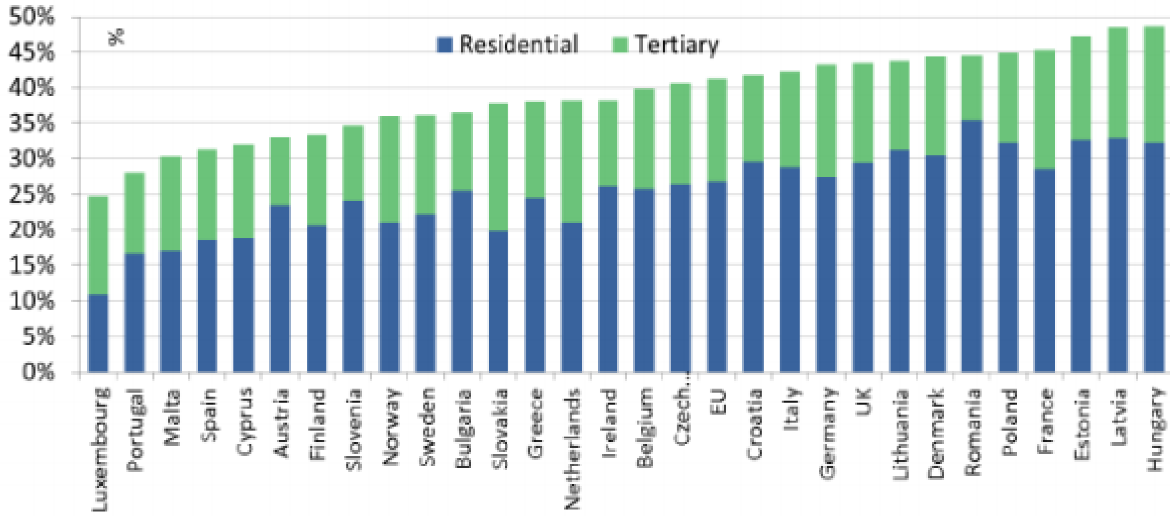


Figure 3.8, Final Energy consumption in buildings, Source: [28]

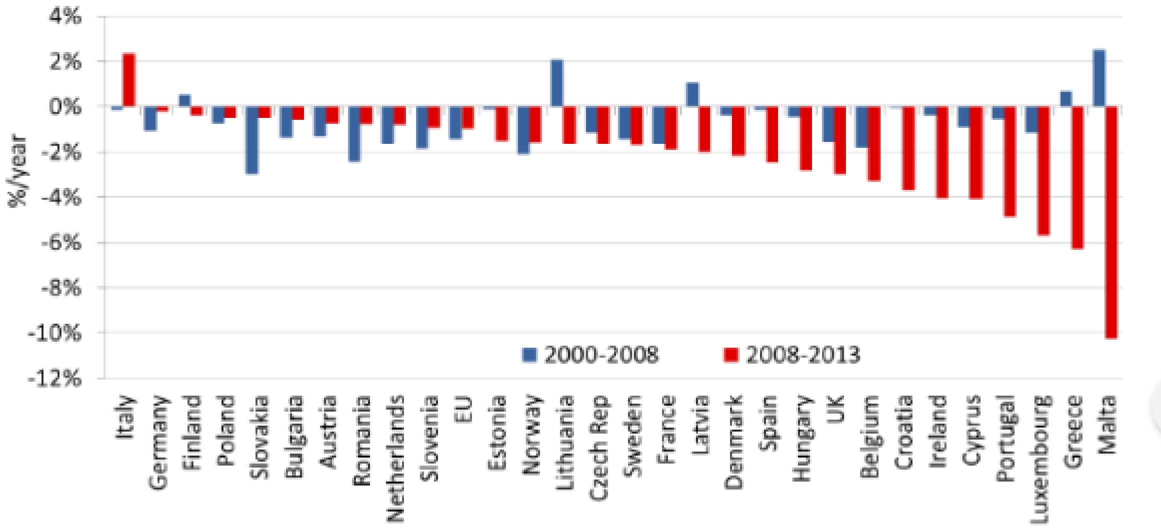


Figure 3.7 Energy Usage throughout the years, Source: [28]

3.4 Conclusion

Energy performance in buildings was never given utmost importance in the past, mainly due to the mild climate. As a result, the first energy performance regulation in the Maltese Islands was set up in 2007. As per the legal notice 376 of 2012, new and renovated buildings need to exercise a set of minimum energy, with the aim of achieving a Nearly Zero-Energy Building (NZEB). This will all be according the Directive 2010/31/EU [28].

One way to improve energy performance in a building is by the introduction of NV. From this questionnaire, it became evident that people are not educated enough with regards the potential of exploiting environmental benefits in their favour, such as the sun and use of solar panels or solar water heaters. The media constantly tries to promote alternatives such as HVAC systems in order to improve comfort. Although such systems will be more than required at certain times, these could be avoided in others.

The chapters to come will study the potential of NV through different apertures in order to improve the energy efficiency of a particular Maltese households.

Summative Points

- Energy use in building accounts for a large proportion in overall consumption in the EU.
- The questionnaire showed that Maltese citizens can lack knowledge when it comes to energy efficiency and lack the idea of a payback period when it comes to savings associated with energy systems such as solar panels.
- Maltese housings use more energy than that predicted.
- Thermal sensation is a totally subjective feeling which can be easily improved by small changes, such as improving the clothing depending on whether one is feeling cold or warm.
- Natural Ventilation can be applied to housing in the Maltese Islands to improve energy efficiency.

4. DESIGN DOCUMENTATION

4.1 Introduction

The house which will be modelled and analysed was built in the 1980s and was later modified in the year 2015. The google street view with house co-ordinate location being 35.87 and 14.44 can be seen in Figure 4.1. Figure 4.1 also gives an idea of a typical Maltese village, and an idea of the house design which is most commonly found.

Figure 4.1. Street view of house location.

4.2 House Design and Documentation

Figure 4.2 shows the original ground floor architectural drawings of the building and the new designs with the different zones in the ground floor to be modelled clearly indicated.

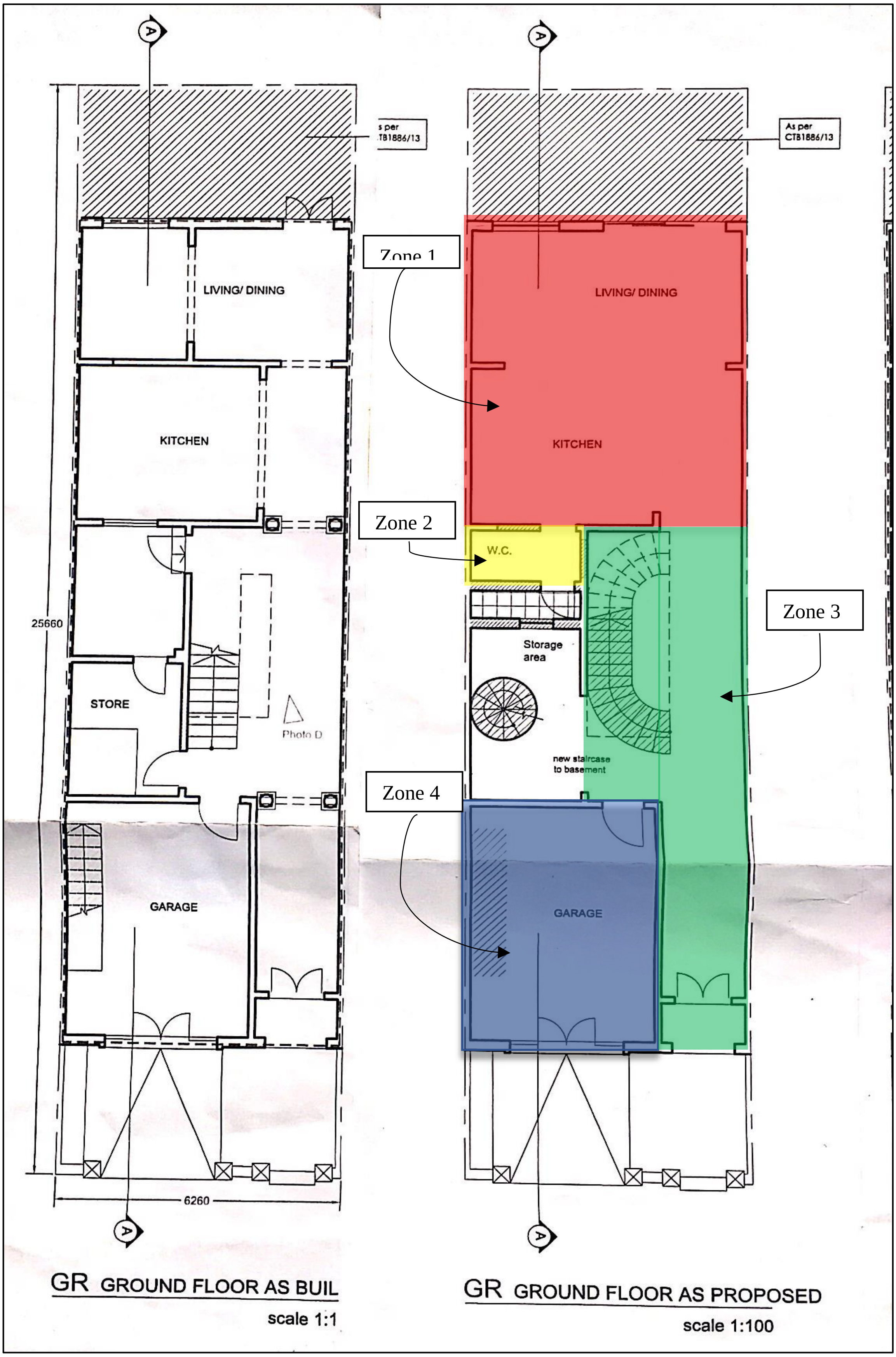


Figure 4.2. Architectural Plans of building before and after Alterations

4.3 Weather Data

The in-built weather data for Palermo 2001 was used throughout the simulations since this is very similar to the Maltese climate. Palermo is a place in Sicily which apart from being a small island, it also located in the centre of the Mediterranean. The co-ordinate for Palermo are 38.1157° N, 13.3613° E; very close to Malta. Figure 4.4 show the annual ambient temperature of the region, and indicated by the blue square is the month of August, which is one of the warmest months. Figure 4.3 shows the climatic data, mainly the ambient temperature and wind speed recorded for the month of August. The highest ambient temperature recorded is 30ºC and the lowest is 23ºC.

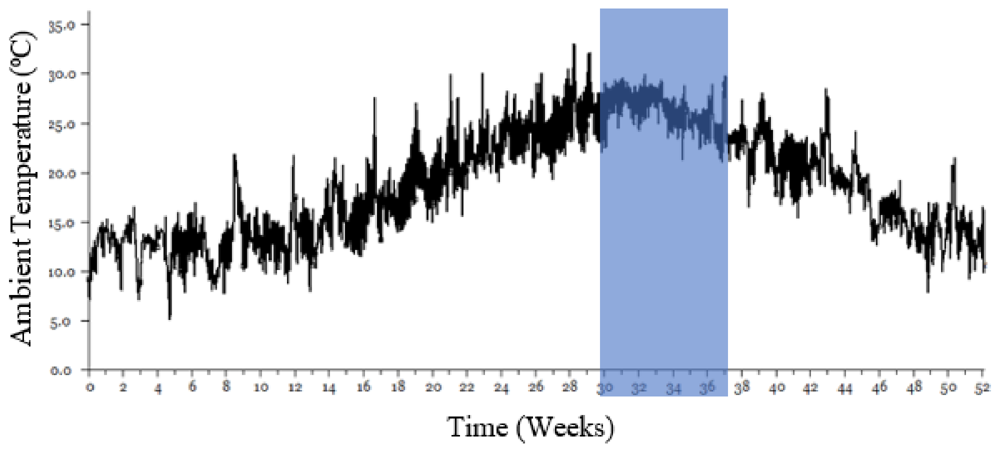


Figure 4.4 Ambient Temperature

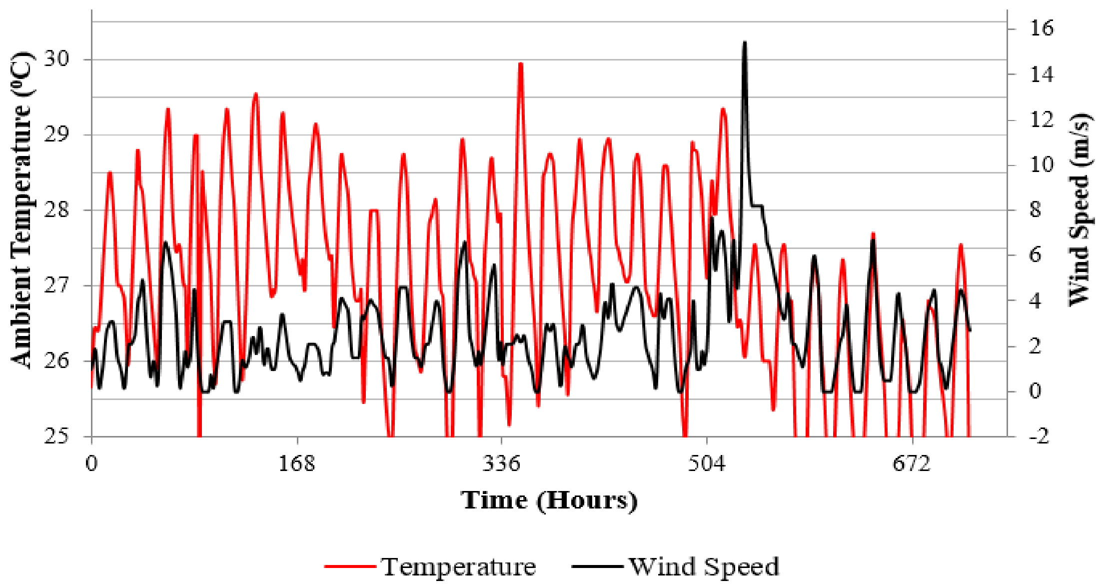


Figure 4.3 Weather Data used in Simulation

4.4 Accuracy in the Simulation and Result Analysis

Validation is an essential process in any modelling and analysis process. Due to time and resources limitations, validation of the modelling was limited in this individual project. Future work can include better validation techniques, such as measuring the temperatures within the building under different conditions and/or or simulating different models using different software packages and then comparing all the gathered data.

Throughout the completion of this individual project, special attention was given to the parameters which were modelled using ESP-r to assure more realistic and accurate results. The following are the steps followed for the completion of every simulation:

4.4.1 Model Dimensioning and Sketching

The first step carried out during the modelling included the sketching and dimensional input of the drawing/plan. This was done by carefully understanding and measuring the architectural plans previously shown in Figure 4.2. This was done to first and foremost facilitate the process for geometry creation in ESP-r. Figure 4.5 shows one of the sketches done with clear reference to all openings and co-ordinates of the zones.

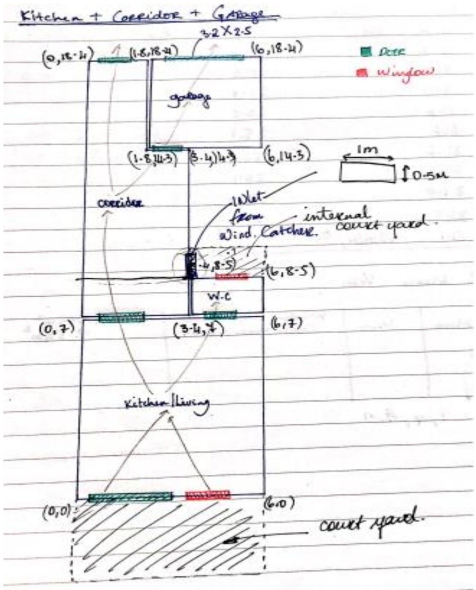


Figure 4.5. Ground Floor Sketch and Dimensioning

4.4.2 Material and other Parameters Listing

Having a well-detailed list and description of all the materials used during the construction of the actual building is important to ensure more accurate simulations. An overview of the materials used in the simulation can be seen in Appendix A, Table A.2 These properties where used within the simulation model to achieve more accurate results when the model is run. Many of the materials used were found in-built in the software itself, when no information or detail was found, material properties were manually entered [29]–[33].

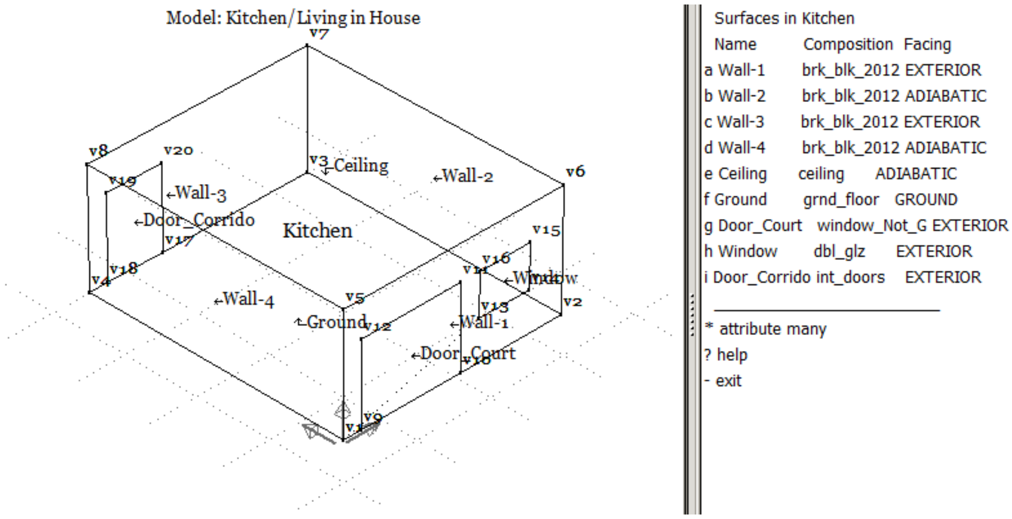


Figure 4.6. Snapshot from ESP-r showing the attributes during the Kitchen/Living Zone Modelling

4.4.3 Composition-Geometry and Attributions

Using the software feature to build a model from scratch, the CAD drawing was created, attributing all the material properties and boundary conditions to simulate accurately. As can be seen in the street views in Figure 4.1, the construction of the house is in a way that it touches the adjacent buildings. This was modelled using the adiabatic function, to simulate no heat flow. Walls facing externally, such as the façade, were modelled using the Exterior function. Figure 4.6 shows a snapshot for the attributes associated with the Kitchen/Living Zone modelling.

4.4.4 Composition – Operational Details

A table which lists the timing and operational gains used in the simulation can be viewed in Appendix A, Table A.3. These values listed are according to the CIBSE Guide A Chapter 6 'Internal heat gains' A list of assumptions was completed after a brief interview with the owners of the property, questioning about their lifestyle. Figure 4.7 shows the operational gain graph generated by ESP-r for the kitchen/living area [34], [35].

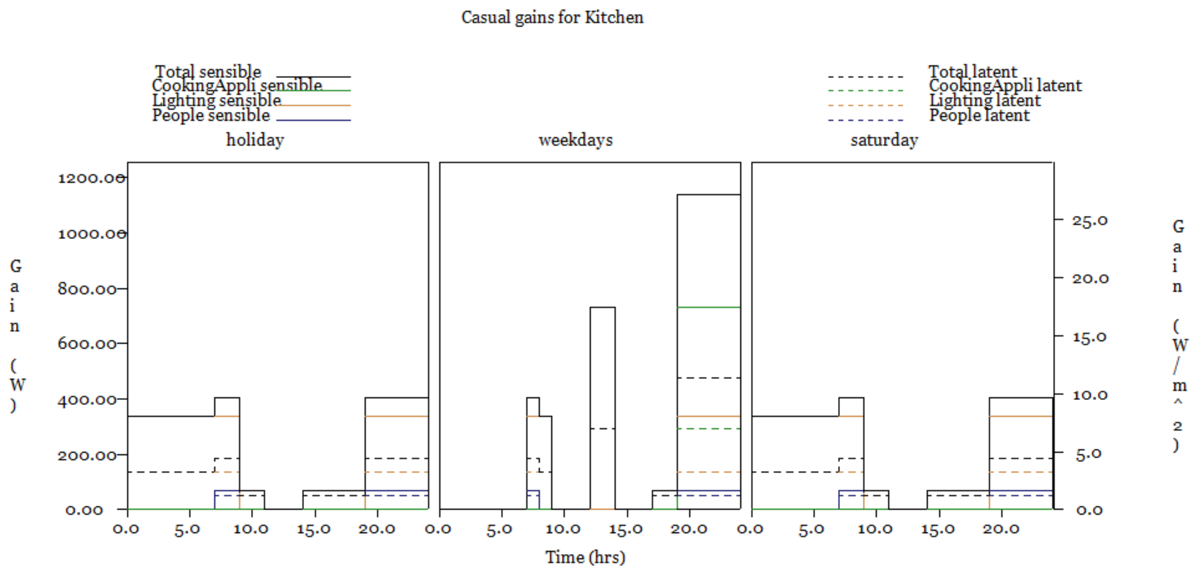


Figure 4.7 Casual gains within the kitchen/living area for human occupancy

4.4.4.1 Casual Gains Modelling Assumptions

- Common working hours on week days
- Cooking in oven or on stove will take an average of 4 hours per day
- Lights will be off between 07:00 and 19:00 every day
- Occupants will be sleeping between 00:00 – 07:00 every day
- 3 hours doing errands on weekends
- Occupants Sensible and Latent heat is based on a temperature of 24^o, seated and doing very light work
- Zones which will not be frequently used, (e.g. bathrooms and corridors) will have no Casual gains assumed/associated to them

4.4.4.2 Cooking Appliances Casual Gains

The rate of sensible heat gain for cooking appliances can be calculated using equation 5.1 where Φ_h is the rate of sensible heat gain in watts and accounts to approximately 60 per-cent of the heat loss, F_r is the radiation factor which is dependent on the appliance type and fuel used and F_u is the usage factor. Φi is the manufacturer's input rating Table 4.1 tabulates the parameters used for the calculations [35].

$$\Phi_h = F_r(F_u \times \Phi_i) \quad eqn. 5.1$$

Table 4.1. Casual Gains for the Kitchen/Living Zone

Appliance	Radiation factor, F_r	Usage factor, F_u	Input Rating, Φ_i (W)	Sensible heat rate, Φ_h (W)
Electric Oven [35]	0.17	0.42	3600	**257.04**
Electric hobs [36]	0.45	0.16	6600	**475.2**

4.4.5 Air Flow Network

Implementation of the air flow network is perhaps one of the most important step to generate an accurate simulation for natural ventilation. Table A.4 Network Flow Criteria in Appendix A tabulates the nodes associated to the zones. As discussed in section 2.5.1, the pressure effect on the building play a major influence on the wind acting on the building, and in turn have a major effect on the flow. ESP-r gives the user the possibility to select the exposure that the zone facade/node has with respects to the outdoor environment when a boundary node of wind induced pressure is selected to represent the outside of the zone. The software has included a common file for wind pressure coefficients at 22.5-degree intervals which allow the user to associate them with wind pressure boundary nodes. Figure 4.8 shows a snapshot from the software where the user is asked to select the properties for a boundary node. The highlighted options show the most common selections used in this modelling [19].

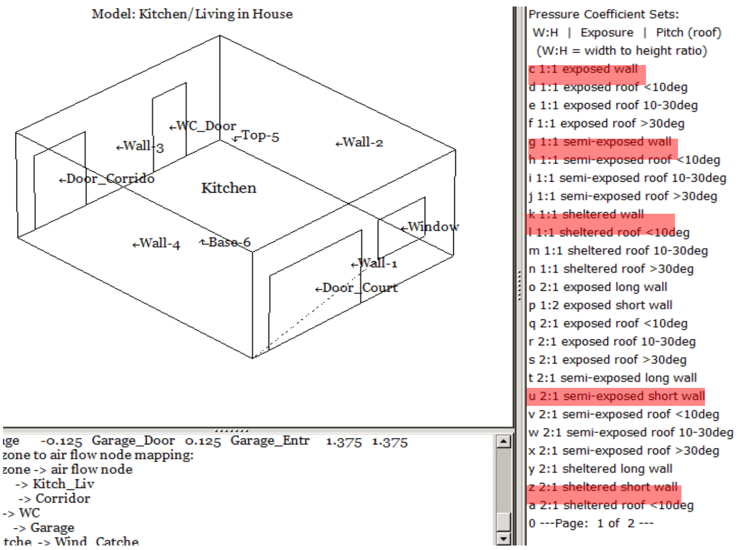


Figure 4.8 Wind induced internal nodes for Network Flow properties

Whilst creating and modifying the airflow network, the user is asked to define a list of components that make up the system prior to creating the connections. Table 4.2 gives an lists of the components which make up the system (Ground floor components). Figure 4.9 is the list of properties which are inbuilt in the software and allow the user to choose and enter the properties, with the component types used in the simulation highlighted in red. With regards to apertures such as door or windows, the user is required to input data such as the discharge coefficient apart from the apertures size. Most of the apertures were set to be Bi-directional flow components (130), with its use suggested for doors and windows which are door shaped where temperature and pressure difference results in a two-flow direction. The discharge coefficient for all apertures was set at 0.6, as explained in section 2.10.2 and as suggested by the BS 5925 in. section 6.3 analyses an added aperture with a mesh. For this model, a different calculated coefficient of discharge was used to model the fineness of the mesh [23], [19].

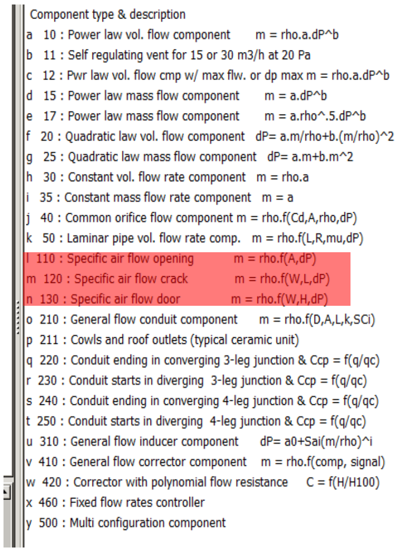

Component type & description
a 10 : Power law vol. flow component m = rho.a.dP^b
b 11 : Self regulating vent for 15 or 30 m3/h at 20 Pa
c 12 : Pwr law vol. flow cmp w/ max flw. or dp max m = rho.a.dP^b
d 15 : Power law mass flow component m = a.dP^b
e 17 : Power law mass flow component m = a.rho^.5.dP^b
f 20 : Quadratic law vol. flow component dP= a.m/rho+b.(m/rho)^2
g 25 : Quadratic law mass flow component dP= a.m+b.m^2
h 30 : Constant vol. flow rate component m = rho.a
i 35 : Constant mass flow rate component m = a
j 40 : Common orifice flow component m = rho.f(Cd,A,rho,dP)
k 50 : Laminar pipe vol. flow rate comp. m = rho.f(L,R,mu,dP)
l 110 : Specific air flow opening m = rho.f(A,dP)
m 120 : Specific air flow crack m = rho.f(W,L,dP)
n 130 : Specific air flow door m = rho.f(W,H,dP)
o 210 : General flow conduit component m = rho.f(D,A,L,k,SCi)
p 211 : Cowls and roof outlets (typical ceramic unit)
q 220 : Conduit ending in converging 3-leg junction & Ccp = f(q/qc)
r 230 : Conduit starts in diverging 3-leg junction & Ccp = f(q/qc)
s 240 : Conduit ending in converging 4-leg junction & Ccp = f(q/qc)
t 250 : Conduit starts in diverging 4-leg junction & Ccp = f(q/qc)
u 310 : General flow inducer component dP= a0+Sai(m/rho)^i
v 410 : General flow corrector component m = rho.f(comp, signal)
w 420 : Corrector with polynomial flow resistance C = f(H/H100)
x 460 : Fixed flow rates controller
y 500 : Multi configuration component

Figure 4.9 List of Component Properties

Table 4.2. Flow Network Components

Component	Description
Door_Court	Specific air flow door
Window_Court	Specific air flow opening
Door_Corridor	Specific air flow door
Door_WC	Specific air flow door
Window_WC	Specific air flow opening
Entry_Door	Specific air flow door
Garage_Door	Specific air flow door
Door_gar	Specific air flow door

A wind reduction factor of 0.58 was used throughout the simulation since the house is located in an urban environment. Table 4.3 summarises the relationship between wind speed and wind reduction factor, which is set as 0.58 in all cases [19].

Table 4.3. Roof height wind speed and wind reduction factor for an Urban environment, Source: [19]

Meteorological Wind Speed (m/s)	Wind Reduction Factor	Roof Height Wind Speed (m/s)
1	0.58	0.58
2	0.58	1.16
5	0.58	2.9
10	0.58	5.8

4.4.6 Simulation and Result Analysis.

The simulation was run using the 'run silently' feature on the software after specifying the weather location, year and specific months for which the simulation is to be run. The majority of the results were based on the hottest month of the year, August and analysis was done for the whole month or for the first week to have a more accurate insight of what is happening. This was done since a pattern could have been observed for the whole month where the highest and lowest temperatures were being recorded to closely the same time of the day.

The results generated by ESP-r were exported into a .CSV file and then were analysed using Microsoft excel. This made the analysis simpler since all the data was more easily readable and modifiable. The formatted excel sheets with the results can be seen in Appendix C.

4.4.6.1 Zone Dry Bulb Temperature

A graph for the DBT for each simulation was analysed. This result will be a clear indication of the realistic temperature conditions in a Maltese house due to the high humidity levels, thus the Wet Bulb temperature (WBT) will have a similar value to the DBT.

4.4.6.2 Predicted Mean Vote

As explained in section 3.2.4, the PMV is a predicted vote in the range of -3 to +3. The software based its result on the assumption of the occupants constantly in the room in order to understand how the sensation will vary by time, and by thermal conditions in the zones. It was assumed that the occupants have a clothing level of 0.7 and have an activity level of $70W/m^2$, which is based on the idea of the occupants being standing and/or relaxed as indicated in Table 4.4 [37].

Table 4.4. Metabolic rate associated with different activities. Source: [37]

Activity	Met	Wm^{-2}
Lying down	0.8	47
Seated quietly	1.0	58
Sedentary activity (office, home, laboratory, school)	1.2	70
Standing, relaxed	1.2	70
Light activity, standing (shopping, laboratory, light industry)	1.6	93
Medium activity, standing (shop assistant, domestic work, machine work)	2.0	116
High activity (heavy machine work, garage work)	3.0	175

All the results were compared with the ambient temperature, wind velocity and the effect of casual gains and solar gains in order to have a better understanding of what was happening, and why the results were varying.

Summative Points

- Having a well-planned design documentation improves time efficiency in delivering optimal and accurate results.
- The zone temperature will be the main criteria to be analysed, this will be mainly compared with the ambient temperature.
- Actual validation of the obtained results can be hard to get due to the location and tie restriction. To overcome this, special attention was given to obtain the correct data and input the correct data into the software.
- Validation will also be carried out by comparing the results obtained from the siulations with available literature.

5. ANALYSIS OF NATURAL VENTILATION ON THE EXISTING DESIGN

5.1 Introduction

Chapter 5 analyses the natural ventilation on the current design for the different zones. The simulations and analysis were carried out in a number of steps. Initially only one zone, the Kitchen/Living area was modelled and analysed. The results from this simulation were thoroughly analysed and patterns were observed. The results were an indication to whether the software and model were correctly set up. The Dry bulb temperature (DBT) and the PMV were the main results analysed to obtain an indication of the effect of in built natural ventilation systems, such as aperture areas, and location.

Following the Kitchen/Living zone analysis, the entire ground floor was modelled and the operational details were modified accordingly as explained in chapter 4. This model was also helpful to understand whether the flow network was correctly designed. The results obtained for the kitchen/living zone in the full ground floor model varied slightly since the zones are now linked and a higher volume to better distribute the operational and solar gains exists. Finally, an analysis of the entire building was carried out giving most importance to analysis for the bedrooms as these will have the major influence on the occupants during the night. A simulation to study the effect of opening the apertures at night and/or during the day (night purge ventilation) have on the DBT results was also carried out in this chapter, in section 5.7.

5.2 Solar Gains

The result analyses carried out throughout sections 5.3-5.6 often see the use of the term Solar gains. Figure 5.1 graphically shows the solar gains for the different building zones which have an aperture build registered during the first week of August. The trendlines for each zone follow a similar pattern in which the solar gain peaks at mid-day and reaches a minimum of 0 watts during the night. Having the largest apertures, the kitchen/living and bedroom_1 zone registered the highest values peaking at over 1300 watts.

As can be seen from in Figure 5.2, a relationship exists between the aperture size and maximum value of solar gain in the zone. This in term would affect the DBT inside the zone, and as discussed a number of times, the kitchen/living zone reaches extremely high temperatures during simulations in which the apertures are modelled as closed.

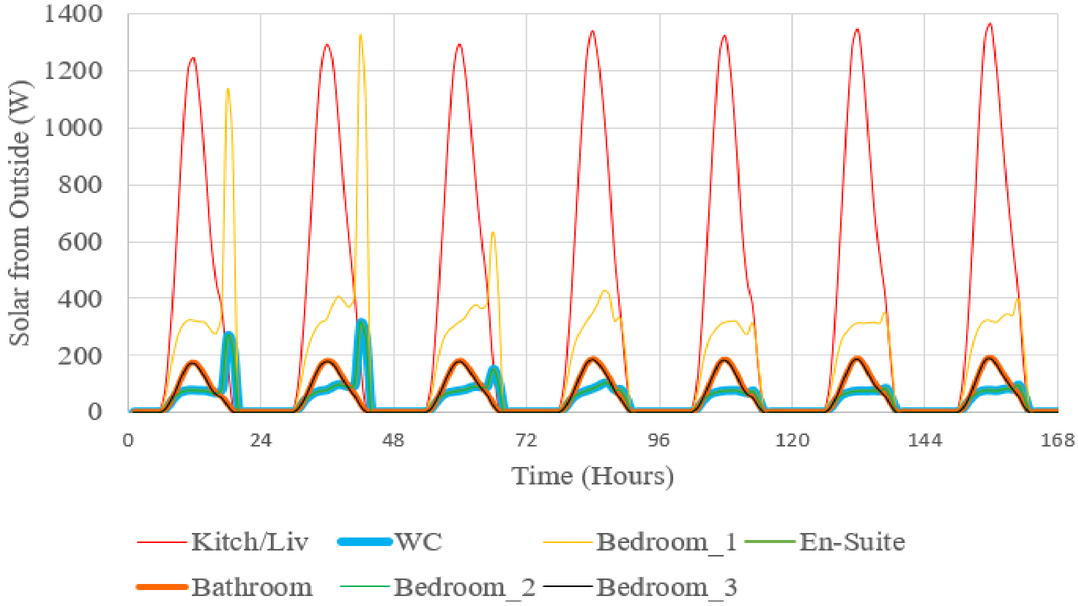


Figure 5.1. Solar gain in Zones from Outside

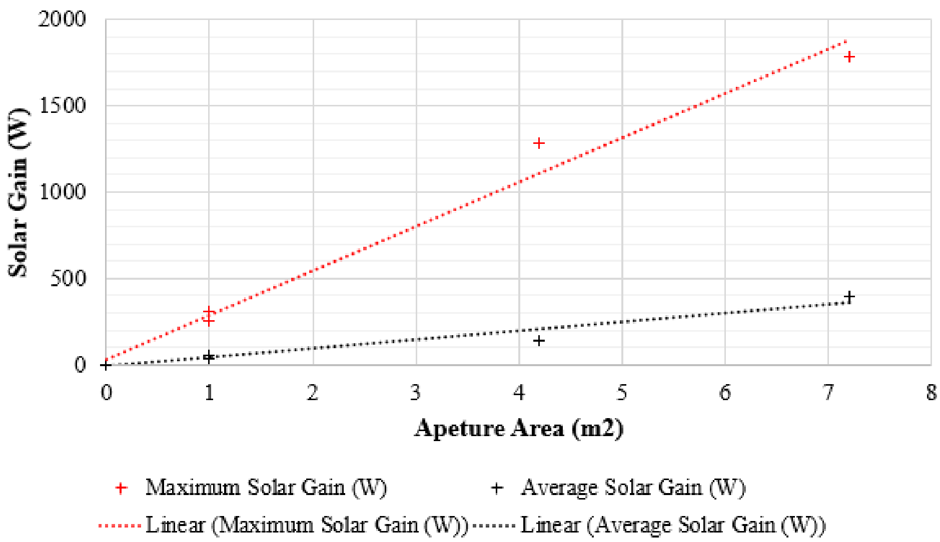


Figure 5.2. Solar Gain and Aperture Area Relationship for the Kitchen/Living Zone

5.3 Kitchen/Living Zone Modelling

5.3.1 Kitchen/Living Window Effective Surface Area Calculation

The window in the kitchen, which is seen in Figure 5.3, is constructed from a double-glazed, low-E and Argon filled glass. It has a bottom hung design with a height of 1.4 m and a width of 1.1m. Equation 2.47 can be applied to estimate the effective area and height, which was used to simulate several conditions using ESP-r. Table 5.1 tabulates the total effective area in relation to the window's opened angle with the results graphically seen in Figure 5.4.

Figure 5.3. Photo of the Kitchen area showing the door and window in red.

Table 5.1 Effective Area in relation to angle opening

Angle (°)	A_{eff} (m^2)
0	0
5	0.237
10	0.457
15	0.649
20	0.808
25	0.936
30	1.037
35	1.116
40	1.179
45	1.228

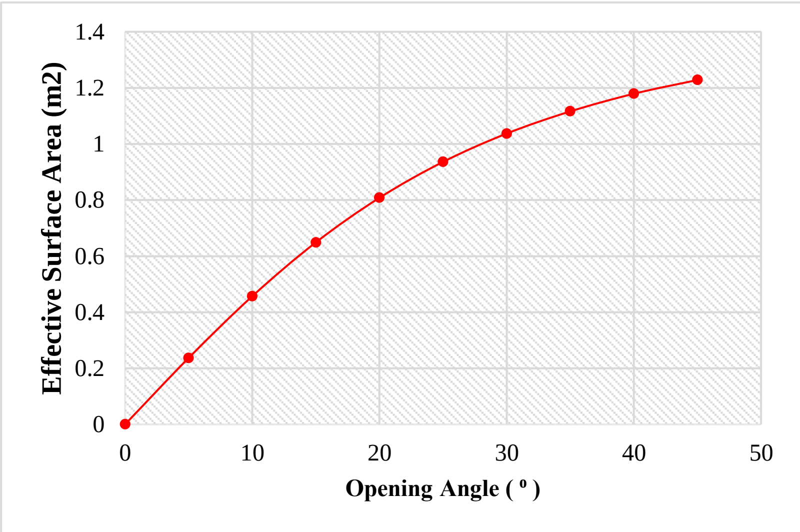


Figure 5.4 Effective Area Vs. Opening Angle of the Window

5.3.2 Kitchen/Living Zone CAD Drawing

Figure 5.5 shows the CAD drawing for the Living/Dining area with the flow network showing the internal and boundary nodes and probable cracks in doors and windows. The model assumes the zone to be of a retangular shape, and any features in the design of the wall were not considered in the simulation. The model is assuming a single-sided ventilaiton network.

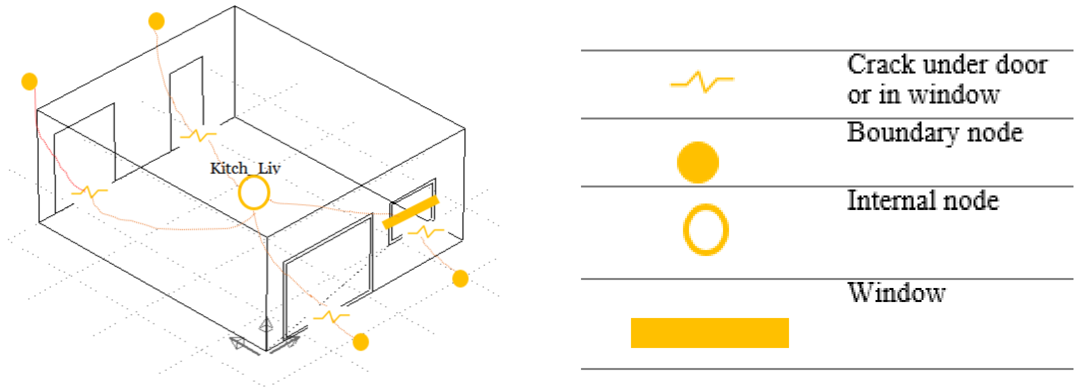


Figure 5.5. Simple Network flow of Kitchen/Living area

5.3.3 Kitchen/Living Zone Airflow Network

The flow network modelled for section 5.3 can be seen in Figure 5.6, where the exterior nodes are connected to the interior zone via two components. The two components are the window that was modelled as an aperture whose area varied between 0m^2 and 1.54m^2 and the door whose height was kept constant at 2.1 m and width varied accordingly. Another external node was linked to the interior node via a crack under the door which will link the kitchen/living to the corridor zone.

5.3.4 Kitchen/Living Zone Modelling Criteria

Simulation and Analysis on the Kitchen/Living zone was carried out on several designs. The 11 designs analysed were based on different aperture dimensions. Tabulated in Table 5.2 is a summary of the apertures dimensions associated with the design number.

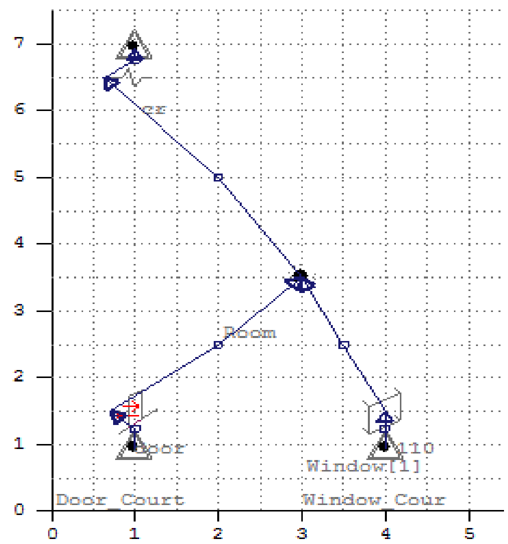


Figure 5.6. Flow Network for Kitchen/Living Zone

Table 5.2. Different design parameters for the Kitchen/Living Zone

Design No.	Window Effective Area (m^2)	Door Surface Area (m)	Design No.	Window Surface Area (m^2)	Door Surface Area (m)
1	0	0	**7**	1.037	2.84
2	0.237	2.84	**8**	1.116	2.84
3	0.457	2.84	**9**	1.179	2.84
4	0.649	2.84	**10**	1.228	2.84
5	0.808	2.84	**11**	1.54	5.67
6	0.936	2.84			

5.4 Kitchen/Living Zone Results

5.4.1 Dry Bulb Temperature

Figure 5.7 graphically shows the results obtained for the DBT in the Kitchen/Living Zone for the month of August. As predicted, with no sign of NV in the room, i.e. all apertures closed (red line graph), the temperatures registered are high as opposed to when the apertures are open. Temperatures registered in this simulation are higher than the ambient temperature, peaking at 37.6 ºC. This is a clear indication of the benefits that occur when ventilation is introduced into a zone. Numerical values are tabulated in Table 5.3. The highest registered temperature was 6.5ºC, or 18 per-cent higher than the coldest registered temperature registered in design 11.

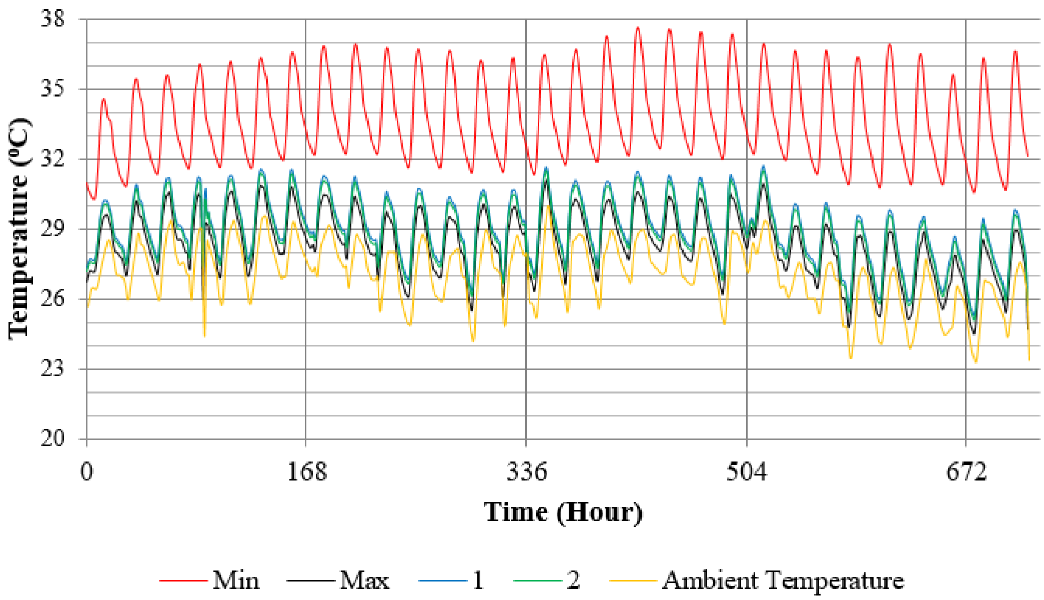


Figure 5.7. Zone Dry Bulb Temperature Comparism in Kitchen/Living with different parameters according to Table 5.2 for the month of August

Table 5.3. Dry Bulb Temperature results for Kitchen/Living Zone obtained during the month of August

Design No.	Registered Maximum Temperature (⁰C)	Registered Minimum Temperature (⁰C)	Average (⁰C)
1(Min)	37.6	30.3	33.8
2	31.8	25.3	29.0
3	31.7	25.3	29.0
4	31.7	25.3	29.0
5	31.6	25.2	28.9
6	31.6	25.1	28.9
7	31.6	25.2	28.9
8	31.5	25.1	28.8
9	31.0	25.0	28.8
10	31.5	25.0	28.8
11 (Max)	31.1	24.5	28.3

As the aperture sizes increase, the DBT decreases, this can be seen in Figure 5.8 and which graphically shows the average temperatures obtained in each of the designs. The highest average, 37.8ºC is 8.8ºC higher than the average DBT from design 2 and 9.5ºC from design 11. The small discrepancy in temperature difference between the average of designs 2-11 show that even though a larger opening would provide a cooler temperature, the difference with opening window size is minimal. A higher drop is noticed when the door area is increased. Reason for this will be briefly discussed in section 5.4.4.

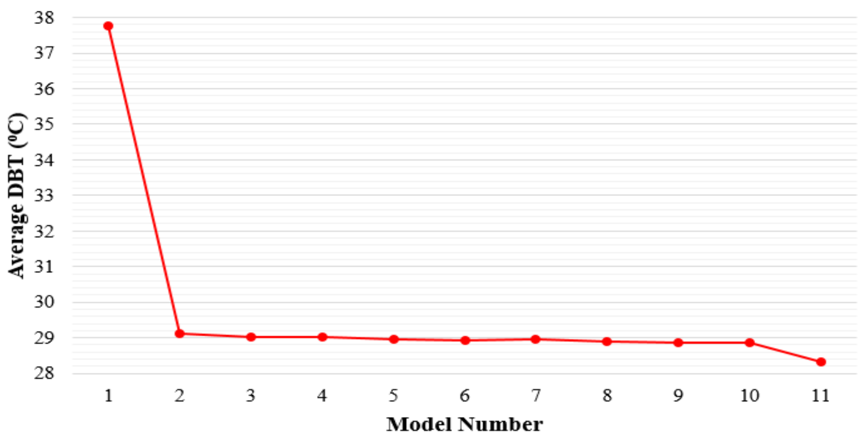


Figure 5.8. Average DBT for Kitchen/Living Zone Analysis for the month of August

5.4.2 Kitchen/Living Zone Predicted Mean Vote

Table 5.4 shows a summary of the obtained PMV values for the kitchen/living zone, and as predicted, the highest values are associated with design number 1 as this also registered the highest temperatures. The maximum value is 5.6, which indicates a high level of discomfort due to high temperatures. The lowest value is 3.6 for this design also signifies slight levels of discomfort, even though this is a subjective condition. With the introduction of an aperture, the PMV decreases with the lowest value being registered at night in design 11 being 0.8, which can be indicative of a comfortable zone.

Table 5.4. PMV Results for Kitchen/Living Zone for the month of August

Design No.	Max PMV	Lowest PMV	Average PMV
1(Min)	5.6	3.6	1.8
4	2.7	0.9	1.9
9	2.7	1.0	1.9
11 (Max)	2.5	0.8	1.5

5.4.3 Kitchen/Living Zone Air Flow and DBT relationship

Figure 5.9 gives an overview of the relationship between the flow rate in m^3/s and the DBT in a zone which has one aperture and can be therefore defined as a single-sided ventilation. The flow rate which can be seen in the secondary y-axis was calculated using equation 2.23, a simple analytical equation which can be used to calculate the flow rate through an aperture. The yellow box in Figure 5.9 highlights the peak air flow reached, which happens to be synonymous with a drop-in temperature when compared to previous days.

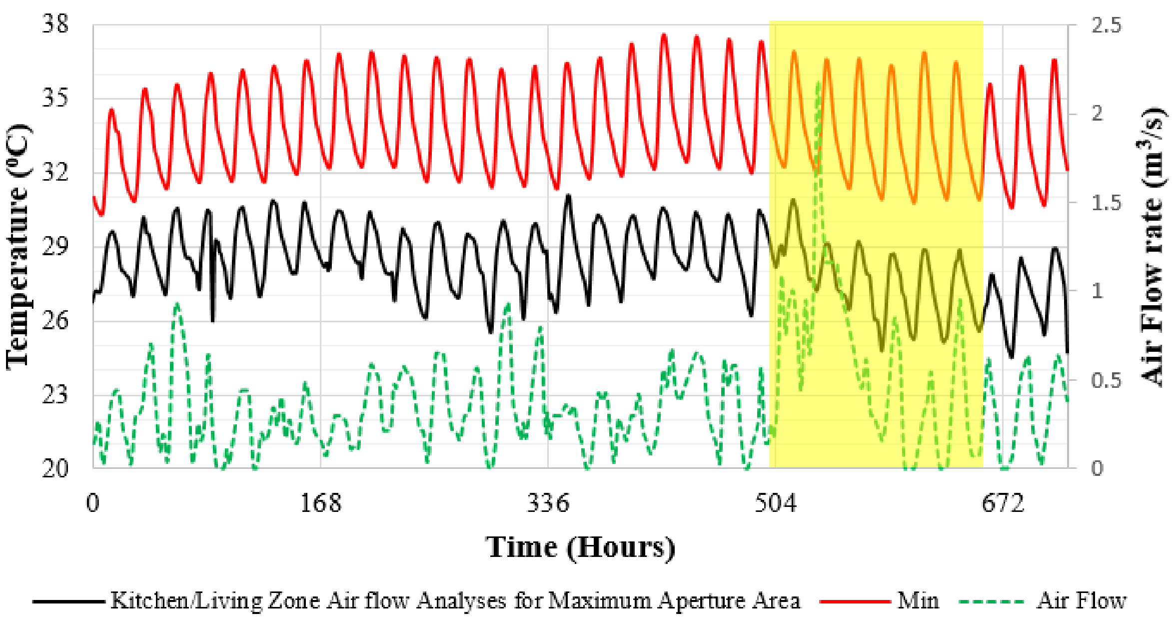


Figure 5.9. Air Flow and Kitchen/Living zone DBT relationship

5.4.4 Kitchen/Living Air Change Rate

The air change per hour (ACH) in a room can be calculated using equation 5.1, where q is the air flow rate in m^3/s and V is the zone volume in m^3. Applying equation 5.1 to the air flow rate calculated for the kitchen/living area in section 5.4.3, the air change rate was found which is graphically displayed in Figure 5.10. The kitchen/living zone has a total volume of $126m^3$ and the main flow occurs through the window and door facing towards the court [19].

$$ACH = 3{,}600 \times \frac{Q}{V} \quad (5.1)$$

The calculated values are in the range of 0 ACH, a value synonymous with a zero-wind velocity in the direction of the opening, to a maximum of 34 ACH, which occurs when all apertures are modelled as being open. The high air change rate can lead to an uncomfortable state for the occupants. This can be easily reduced by closing the apertures manually, thus reducing the air flow rate since this is a function of the flow rate, which in turn, as equation 2.23 suggests it's a function of the opening area.

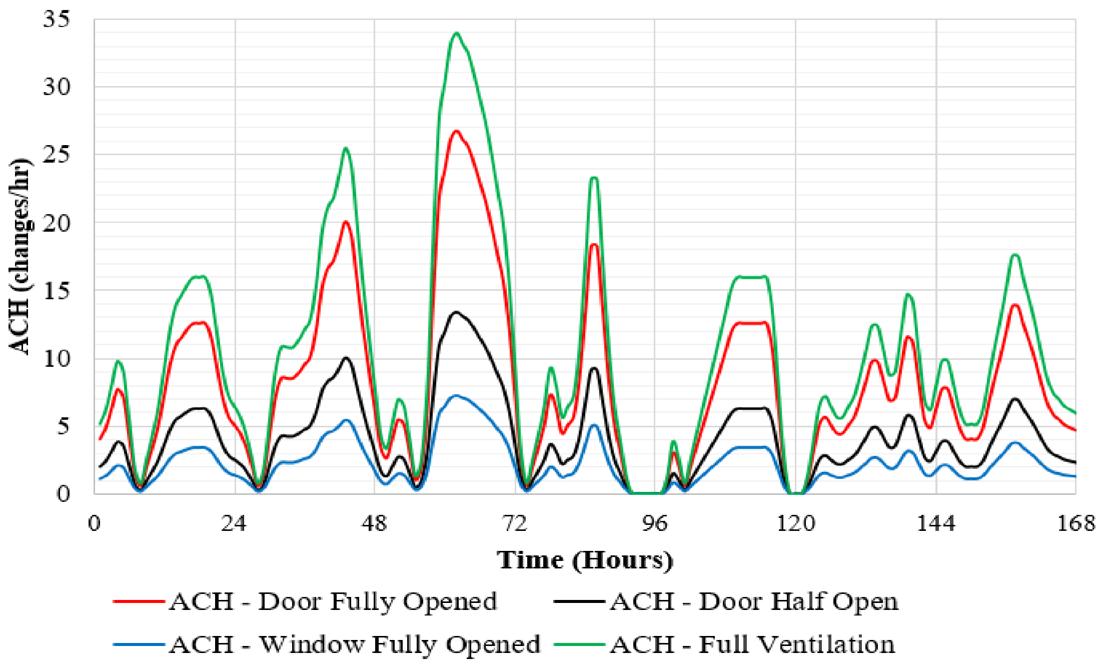


Figure 5.10. ACH in Kitchen/Living Zone

5.4.5 ACH Literature Study and Comparism

Online material suggests that the ideal air change rate in a domestic kitchen ranges from 8 to 15 ACH. The average air change rate values for this simulation resulted in a maximum of 10.4 ACH when all apertures are open and a minimum of 2.5ACH when only the kitchen window is open, which is about 75per-cent lower [38].

From the analysis of these results one can conclude that a higher ACH is synonymous during the night period, as evident in Figure 5.10. This give rise to a number of benefits to use night purge ventilation, which will be later discussed in section 5.7.

A study carried out in Israel by Becker et. Al. involved a research associated with IAQ and ACH within a building, whose layout can be seen in Figure 5.12. The layout is similar to that found in the majority of the Maltese buildings, and also subjected to a similar climate conditions. As can be observed in Figure 5.12**,** just like Malta, Israel is characterised by warm days and cooler nights during the night of August. Different scenarios were tested where different opening conditions were tested.

The study results show that by increasing the openings' area, the air change rate drastically increases (similar to the results obtained from the simulations and shown in Figure 5.10). With the window and regular door closed, the air change rate was lower than 0.25 ACH, which is considered to be too low and unacceptable according to CEN, 2007 standards. The rate increased to 1-3 ACH when the window was tilted, such value ensures adequate IAQ in dwellings. Opening the door resulted in an air change rate between 3-20 ACH, this being a larger range when compared to just the tilting of the window. Such values are ideal for aiding the removal of internal heat gains, and thus preventing any overheating in the zone. Having a combination of a opened apertures resulted in a value of between 20-100 ACH, which might be considerably too high but an ideal air change rate for the removal of heat mass and energy during the summer period by the use of night cooling (or night flushing) [39].

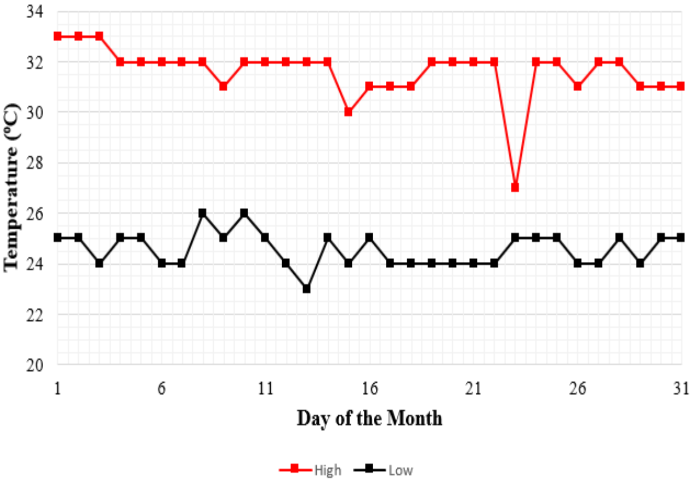


Figure 5.12. Tel Aviv Weather Data for August 2016., Source: [50]

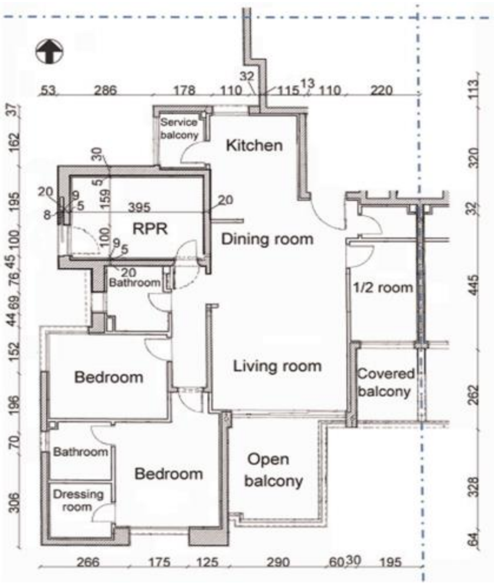


Figure 5.12. Layout of building tested for IAQ and ACH. Source: [39]

A number of studies, such as that carried out by M. Gil-Baez et al. show how in fact lower temperatures are synonymous with an increase in air change rate. This research was carried out on two different 21st century schools which were built with the purpose of achieving a near zero energy building. One building has a mechanically ventilated system whilst the other naturally ventilated systems. The author discusses how in warmer regions, there is less need of heating systems, and having a naturally ventilated building can maintain adequate indoor air qualities. Being carried out in southern Spain, the results can be compared to results obtained in the Maltese Islands, since this location is also characterised by a warm Mediterranean climate. Results showed that for a naturally ventilated system, makes use of 18-33 per-cent less energy whilst still maintaining adequate comfort levels in the classroom [40].

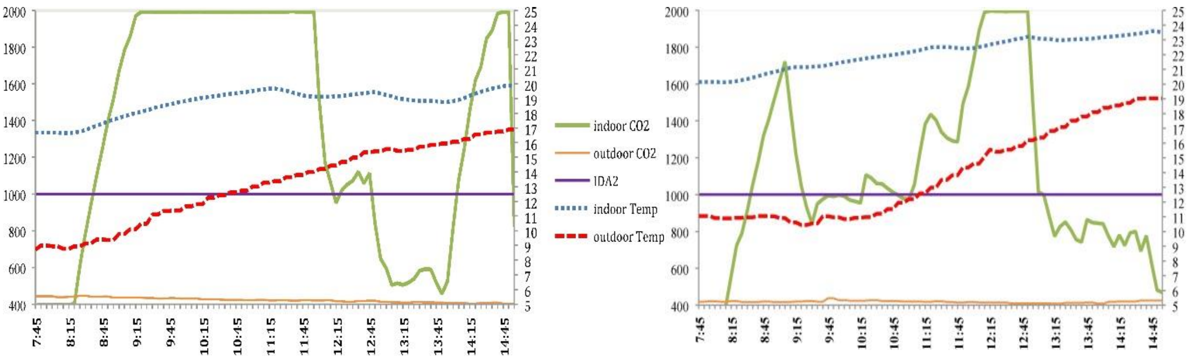


Figure 5.13. Results for the work carried out by M. Gil-Baez et al for a NVS (Left) and MVS (Right). Source: [40]

5.4.6 Causes for Temperature Drop in Kitchen/Living Zone

Chapter 2 discussed the possible means which are useful in maintaining a lower temperature in the zone. As can be observed by the 3D CAD drawing of the kitchen/living zone, both the door and window are located on the same wall, thus being subjected to the same pressure coefficient. This is turn should result in no ventilation caused by a difference in pressure. The main zone temperature difference was evident to when an opening on the wall was modelled as open as open as opposed to when the zone was subjected to no ventilation. Altering the opening area had no drastic effect on the resultant temperature.

The phenomena in which a pressure difference results in a temperature drop is known as the stack effect, which was discussed in section 2.4.2. Section 2.4.3 and 2.4.4 discussed the combination of wind effect and stack effect which would then also result in a temperature drop. The drop-in temperature in this zone can be the result of a pressure difference in the door opening. Figure 5.14 shows the movement of warm/cool air schematically.

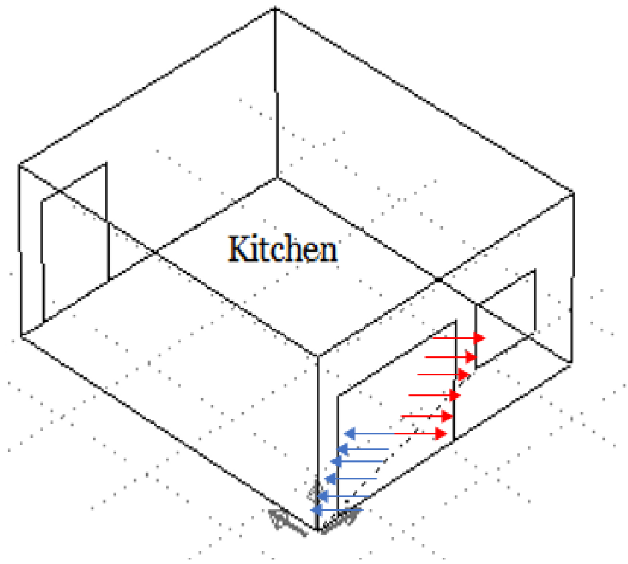


Figure 5.14. Representation of temperature drop in zone due to pressure difference occurring in door

5.5 Ground Floor Modelling

The ground floor model is a representation of the actual ground floor of the house whose architecture plans were displayed in Figure 4.2. Figure 5.15 shows a CAD drawing for the ground floor model. Following a number of simulations, a better understanding of the thermal comfort in the ground floor zones was achieved. The first simulation was completed to analyse the correctness of the model, firstly by comparing the results with the results obtained in section 5.4 and then to analyse the effect of NV on the ground floor.

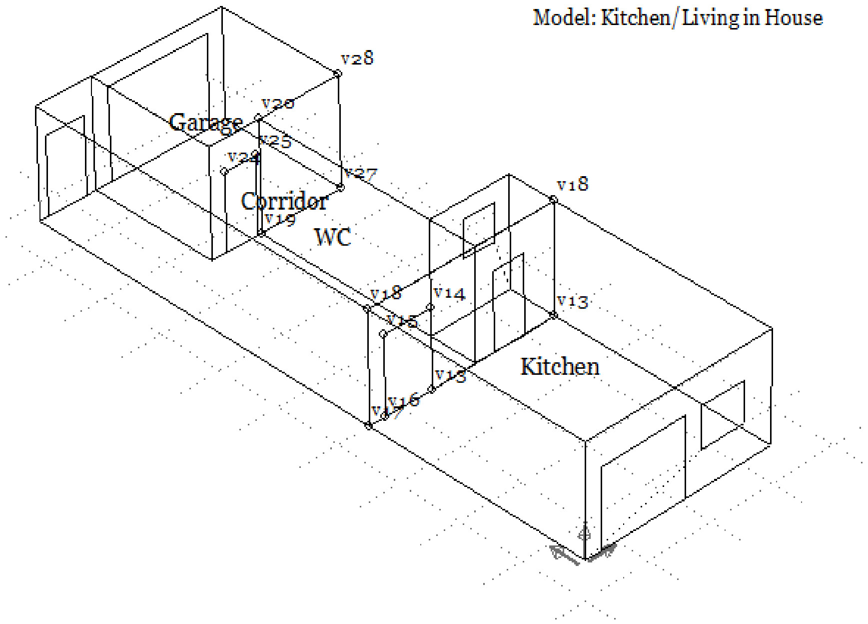


Figure 5.15. First Floor Zones CAD Drawing

5.5.1 Ground floor Network Flow

The flow network for the ground floor model is schematically visualised in Figure 5.16. This model can be defined as being a cross-ventilated system if all the apertures are left open. A description of the nodes and components used is given in section 4.4 and the nodes applied are tabulated in Appendix A, Table A.4.

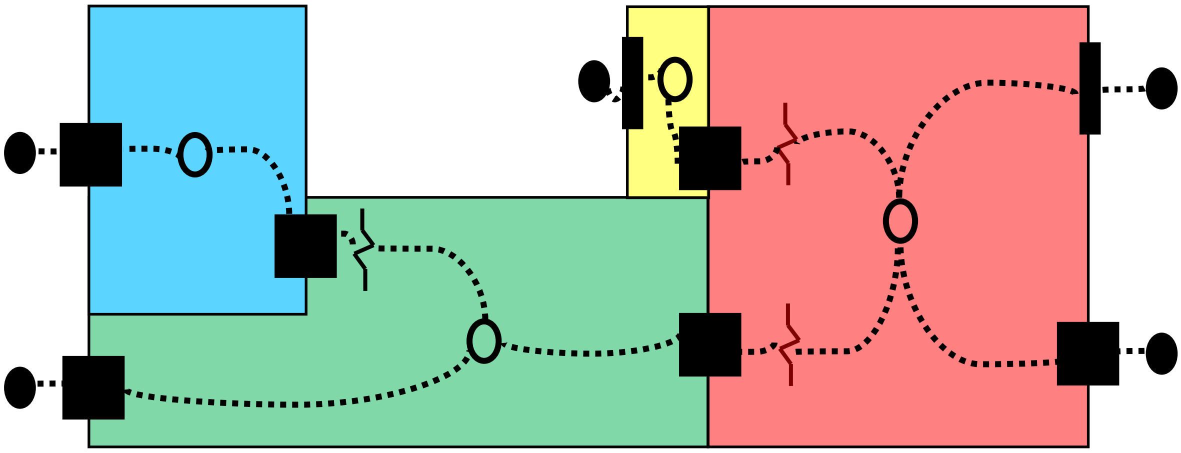


Figure 5.16. Ground Floor Zone Network Schematic

5.5.2 Ground Floor Modelling Criteria

Different conditions were simulated and the results were compared and analysed. The idea behind this model was to study the effect of natural ventilation, derived from a single source, i.e. NV starting from the Kitchen/Living zone. The entrance door and garage door were modelled as being closed to simulate a realistic condition, but also as open to see the full potential effect of cross-ventilation. Table 5.5 gives a summary of the three sets of different combined conditions used in the simulation.

- □: denotes closed aperture
- ■: fully opened aperture

Table 5.5. Model parameters for Ground Floor modelling

Design No.	**Kitchen/Living door**	**Kitchen/Living Window**	**W.C. Door**	**W.C Window**	**Corridor Door**	**Garage Door**	**Garage Opening**	**Entrance door**
1	■	■	■	■	■	■	■	■
2	□	□	□	□	□	□	□	□
3	■	■	□	■	■	□	□	□

5.5.3 Ground Floor Results

Figure 5.17 show the annual results for the DBT for all the zones in the Ground Floor. The red shaded area indicates the results for the month of August, which resulted in the warmest temperatures. Further analysis was carried out on this month, giving more importance to the first three days in order to be able and better compare the effect of the apertures/NV on the obtained results. This section will also explore the effect which the wind velocities might have in the resulting DBT, and thermal comfort. The hourly wind velocities are superimposed on the DBT graphs so as to see the effect of wind velocity as discussed in section 2.5.4.

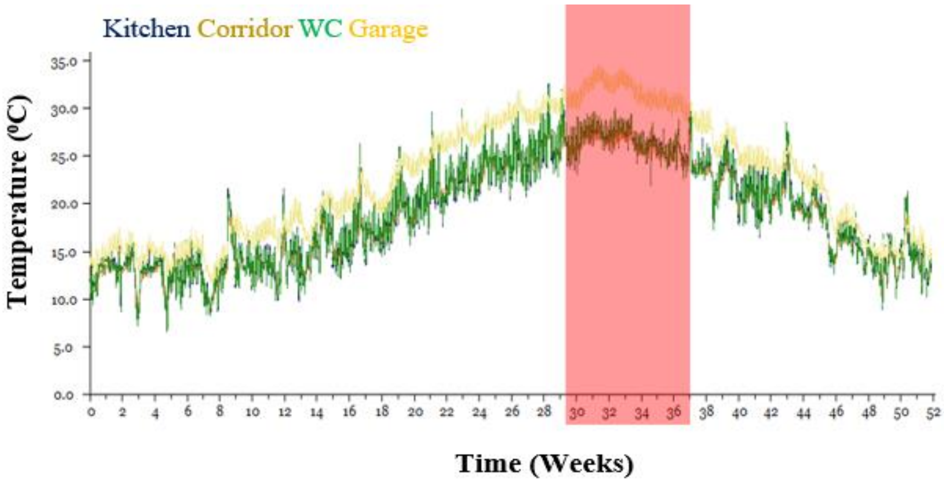


Figure 5.17. Ground Floor Results for the entire year

Table 5.6 tabulates the highest and lowest DBT values for the registered for the entire month of August for the different zones and designs.

Table 5.6. Maximum and Minimum DBT obtained in Ground Floor Modelling for August

Design No.	Zone	Max. Temperature (^0C)	Min. Temperature (^0C)
1	Kitchen/Living	29.65	23.73
1	Corridor	29.73	23.82
1	WC	31.57	24.56
1	Garage	29.97	23.72
2	Kitchen/Living	32.90	27.78
2	Corridor	26.21	23.90
2	WC	32.68	28.63
2	Garage	34.36	29.91
3	Kitchen/Living	29.60	24.08
3	Corridor	28.34	24.48
3	WC	29.95	23.70
3	Garage	34.42	29.99

5.5.3.1 Kitchen/Living Analysis

Section 2.5.4 discussed the positive effect associated with higher wind velocities and there effect in improving temperatures in the zone. This is not shown to be the case during these simulations, which, as can be seen in Figure 5.18 make no effect, and higher wind speeds are synonymous with both higher DBT and higher ambient temperatures. The wind speed however follows a different trendline to both DBT and ambient temperature, this being much less predictable. As previous results have shown, the highest temperatures are registered in the kitchen/living area when all apertures are closed due to internal gains resulting from lighting, occupants and cooking appliances. Also, the door court and window are modelled as double-glazed windows, and their larger size (when compared to other apertures) will also have a major effect on internal temperatures due to Solar gains.

The highest recorded temperature with all apertures closed is 32.9ºC which drops down to 29.7ºC and 29.6ºC when means of natural ventilation is introduced in the building. A drop-in temperature of around 9 per-cent in both simulations indicate that introducing NV does again have a major effect on the internal zone DBT.

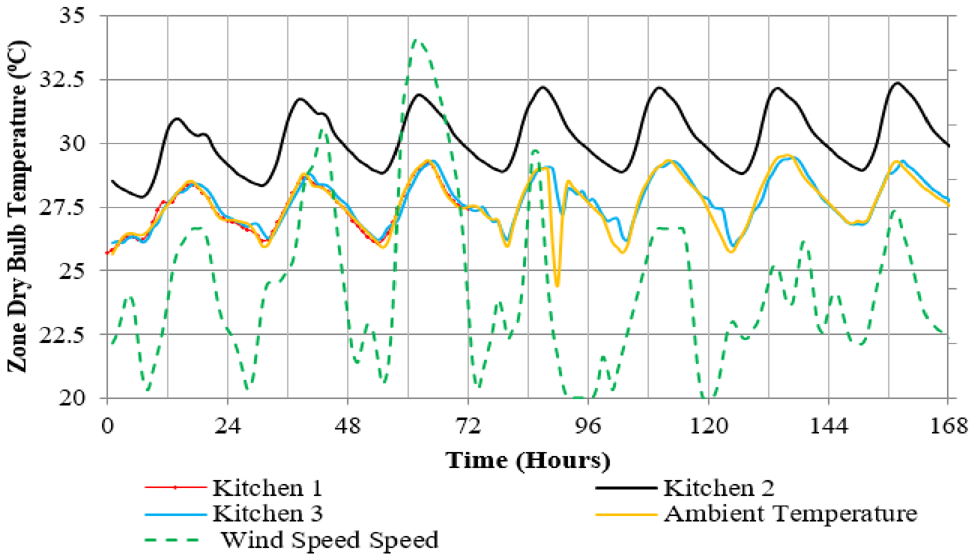


Figure 5.18. Ground Floor: Kitchen/Living Zone Results for the first week of August

5.5.3.2 Corridor Analysis

When compared with the other zones, the ground floor corridor registered the lowest from all the maximum temperatures at 26.2ºC. this resulted in the second simulation, when all apertures were modelled as closed, and there was no link between the zones. This lower temperature is the result of having zero internal gains in the zone and the solar gains are slight to none since there are no externally facing apertures.

When the apertures are all modelled as being fully opened, thus creating a link between the kitchen/living zone and the corridor, the resultant DBT is very alike to the ambient temperature. Similarly, to the results of section 5.4.3.1 the wind velocity seems to have no major effect on the zone's DBT. The maximum temperature recorded in this condition is 29.7ºC. A rise in temperature in the first simulation of 11per-cent when compared to the result of corridor 2 indicate that the internal and solar gains generated in the kitchen/living are have a major influence on the zone. On running the third simulation with the door dividing the two zones modelled as a fully opened component, a drop in the maximum DBT to 28.3ºC resulted, this being 4.7per-cent lower when compared to the results of the second simulation.

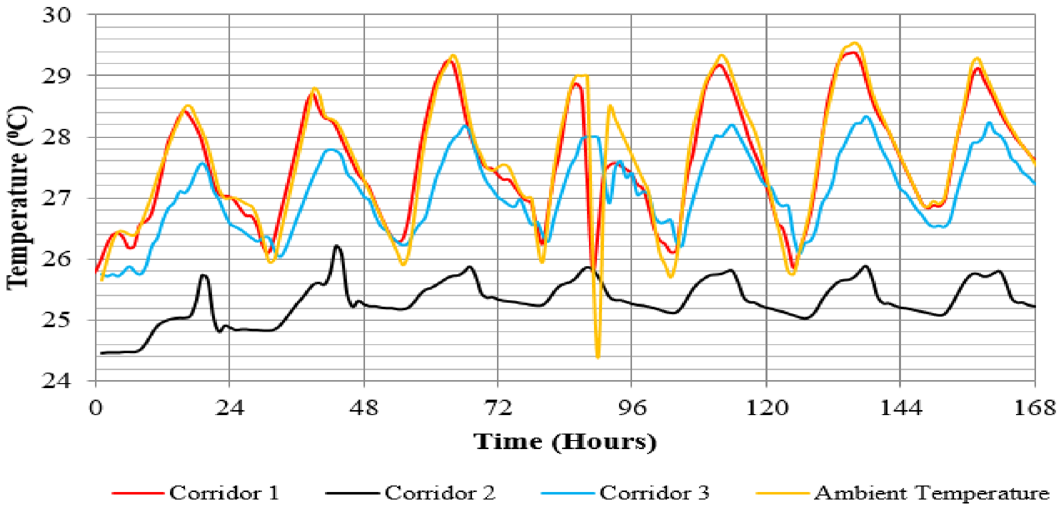


Figure 5.19. Ground Floor: Corridor. Zone Results for the week of August

5.5.3.3 WC Analysis

As with the analysis carried out in section 5.4.4.1, the highest DBTs are registered when the simulation is carried out with all apertures closed. All of the data follows a similar trendline, apart from the first simulation. During this simulation, such as at hour 48, the temperature peaks up instantaneously as shown by the superimposed yellow boxes in Figure 5.20. This peak in temperature is registered at the same instant during a drop-in wind velocity, indicating that in this instance the wind velocity has an effect on the DBT-as opposed to results obtained in the kitchen/living and corridor analysis. This temperature change might be caused by the different location of the aperture, this facing a different direction than the apertures in the other zones.

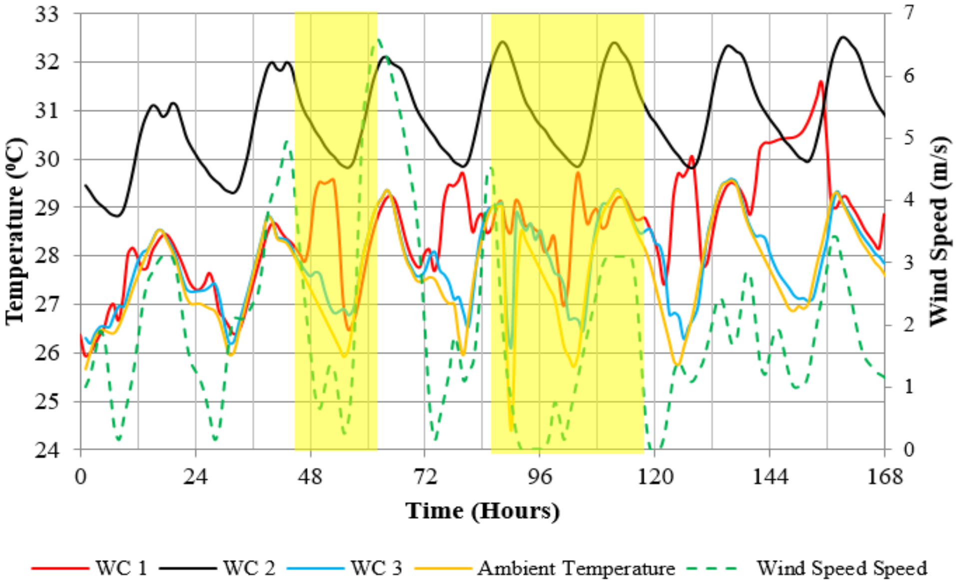


Figure 5.20. Ground Floor: WC Zone Results for the week of August

5.5.3.4 Garage Analysis

Similarly to the analysis in sections 5.4.4.1 and 5.4.4.2, the wind velocities have no major effect on temperatures in this zone. Simulations 2 and 3 are practically the same model, since they both imply a closed zone, as indicated by the graphical representation in Figure 5.21. As for the first simulation, all apertures are left open, the registered DBT is very similar to the ambient temperature. During this simulation, the garage door, which is the largest aperture modelled in the house is left open introducing a major aspect of NV in the model. This creates an unlikely condition where full natural ventilation in the house (cross ventilation) is created.

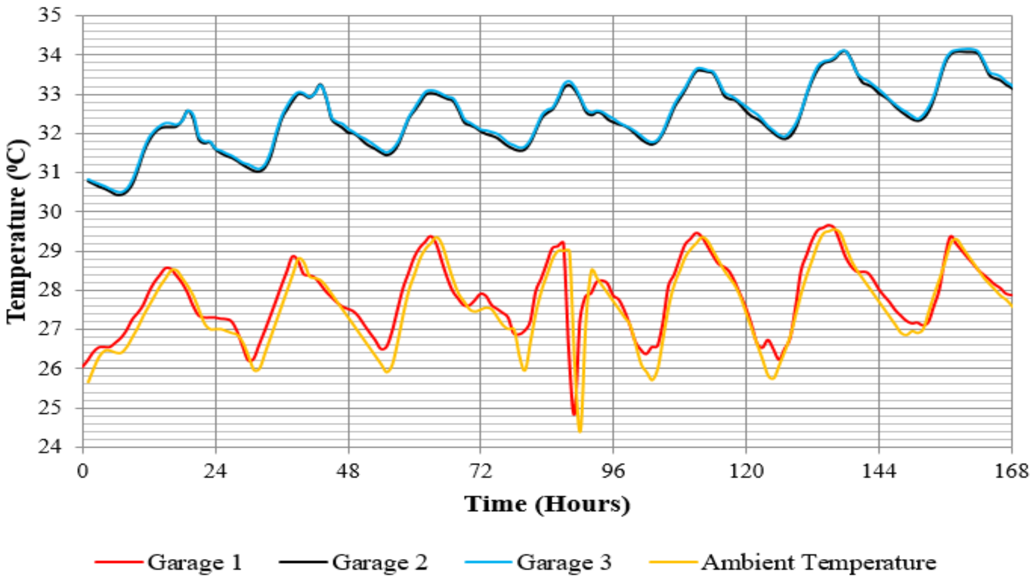


Figure 5.21. Ground Floor: Garage Zone Results for the first week of August

5.6 First Floor/Full House Modelling

Section 5.5 includes the analysis for the complete model which is shown in Figure 5.22, this being constructed of two floors and a total of 11 zones, which are tabulated in Appendix A, Table A.5. During the simulation of this model, special attention was given to the bedrooms, as these will be occupied for most of the night period and are the most used rooms after the kitchen/living room. As with the other models, an assumption where all the zones are of a square shape was made, and no details regarding the geometry of the walls, which might influence the overall area, was implemented in the design.

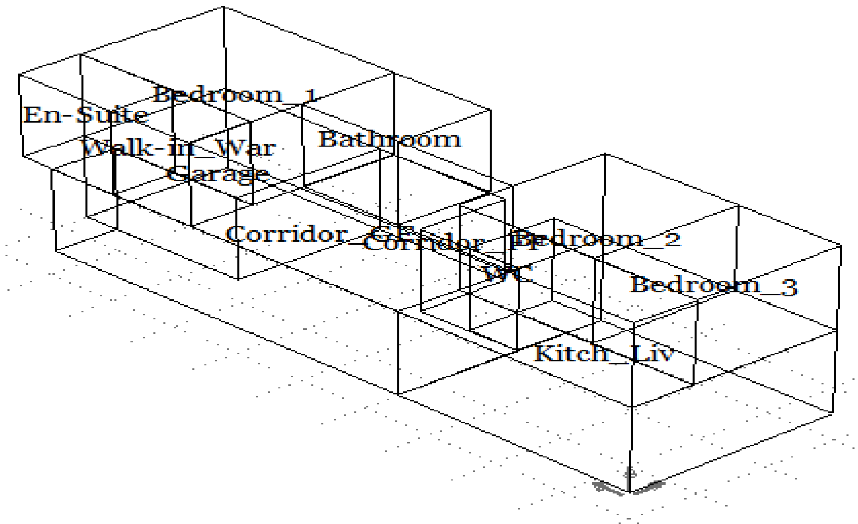


Figure 5.22. CAD Model for the entire house

5.6.1 Result Analysis

A total of four simulation under different conditions, which can be seen in Table 5.7 were run. The results for each zone were thoroughly analysed, mainly by looking at the DBT of each zone for the month of August.

Table 5.7. Full house modelling conditions

Model Condition	Description
All Open	All apertures in the house, including the entry door and garage door are left open in order to model the highest possible flow in the house. As later on discussed in sections 5.5.1.1 – 5.5.1.3, this simulation yielded the lowest DBT in all zones when compared to other modelling criteria.

All Closed	During this simulation, all apertures are modelled as closed. As with previous models, this resulted in the highest DBT in all zones. Solar and casual gains have a major influence on these results.
Balcony Closed	This simulation was mainly carried out to study the effect that the balcony's condition in Bedroom_1 has on this and other zones. This is the third largest aperture after the garage entrance and the door to the court in the Kitchen/Living zone.
Realistic	This model simulates the most viable/realistic conditions, where the entrances such as the entry and garage door, and doors which give access to the bathrooms are kept close to simulate daily situations.

5.6.1.1 Kitchen/Living Analysis

As can be seen from the graphical representation of the DBT in Kitchen/Living Zone, shown in Figure 5.23, the results for this zone is similar to previous models. The highest DBT are registered when the model's apertures are modelled as closed, this being the result of casual and solar gains and a lack of ventilation. The results in the other models only register a slight variation in the DBT magnitude, with the peak temperatures being synonymous with afternoon times, and cooler temperatures during the night period. At all times, the registered temperatures are similar to the ambient temperatures, and also follow the same trendline, showing the major influence that natural ventilation and mainly large sized apertures have on the inside temperature. All results follow a similar trend where the temperature peaks and drops to similar values during all the days in the first week of august. The lowest registered temperature is synonymous with the lowest ambient temperature of 24.4ºC. When all the apertures were modelled as closed, the minimum temperature was 29.17ºC and when the apertures were modelled as open, the temperature dropped to 25.72ºC. These results were 16.4per-cent and 5.13per-cent higher than the ambient temperature respectively.

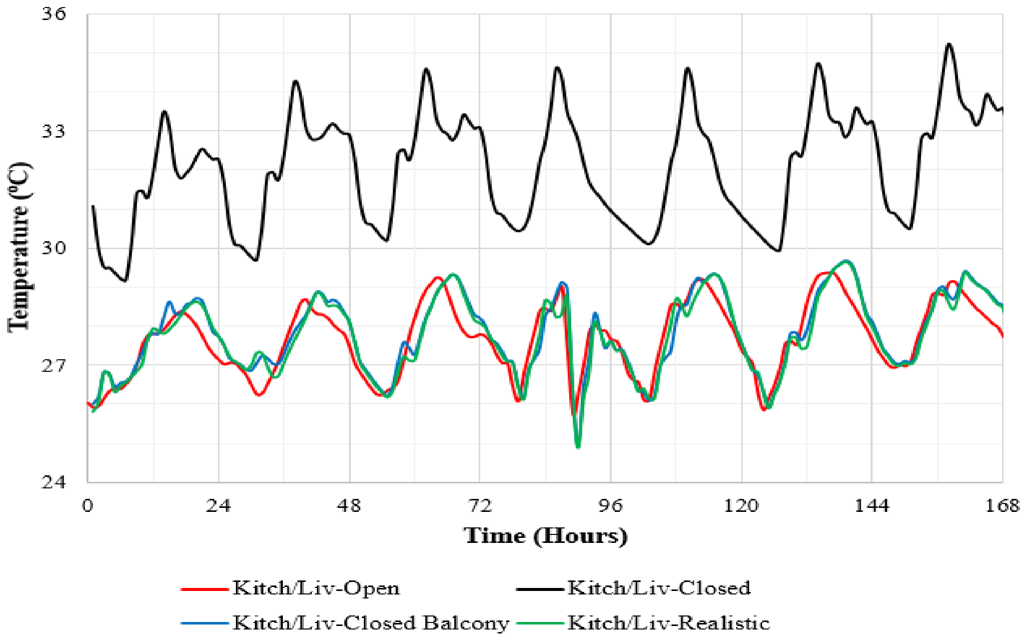


Figure 5.23. Kitchen/Living Zone Analysis for Full House Model

5.6.1.2 Bedroom Analysis

Figure 5.24 shows the CAD drawing for the 3 bedrooms analysed in this section. All three zones are located on the first floor with only Bedroom_1 having an aperture fully exposed through a door giving access to a balcony with a total surface are of 4.7m^2 when fully opened. Bedroom 2 has one aperture having a surface are 1m^2 and is semi exposed to an internal court. Bedroom 3 also has one aperture with a surface area of 1m^2 and semi-exposed to the back court. As with section 5.6.1.1, analysis was carried out under 4 conditions and the results are graphically represented in Figure 5.25, which shows the simulated results for bedroom_1 and bedroom_2 with bedroom_3 following a similar trendline as to bedroom_2. Figure 5.26 graphically shows a summary of the maximum and minimum temperature results achieved from this simulation, clearly representing the benefits in temperature reduction with introducing natural ventilation.

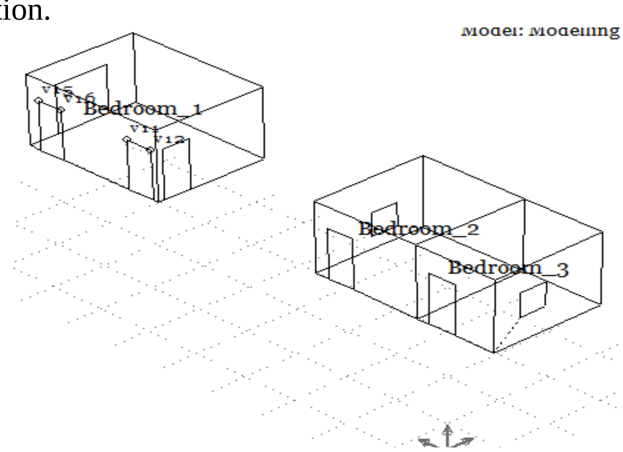


Figure 5.24. CAD drawing and location for the 3 different bedrooms

Figure 5.26. Maximum & Minimum temperatures registered in the bedrooms

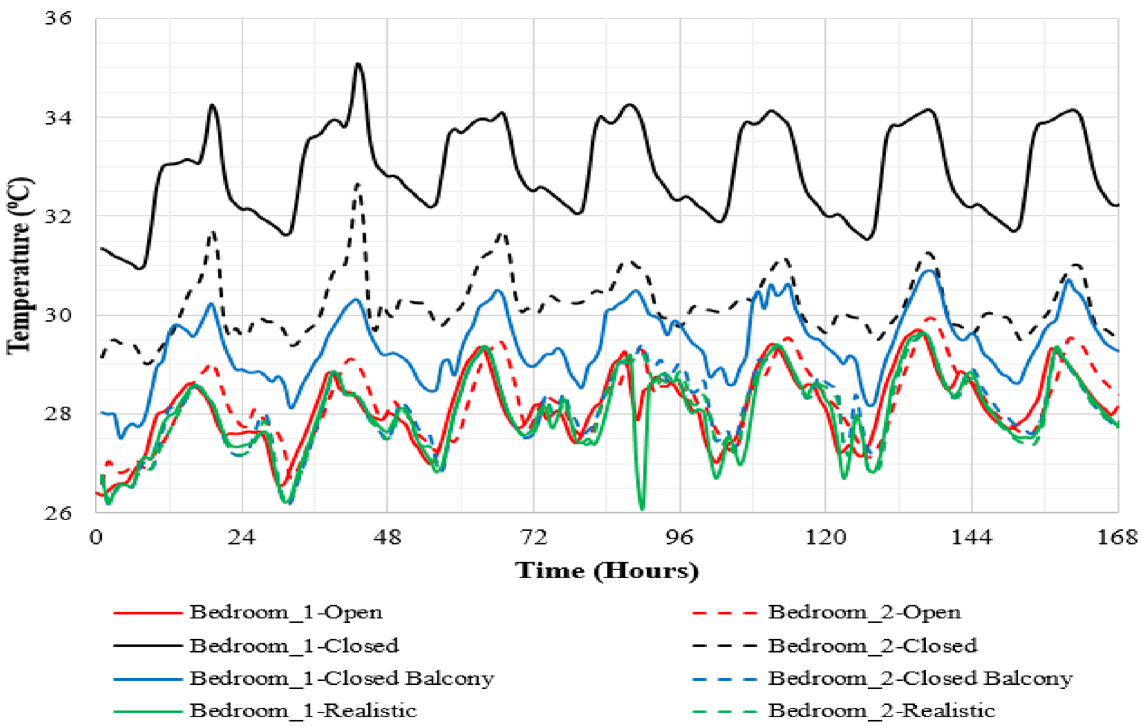


Figure 5.25. Bedroom Analysis for Full House Modelling

All Closed Simulation Condition

As predicted, the highest temperatures were registered when all apertures are closed, with the highest temperature of 35.08ºC being registered in bedroom 1. The highest temperatures for bedroom 2 and 3 are 32.64ºC and 34.04ºC respectively. All temperatures are higher than the registered ambient temperature as seen in Figure 5.25. The highest temperatures in all three zones peak during the afternoon times, and all the zones follow a similar trendline, where with higher ambient temperature, the zone DBT is higher and with lower (night) temperatures the zone DBT are lower. These high values are the result of the internal solar gains, since the rooms are entirely closed throughout the day. The highest temperatures are always registered in bedroom 1, with minor variation between bedroom 2 and bedroom 3. This is a reflection of the aperture area, which is modelled as a double-glazed glass in all instances. The lowest temperatures recorded was in bedroom 3 at 28.13ºC and this temperature is still considerably high and uncomfortable as a result to the solar gains and operational gains from the occupants during the night period.

All Open Simulation Condition

When all the apertures are modelled as open, the temperatures registered in all bedrooms resulted in similar values with the highest of 30ºC being registered in bedroom 3 and the lowest in bedroom 2 being just 0.3 per-cent lower. As with other zone and conditions results, the lowest registered temperatures was attained during the night period with the lowest being 23.4ºC in bedroom 1, and 24.2ºC in bedroom 2 and 3. The similar values indicate that the aperture area and exposure affect the internal temperature slightly with the larger aperture area bedroom 1 resulting in a lower temperature by 3.2 per-cent even when the aperture area larger by about 75per-cent.

Balcony Closed Simulation Condition

As opposed to other conditions, simulation with the balcony closed resulted in the warmest temperatures registered in bedroom 1. This simulation implied that no ventilation from the external side of the house was entering bedroom 1, but only ventilation through link from other internal nodes through the door of this room. The highest temperature registered is 30.9ºC and the lowest 25.5ºC. When compared to the analysis of all apertures left open, these values are 3 per-cent and 8per-cent respectively higher. The temperature at night is higher since the zone will be occupied, thus having operational gains associated with the people sleeping at night.

Figure 5.27 compares the temperature results for the bedroom for two conditions – open balcony and closed balcony, for a 24 hour period. As clearly indicated by the line graph, when introducing natrual ventlation though the balcony there is a considerable drop in temperature, improving the thermal comfort. The drop in temperature rages from 0.9 to 1.7 ºC. this results proofs once again the benfits associated with natural vntilation when it comes to improve temperature conditions for warm climate conditions.

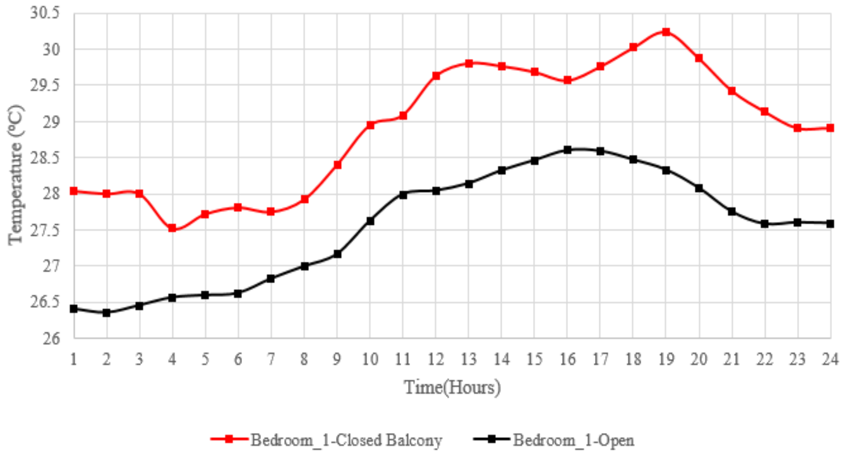


Figure 5.27. Temperature comparism in bedroom 1 depending on the balcony status for a 24-hour period

Realistic Simulation Condition

The highest registered temperatures from this simulation were in the range of 30ºC, which is about 0.85ºC higher than the maximum ambient temperature. This temperature indicates a high level of natural ventilation even though the temperatures might still be slightly uncomfortable. In these instances use of mechanical ventilation system would be suggested in order to improve the comfort of the zones during the day. The lower DBT values, which as with all models are registered during the night period, range between 22ºC and 24ºC with the lowest value of 22.07ºC being registered in Bedroom 1, synonymous with the larger aperture from all the bedrooms. Figure 5.28 shows graphical data for both DBT and PMV results for this simulation. As with previous results, the zone temperatures follow a similar trendline to the ambient temperature. The lowest ambient temperature of 24.4ºC was registered at hour 91, and during this hour, the lowest temperature was recorded in Bedroom_1. This drop-in temperature was not as effective as with the other bedrooms due to the smaller area and location. Bedroom_1 registered a minimum temperature of 26.1ºC whilst bedroom_2 and bedroom_3 registered during the same time, 29.1ºC and 28.9ºC these being 16.2 and 15.6 per-cent higher than the ambient temperature.

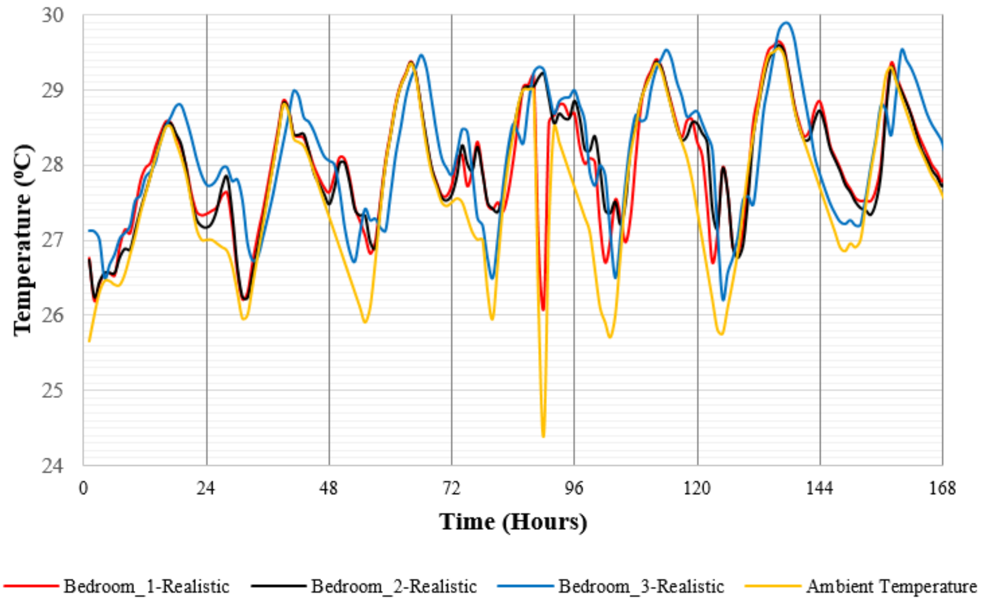


Figure 5.28. Bedroom DBT and PMV graphical representation during the Realistic Model Simulation

5.7 Night Cooling

This section will analyse the effect of opening the apertures and making use of NV during the night period, also known as Night Purge Ventilation which is one type of passive cooling. As explained in section 2.3, this should result in a positive effect when it comes to improve thermal comfort efficiently during the day.

5.7.1 Night Purge Ventilation Available Literature and Studies

Night purge ventilation was discussed in section 2.3, and correct application of this method can results in a lowering the daytime temperatures. This would result in a higher efficient building since the cooling load of the HVAC systems will be less.

Solgi et al. carried out a study regarding night purge ventilation for offices in Yazd, Iran, a city with similar climatic conditions to Malta. Results following this study showed that the ideal air change rate is 15 ACH. An effective night ventilation system can result in a reduction of about 47 per-cent in annual cooling load. Commencement of the night ventilation was set to initiate when the outdoor temperature drops below a particular temperature, say30ºC. Night ventilation will therefore be more efficient during the late summer days, when a cooler night starts earlier. Figure 5.29 shows the results obtained following this study for a day in July and a day in September, with an air change rate of 15ACH. The dashed lines show the start and stop of the night cooling. The positive results associated with this method can be seen as the indoor air temperature is kept lower when the outdoor temperature is increased [41].

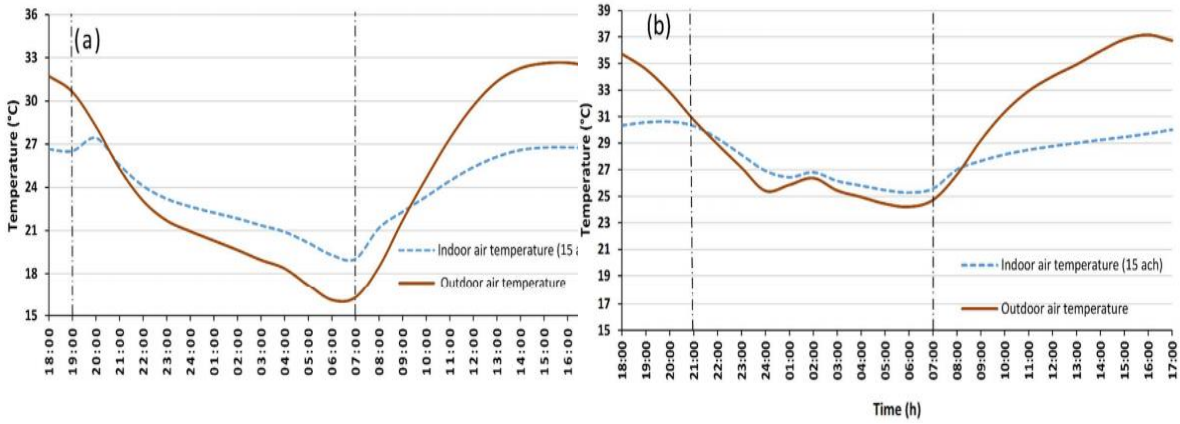


Figure 5.29. Results for implementing Night Purge Ventilation during a day in September (a) and July (b). Source: [41]

5.7.2 Operational Details

The simulation on the model was conducted two times, one condition to simulate open apertures during the day and closed at night, and another to simulate having the apertures closed during the day and opened during the night. In section 5.6.1 the experiment for study analysed was carried out in a way to initiate night purge ventilation with temperature drop. A different approach was adopted in this section where the apertures resulting in night ventilation will be left open daily from 20:00-06:00 as shown in Figure 5.30. Table 5.8

```
per| start|sensed  |actuated | control law     | data
no.| time |property|property |               |
a  1   0.00 outside ambient >  on / off        0.00 1.00 0.00
b  2   6.00 outside ambient >  on / off        0.00 1.00 1.00
c  3  20.00 outside ambient >  on / off        0.00 1.00 0.00
```

Figure 5.30. Operational data using ESP-r for the full house model

Table 5.8. Aperture opening times

Design	Apertures Status 00:00-06:00	Apertures Status 06:00-20:00	Apertures Status 20:00-24:00
Open at Night	■	□	■
Open at Day	□	■	□

5.7.3 Result Analysis

Figure 5.32 and Figure 5.31 display the graphical results of the DBT in the kitchen/living and bedroom_1 zone during the first week of August. Both results show how the inside temperature follow a similar trend to the ambient temperature, as with the majority of previous results. During hour 87, an evident drop in ambient temperature of 1.5ºC can be seen, this in turn had an effect in the zone temperature in the following hours. The lowest temperatures, 26.1ºC in the kitchen/living zone and 25.6ºC in the bedroom_1 zone were registered after this period. Both temperatures were registered when the simulation was run to study the effect of night cooling, i.e. the apertures were modelled as open from 20:00-06:00. These results are indicative of the benefits of applying night purge ventilation. As will be seen in section 5.6.3.2, ACH is essential to provide optimal results.

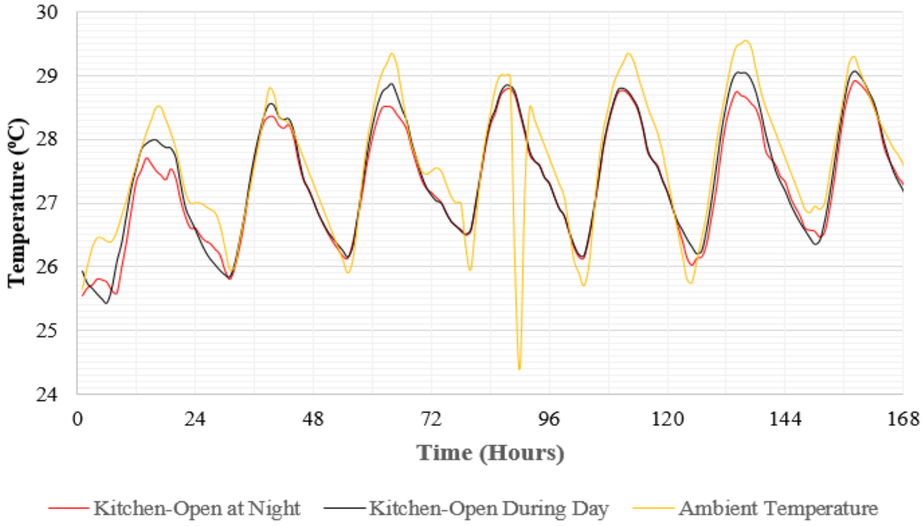


Figure 5.32. Kitchen/Living Zone DBT results for the first week of August

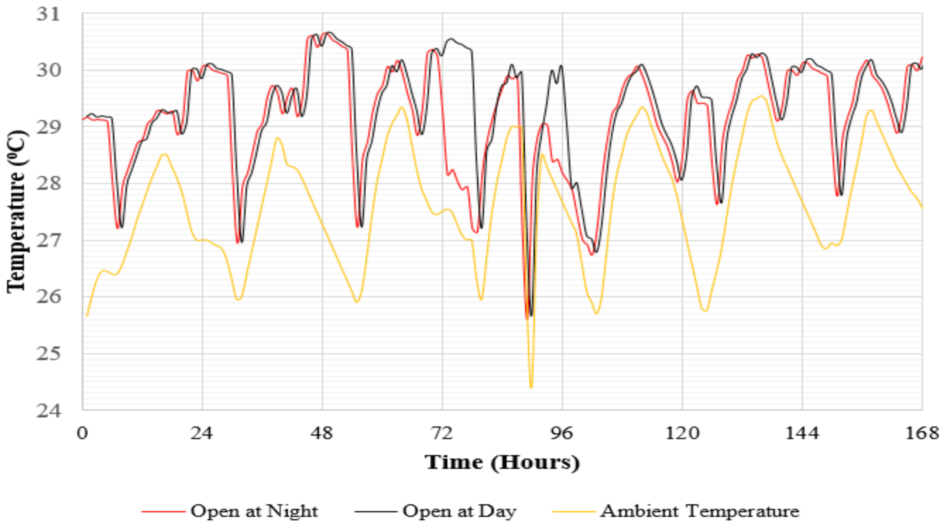


Figure 5.31. Bedroom_1 Zone DBT Results for the first week of August

Figure 5.33 shows the resultant zone temperature drop when compared to the ambient temperature for the first 2 weeks of the month of August. A negative value shows a higher inside temperature (when compared to the ambient temperature) whilst a positive temperature difference indicates a cooler internal temperature. Comparing the graphical results, it is evident that a temperature drop is more common to occur during daytime.

As predicted and as previously discussed, a temperature drop during the time is more commonly obtained with night purge ventilation. The kitchen/living resulted in higher temperature drops, this being synonymous to the larger apertures located in this zone. The temperature difference never resulted in higher than 1ºC than the ambient temperature, however this would still result in a higher energy efficiency as lower cooling loads would be required to maintain thermal comfort in the zone during the night time period.

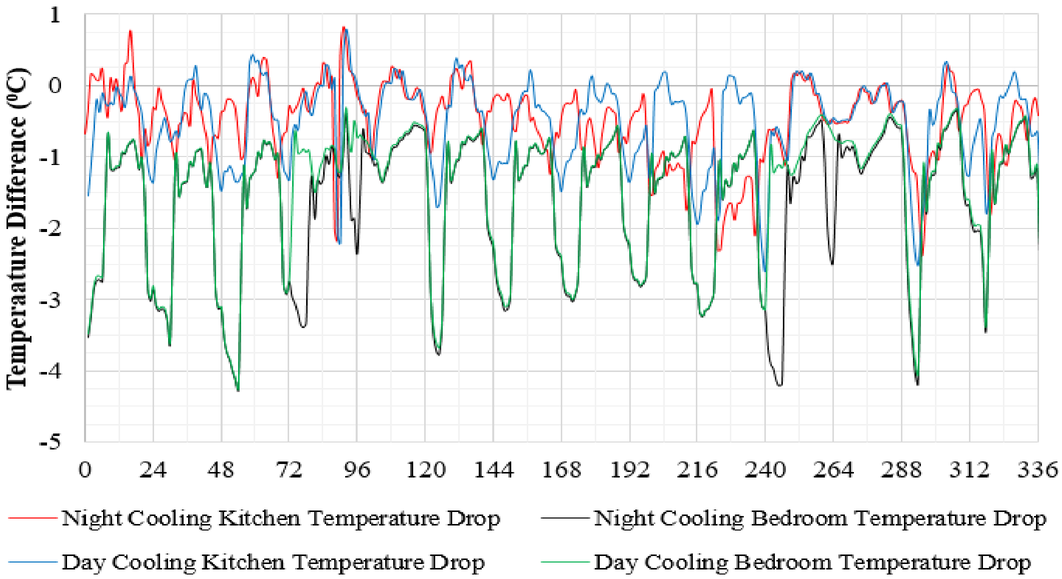


Figure 5.33. Zone and Ambient Temperature comparism

5.7.3.2 ACH and Temperature for Night Purge Ventilation

Figure 5.34 shows the DBT results obtained for the kitchen when night purge cooling was modelled. Superimposed on the same graph are the air change rates which were calculated using equation 5.1. This graph indicates that with an increased air change rate, the temperature drops, as suggested by the literature by Solgi et al. in [41]. The yellow boxes indicate three distinctive days which will be more thoroughly analysed. Days 3, 17 and 22 were selected as these are an indication of a low, medium and high ACH value.

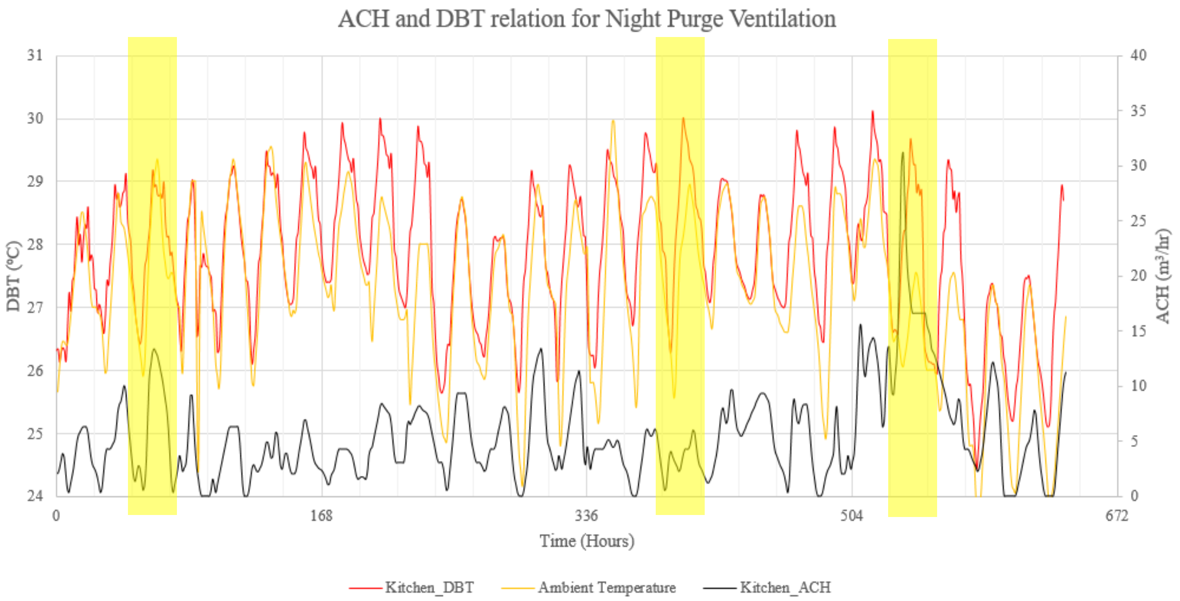


Figure 5.34. ACH and DBT relationship for the kitchen/living zone

5.7.3.3 Effect of ACH on Night Purge Ventilation - Daily result

Figure 5.36 shows that a lower temperature is achieved with a higher air change rate, a result which can be compared to previous studies such as results shown in Figure 5.35**,** which shows how an in fact an increase in air change rate results in a higher temperature reduction.

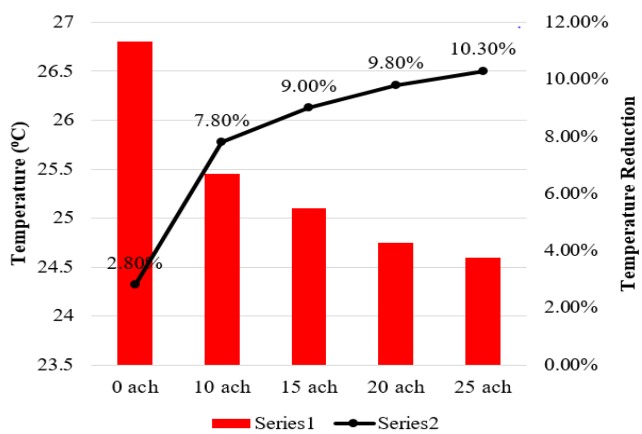


Figure 5.35. Relationship between temperature reduction and ACH, Source: [41]

The results from the simulation follow a similar trend in which, similarly to the ambient temperature, lower temperatures are more common during the night period which then increase throughout the day period and then decrease again during the night. Following a night purge ventilation, cooler temperatures were achieved during daytime, resulting in a lower cooling load requirement to maintain thermal comfort throughout the day-and thus improving energy efficiency. The lowest day time temperature was achieved when the air change rate is the highest, at day 22. Between hours 15 and 18, a lower temperature than the ambient temperature was achieved with the minimum being 28.8ºC, 1.2per-cent lower than the ambient temperature. During the same hour, day 3 registered a temperature of 29.3ºC and day 17 registered 29.7ºC, these being 1.7per-cent and 3per-cent higher than the temperature resulted in day 22. The results obtained show the benefits of night purge ventilation, like the results obtained by Solgi et al. as discussed in section 5.6.1. Night ventilation is however limited in its use due to some of the reasons associated with barriers to natural ventilation previously discussed in section 2.2, and it is most likely to be used in offices.

Table 5.9. ACH legend for results shown in Figure 5.36

	Day 3		Day 17		Day 22	
	Kitchen	**Bedroom**	**Kitchen**	**Bedroom**	**Kitchen**	**Bedroom**
Average ACH (m^3/hr)	6.8	18.4	3.4	9.2	17.8	47.9

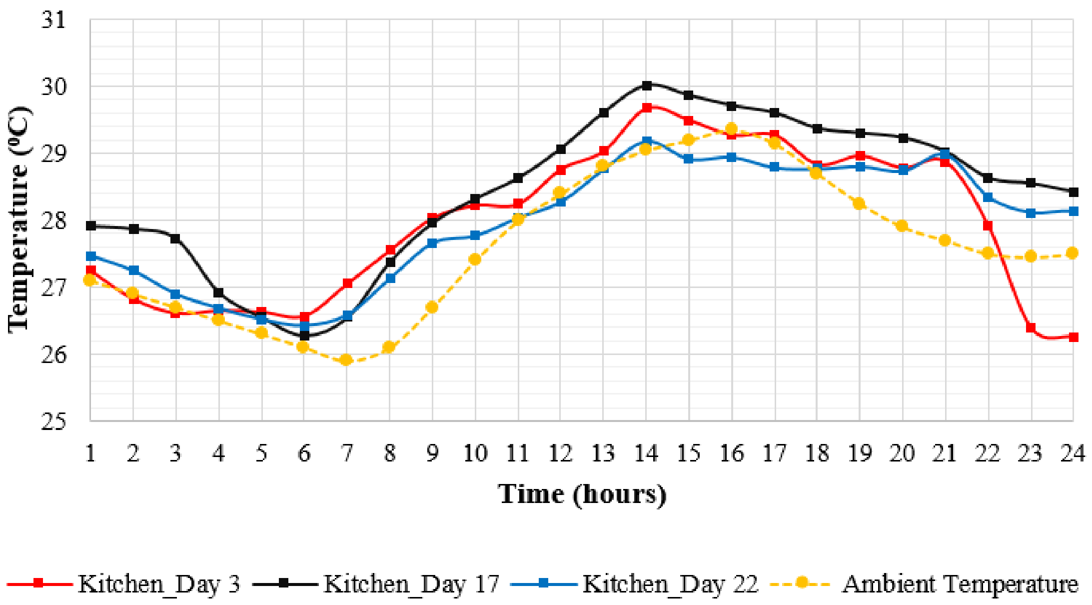


Figure 5.36. Results for the kitchen/living Zone DBT with increased ACH

5.8 Overview of Analysis

The results obtained from these simulations show the effective implemented design to improve thermal comfort by natural ventilation. Table 5.10 gives an overview of the zone's area and apertures area, and as discussed in section 2.5.2 an effective aperture for natural ventilation should be at least 5 per-cent in are of the zone's floor. This is the case for all the analysed zones as seen tabulated, thus being a benefit for natural ventilation.

Table 5.10. Aperture to Zone Area ratio

Zone	Area (m^2)	Total aperture area (m^2)	Aperture to floor area ratio (%)
Kitchen/Living	42	7.2	17%
WC	3.9	1.0	26%
Bedroom_1	23.1	4.2	18%
En-suite	5.4	1.0	19%
Bathroom	9.45	1.0	11%
Bedroom_2	12.6	1.0	8%
Bedroom_3	12.6	1.0	8%

The majority of the apertures modelled can be compared to casement windows, shown in Figure 5.37. A study carried out by Wang et al. in [21] compared the flow rate through different window types via a CFD simulations. The results, which are shown in Figure 5.38, show that a higher ventilation rate is achieved with this type of window configuration [21].

Figure 5.37. Casement Window Source: [51]

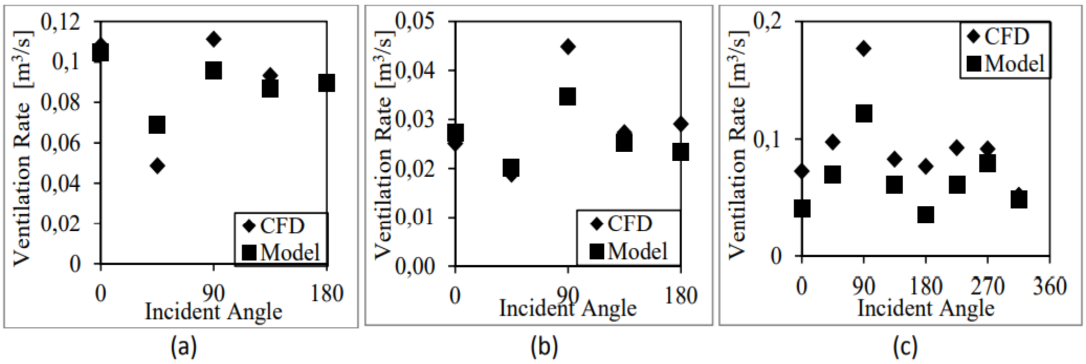


Figure 5.38. Ventilation rate results for different window configurations. (a) hopper (b) awning (c) casement. Source: [21]

5.9 Conclusion

The results discussed in this section show an evident drop in internal temperature with the introduction of a natural ventilation system. Systems modelled in this section were simple apertures, having a simple rectangular geometry such as doors and/or windows. The temperatures achieved in the zones when the apertures were modelled as open show that thermal comfort could be achieved. The building analysed, which was recently subjected to alterations, showed to be enough to produce comfortable living conditions. However, at times the occupants will choose to use HVAC instead of natural ventilation due to a number of drawbacks as discussed in section 2.2. Indoor air quality could be improved by high levels of air change rates, which according to several studies and paper carried out by Wargocki in [42] should be higher than 0.4 ACH to avoid any health risks.

The optimal temperature that can be achieved inside a building via natural is that of the outdoor temperature. Keeping a steady indoor temperature as the outdoor temperature increase can signify a well-designed naturally ventilated system.

Chapter 6 will first and foremost explore an improved ventilation system with the introduction of an extra window in the kitchen/living zone resulting in cross ventilation, a simple wind catcher design, and an added window in the kitchen/living zone to explore the use of a net in the aperture-thus tackling some of the drawbacks associated with natural ventilation. The idea behind the alterations carried out was that to obtain a higher energy efficiency building even through the use of materials, such as the double-glazed windows.

Summative Points

- When the apertures are closed, extremely high temperatures result in the zone mainly due to the internal gains.
- Solar gains have a major effect on the internal temperature when the apertures are closed.
- Night purge ventilation was proven to be effective in reducing the temperatures during the day thus resulting in a lower cooling load need to reach thermal comfort throughout the day.
- Natural ventilation plays a major role in improving the thermal comfort in a building.

- Improving the air flow by enlarging the aperture size also results in a higher air change rate which is essential in having good IAQ.
- Altering the height, rather than the width, of the aperture results in a more effective way to improve natural ventilation due the stack effect.

6. DESIGN AND ANALYSIS OF AN IMPROVED NATURAL VENTILATION SYSTEM

6.1 Added Window in Kitchen instead of W.C.

This section explores the benefits of adding an aperture to a room in terms of improving natural ventilation. As can be observed from the architectural plans in Figure 4.2, the WC zone, which is directly linked to the kitchen/living zone via a door is also linked to an internal court. This model explores the results of having a window instead, just creating a direct link between the kitchen/living zone and the internal court. Such a design can be achieved in the current model by opening both the WC door and WC window, thus creating a cross ventilation.

6.1.1 Added Window in Kitchen/Living Zone CAD Drawing

Figure 6.1 shows the CAD drawing with the added window instead of the WC zone which is indicated by the red box. This model is identical to the simulation which was analysed in section 5.2, with an added window which is externally facing. The aperture is modelled to be on a long-shaded wall, thus having a pressure coefficient index of 9.0. The door and window apertures to the court and the door dividing the corridor and kitchen/living zone were kept unchanged.

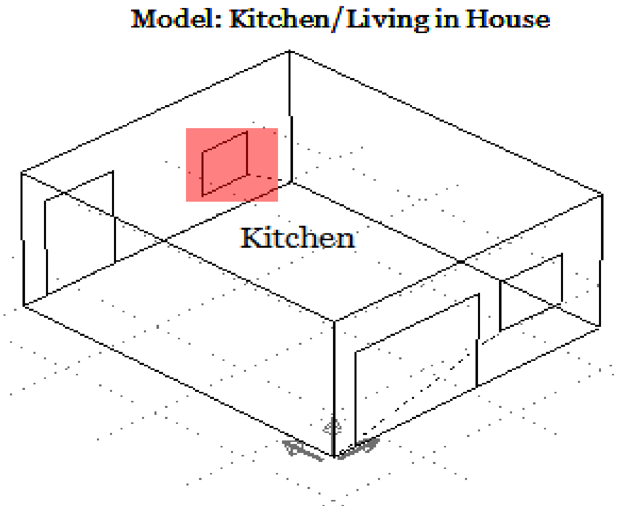


Figure 6.1. Kitchen/Living with added Window Zone CAD Drawing

6.1.2 Added Window in Kitchen/Living Zone Network Flow

The network flow in this model was set in a way to link the court (boundary node) to the kitchen/living zone and then the kitchen/living zone to the corridor via the door and to the internal court via the window on the opposite wall. This creates a cross ventilation system which was discussed in section 2.6.2.

6.1.3 Added Window in Kitchen/Living Zone Results

The simulation for this model explored 3 different configurations. In all simulations, the window to court and door to court aperture sizes remained unchanged having an area of 1.54m^2 and 2.84m^2 respectively. the added window was designed to have an area of 1m^2 and constructed from double glazed glass. Three simulations with changed window area resulted in 3 different results which are tabulated in Table 6.1. The biggest temperature difference can be seen from when design 1 is compared to designs 2 and 3. The designs having an added extra window yielded a maximum temperature which is over 9.5per-cent lower. The values obtained from this design are much higher when compared to other simulations, but this model was mainly conducted to explore the benefits of cross ventilation over single-sided ventilation. The high temperatures obtained in this simulation are synonymous with the high operational gains associated with the kitchen/living zone.

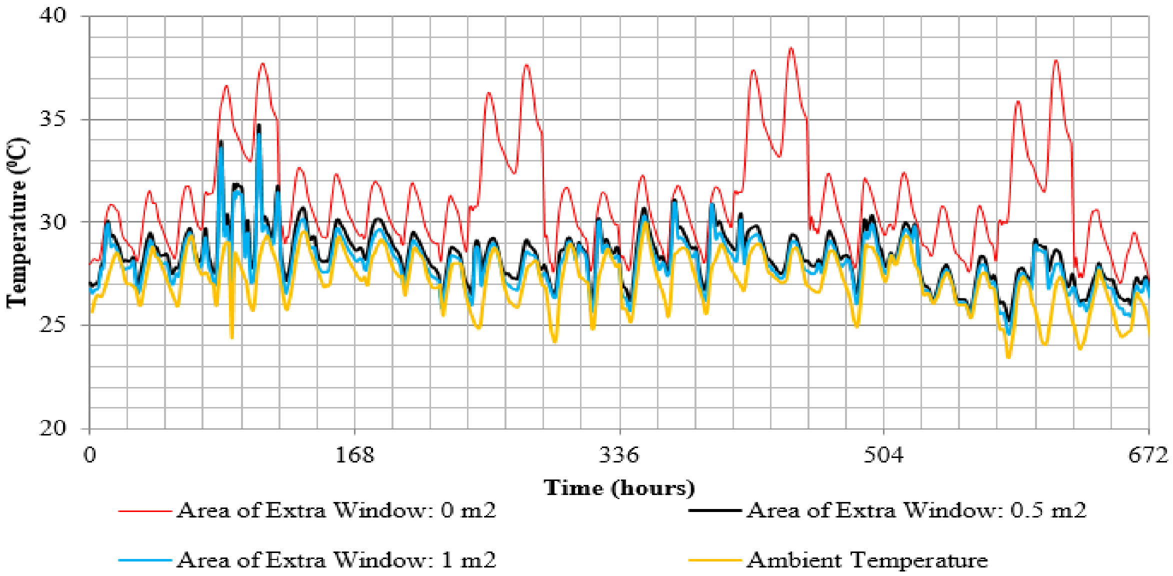


Figure 6.2. Kitchen/Living Zone DBT Results during the month of August

Table 6.1. Design Parameters for the extra window model simulation

Design No.	Extra Window Surface Area (m^2)	Registered Max. Temperature (ºC)	Registered Min. Temperature (ºC)
1	0.0	38.48	25.9
2	0.5	34.72	24.7
3	1.0	34.3	27.9

6.2 Wind Catcher Design

This section explores the benefits of adding a windcatcher, which was discussed in section 2.11, or a similar design in terms of increasing energy efficiency as thermal comfort in the model. As will be discussed in section 6.2.2, a simple model was created in order to analyse the wind catcher whose inlet will be in the corridor zone.

The modelling of the wind flow through a well-designed wind catcher can be a tedious and time-consuming process. For a thorough analysis, the use CFD software packages would be many of the times required. A brief study of an introduction of a wind catcher is carried out in this individual project. Assumptions, and a basic wind catcher model were created using the ESP-r software package to have an overview of what benefits designing a wind catcher, or something similar, would have on the thermal comfort inside the building.

6.2.1 Wind Catcher Potential

As can be observed by the Maltese wind rose pictured in Figure 6.3, high wind velocities (mainly from the west direction) are very common in Malta. Due to the design of the majority of the Maltese houses, wind benefits are not fully exploited. Introducing a wind catcher, or a similar design would mean that the all the top surfaces can absorb all the wind, thus maximising air flow, and thus improving NV and increasing the thermal comfort. Appendix B Table B.1 gives a summary of the wind velocities and direction registered in Malts during the year 2016. These values confirm the potential of applying a wind catcher facing the West direction. Table 6.2 gives a summary and an idea of the high wind velocities which are common in the Maltese Islands. , which give a better representation of the potential of a wind catcher in the Maltese Islands due to the high wind velocities, and predictable direction. [43]

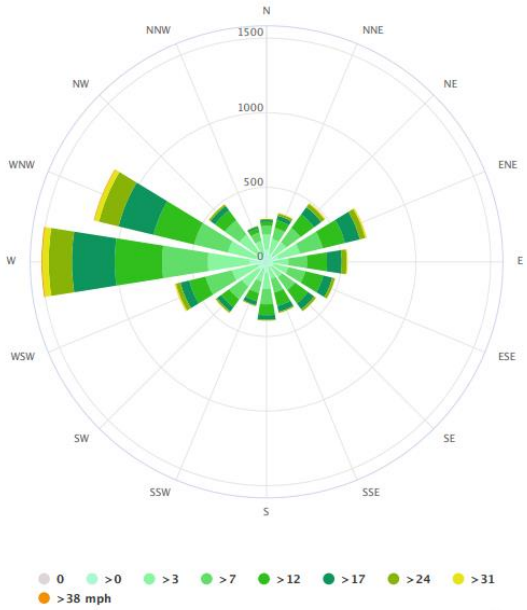


Figure 6.3. Wind rose for the year 2016 Source [52]

Table 6.2. Wind Velocites reached during the warmest months; May, June, August, Septemer

	May (days)	June (days)	July (days)	August (days)	September (days)
0 mph	0	0	0	0	0
>0 mph	0.3	0.3	0.3	0.3	0.1
>3 mph	4	6.5	8.4	8.6	4.2
>7 mph	7.8	9.4	12.5	12	9.1
>12 mph	8.4	8.1	6.5	6.5	9.5
>17 mph	6.6	4	2.5	2.7	5.2
>24 mph	3.4	1.6	0.9	0.8	1.9
>31 mph	0.5	0.1	0	0	0.1
>38 mph	0	0	0	0	0

6.2.2 Wind Catcher CAD Drawing

The wind catcher is modelled in ESP-r as an individual zone located in the place of the inerior court. The wind catcher is linked to the corridor via an outlet. Four inlets (one on each side) at the top of the wind catcher are modelled to replicate a window aperture having a fully exposed boundary node. The schematic of the ground floor and wind catcher can be seen in Figure 6.4. All the properties are kept unchanged from the model analysed in section 5.4.

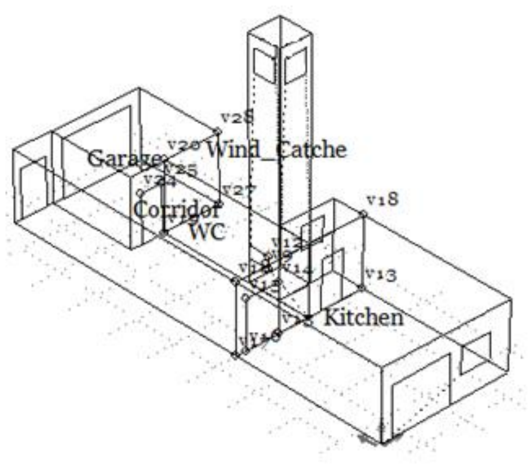


Figure 6.4. CAD Drawing of Ground Floor with Wind Catcher

6.2.3 Wind Catcher Result Analysis

Similarly to section 6.1, this model will explore the benefits of an added component in the model that aims at improving the NV in a building. The graphical results for the kitchen/living zone and the corridor zone shown in Figure 6.5 and Figure 6.6 compare the addition of the wind catcher. Table 6.3 summarises the parameters used to simulate different conditions for comparism.

Table 6.3. Parameters used in the Simulation for an added wind catcher

Design No.	Wind Catcher Outlet	Kitchen/ Living door	Kitchen/ Living Window	W.C. Door	W.C Window	Corridor Door	Garage Door	Garage Opening	Entrance door
1	■ (0.5)	■	■	□	■	■	□	□	□
2	□	□	□	□	□	□	□	□	□
3	■ (1.0)	■	■	□	■	■	□	□	□

6.2.3.1 Kitchen/Living Zone Analysis

As can be clearly observed in the graphical results shown in Figure 6.5, adding an inlet in the corridor zone results in a drastic drop in the DBT for the kitchen/living zone. The hot temperatures associated with the kitchen/living zone are a result of the high operational gains of both the occupants and cooking appliances. The maximum temperature recorded when all apertures were closed was 36.27ºC, which drops down by over 16per-cent to 30.3ºC in model 1 and 29.9ºC in model 3, when the outlet from the wind catcher in the corridor was modelled as open. The DBT in the kitchen/living zone kept a similar trendline to the ambient temperature, apart for the second and third day of the week for design number 3 (yellow box). The average DBT for this modelled resulted in 27.8ºC which is 1ºC less or 3.5per-cent when compared to the average temperature for design 1. This temperature decrease is synonymous with the introduction of a larger outlet (area of 1m^2 instead of 0.5m^2) from the windcatcher into the corridor.

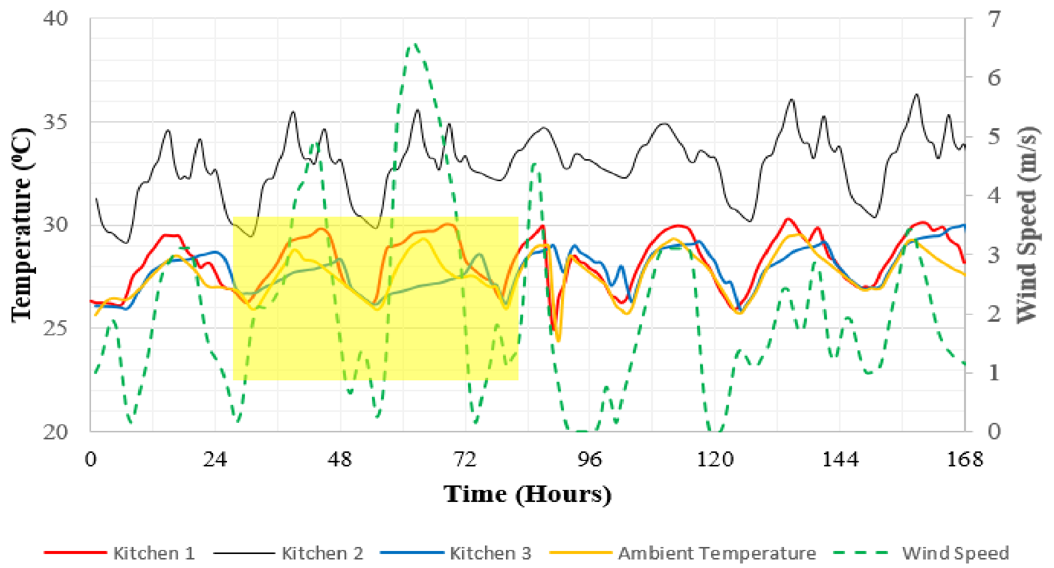


Figure 6.5. Kitchen/Living Zone DBT results for the first week of August

6.2.3.2 Corridor Analyses

When all apertures and interior doors are modelled as closed, the model registers the maximum DBT which is reached in the sixth with the kitchen/living zone, this temperature is considerably low since there are no associated operational gains with this zone. As with much of the simulations, the DBT results follow a similar trendline which increases till, and over mid-day and then decreases by night.

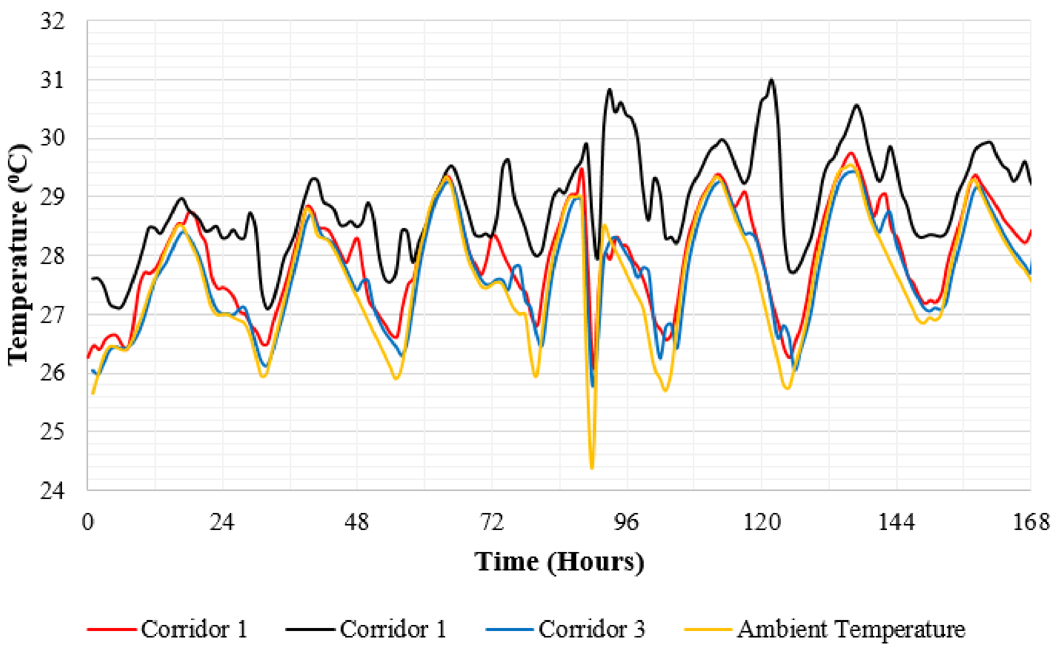


Figure 6.6. Corridor Zone DBT Results for the first week of August

6.2.3.3 Wind Catcher Analysis

The highest temperatures are reached when the outlet is left closed, thus accumulating or solar gain in the wind catcher itself. The highest temperatures when the outlets are closed are reached during night time. This implies that the solar gains accumulated during the day remain trapped in the tower at night time since there is a lack of ventilation.

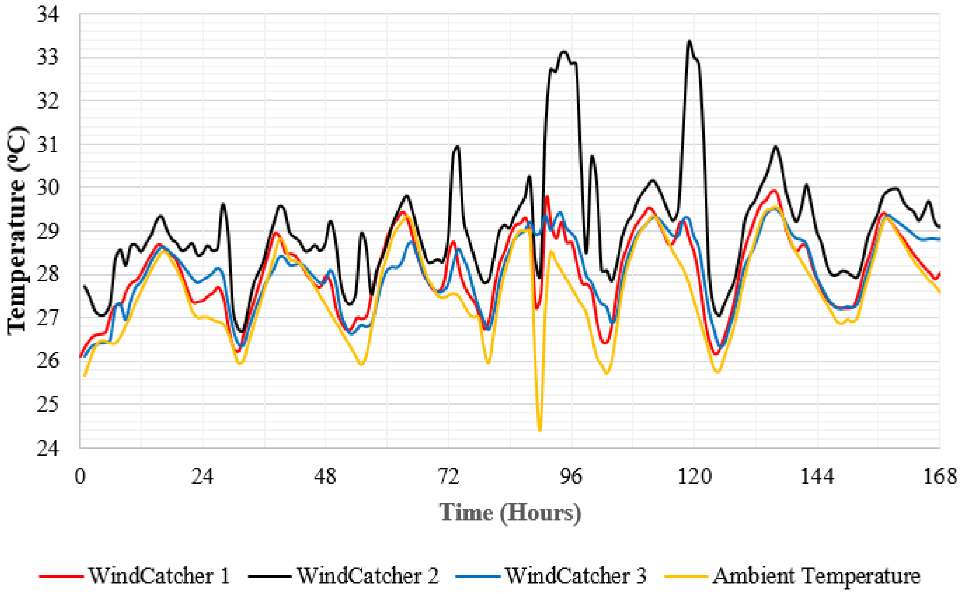


Figure 6.7. Wind Catcher Zone DBT results for the first week of August

6.3 Netted Window

Introducing an extra opening with a netted window will be beneficial in improving the natural ventilation, even when all the apertures are closed to overcome some of the drawbacks associated with having open apertures. The addition of a net will mainly reduce problems associated with bugs and insects. This section will explore this improvement solely on the kitchen/living zone. The main idea of including a netted aperture is to have an element of NV in the zone. This in turn would result in the need of a lower load when operating an HVAC system to reach the desired comfort.

6.3.1 CAD Drawing

Figure 6.8 show the CAD drawing for the kitchen/living zone with an added aperture with a net. The figure on the left shows a configuration where the opening is placed next to the window having a total surface area of 1m^2. The second configuration sees an aperture added on the top of the wall with a surface area of 2.5m^2. A simulation for the two nets was carried out and the results obtained for an August day were analysed and compared to a condition were no ventilation is present and to a realistic condition which was discussed in section 5.4.2.

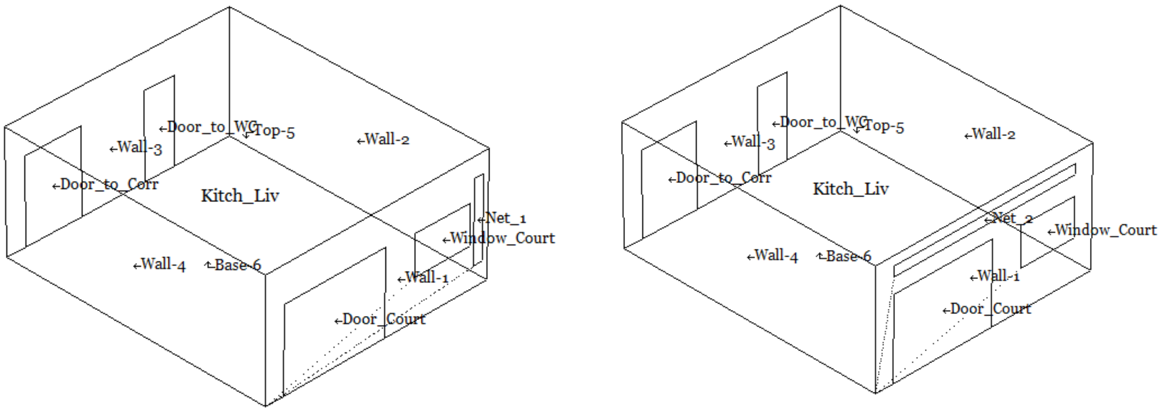


Figure 6.8. CAD model with different net configurations. Net_1 (Left), Net_2 (Right)

6.3.2 Aperture Parameters

The simulation was carried out by altering the coefficient of discharge associated with the openings. As previously described in section 2.9.2, for an open window a coefficient of discharge, C_d, between 0.6-0.65 is usually obtained. In fact, in previous simulations, all apertures were modelled with a C_d of 0.6. To model a net, this value should be lower. The coefficient of discharge was chosen according to the results of a study carried out by López et al. on insect-proof screens in [44]. The results obtained in this study can be seen in Figure 6.9 with the parameters for the screen tested given in Table 6.4. The average wind velocity according to the data obtained is 2.6m/s, and therefore the simulation was carried out with a C_d of 0.25, to model on an average value obtained from insect-proof screen 2.

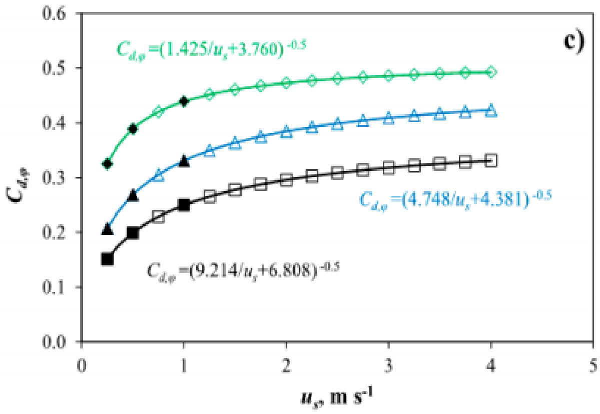


Figure 6.9. Results for Coefficient of Discharge for insect-proof screen. Source:[44]

Table 6.4. Properties for insect-proof mesh studied in [44]

Insect Proof Number	Percentage Porosity	Thread density (threads/cm^2)
1 (blue)	35.0	9.8 × 20.0
2 (black)	26.3	12.5 × 31.3
3 (green)	36.0	9.6 × 20.3

6.3.2 Results Analysis

Figure 6.10 shows a graphical representation for the indoor results obtained on a typical August day for the kitchen/living zone when an aperture fixed with a mesh is added. Four results are superimposed for comparism. Each result shows a similar trend where the higher temperature is recorded around mid-day. The green line visualises the results obtained when all apertures are closed, thus having no ventilation and as predicted reaches higher temperatures. Use of an HVAC system would be required in order to improve the thermal comfort. Including a netted aperture would drastically decrease the indoor temperature by up to over 2ºC, resulting in a lower requirement of a cooling load to reach the desired level of comfort. The two designs shown in Figure 6.10 yielded in comparable results with a slight positive difference with net_2 configuration, this having a larger area.

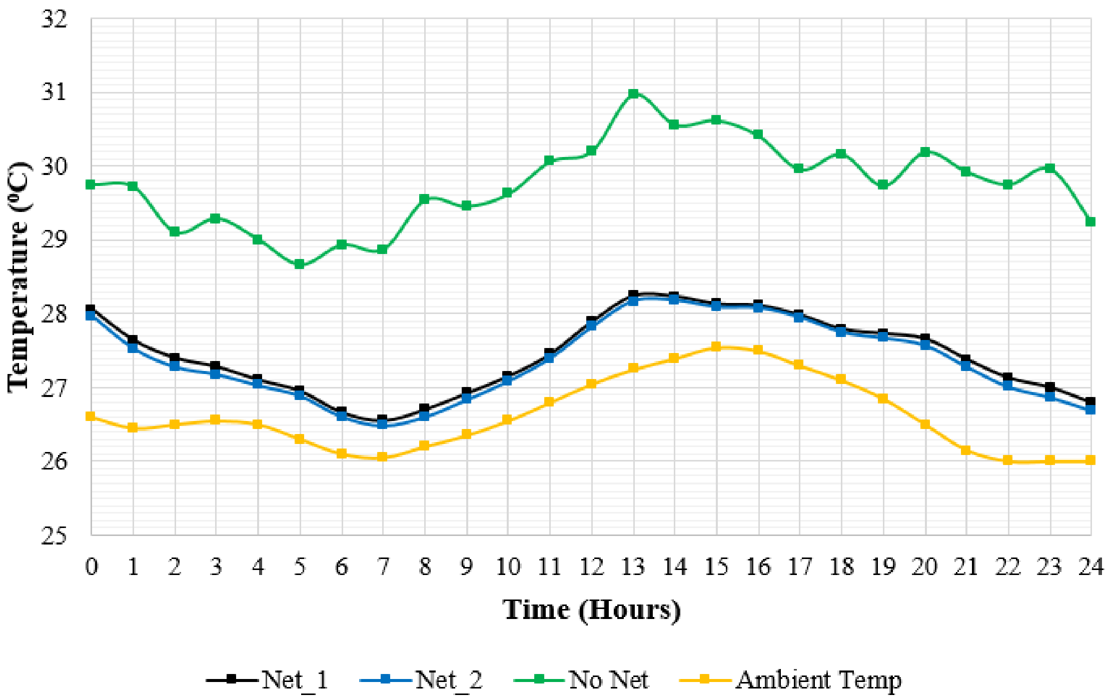


Figure 6.10. Added aperture with net results

6.4 Conclusion

Chapter 6 explored the benefits of introducing better designed natural ventilation system. Analysis for added components was done in three different design simulations. The first saw an added window in the kitchen/living zone, thus creating a cross-ventilation and this in turn improved the thermal efficiency in the building. This can be easily achieved by opening both the window in the WC zone and the door dividing the kitchen/living zone and the WC zone.

Applying in the actual house requires minimum effort and is very easily achievable. Another simulation saw an added zone to the building- a wind catcher. This modification is perhaps the least likely to be implemented due to the construction requirement. The main idea behind this was to introduce another inlet, thus increases airflow naturally inside the building. A final design alteration included an extra inlet in the kitchen/living zone with a net. This was done to tackle drawbacks associated with natural ventilation such as insects and rain but yet still provide means of ventilation. This modification also requires minimal effort by the occupants as nets can be easily bought and implemented in any aperture of any room.

Summative Points

- Cross ventilation resulted in being more effective in providing a better air flow and thus better thermal comfort.
- Wind catchers, which are common in warm Arabic countries do in fact provide better means of natural ventilation.
- A netted window can provide means of natural ventilation and also reduced some of the major drawbacks associated with natural ventilation.

7. CONCLUSION

7.1 Project Overview

This project provided the basis to understand the fundamentals of natural ventilation, primarily achieved through the completion of numerous building simulations using the software package ESP-r and a thorough investigation of the results obtained.

Understanding the physics behind natural ventilation was of great advantage when it came to the understanding of the resulted data. Also, this was of a great benefit when to understand what was happening in the simulation, and why these results were achieved. This gave the possibility to be able go into a deeper analysis.

7.2 Key Findings

The benefits of implementing natural ventilation in warm countries was an evident finding after a thorough analysis of some of the simple ventilation systems which are found in many of the houses located in Malta.

The main systems analysed included doors and windows as a means to introduce natural ventilation in a zone. The dimensions of each were carefully altered and results associated with the new configuration analysed to understand their primary effect on ventilation and thermal comfort. The obtained results showed that a higher energy efficiency can be achieved in any building, located in a warm climate just by a well-planned design.Both single-sided and cross-ventilation systems where included in the simulations, and as predicted, cross-ventilated systems turned out to be more effective in terms of improving the flow within a zone and therefore improve thermal comfort by reducing the temperatures.

Natural ventilation can also be applied to attain a better indoor air quality whilst also improving the thermal comfort. All the simulations carried out in this project resulted in much higher values of air change rates, thus limiting the risks of health issues in the home by the already existing natural ventilation system. Being located in a quiet residential area, intrusion of pollutants caused by vehicles will be highly unlikely, another positive factor of natural ventilation in the studied house.

The results that were obtained and analysed in section 5 and section 6 prove that a well-ventilated system would aid in a temperature drop. In many instances, a relation between the ambient temperature and zone temperature was investigated, with both following a similar trendline. Results showed that in many instances, the indoor temperature was affected by the ambient temperature. The higher temperatures achieved when the apertures were modelled as closed show the large benefits associated with ventilation when it comes to improving the thermal comfort. Having obtained similar temperature values to the ambient temperature show that in fact, the optimal indoor temperature could be achieved with the implementation of large apertures in a correct location.

Theoretically, it is possible to achieve a nearly zero energy building (NZEB) with a well implemented natural ventilation design. Improvement of energy efficiency and thermal comfort can also be achieved by carrying out small modifications in the house. However, due to several drawbacks associated with natural ventilation a number of limitations arose. To overcome these problems, a simple design and modification was conducted on the house model and simulations were run to show the effect that these modifications could have on the comfort of the house. Chapter 6 saw the analysis for a modification on the design, these were simple improvements which could be easily implemented such as netted windows others much less, such as the construction of a wind catcher.

7.3 Challenges During the Completion of the Project

A major challenge associated with the completion of this project is the result validation process. Validation was limited due to time restrictions and the location of the building which was studied. A number of available literature and results from published papers were analysed and compared with the results obtained throughout this project to improve the credibility of the simulated results.

Another challenge that was common with the completion of this project involves the use of software packages. The main energy modelling package used throughout this simulation was ESP-r, with the author having basic knowledge following a unit completed during the first trimester of the course. This was essential to understand the basics of the software; however, a more in-depth knowledge was required to achieve credible and accurate results. A large time frame has been dedicated to further improve skills associated to energy in building modelling, which resulted in less time to tackle other aspects of the project, such as a deeper analysis of the obtained results.

7.4 Future Work and Recommendations

In order to validate the simulations, different studies were analysed and results compared. In doing so, it was confirmed that no odd results where attained. Future work can include a similar study on a building with added validation techniques such as monitoring of the temperatures in the actual site. Adding simulation software such as CFD and comparism of the generated results could also be an improvement in the validation process for this project. Optimisation could also be carried out with packages like CFD which can aid in finding the optimal dimensions for all the inlets/outlets and apertures, guaranteeing maximum energy efficiency whilst also helping in achieving an ideal thermal comfort.

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A. APPENDIX

Table A.1Dwelling type, stock and quantity as per census 2011, Source [28]

Dwelling Type	Area m^2	Quantity as per census 2011
Detached Villa	176	1,030
Owner Developed Semi Detached Villa	235	2,575
Speculatively Developed Semi Detached Villa	235	1,545
Post war Terraced House	219	42,030
Pre-war Urban Terraced House	219	9,380
Pre-War Rural Terraced House	201	9.380
Post War top floor Maisonette	89	14,305
Post War Ground Floor Maisonette	89	14,305
Pre-War top floor Maisonette	129	3,810
Pre-War ground Floor Maisonette	105	3,810
Post war top floor Flat	74	15.675
Post was mid floor Flat	74	15.675
Pre-war top floor Flat	105	1,790
Pre-was mid floor Flat	105	1,790

Table A.2. Material Properties used in simulation

Material	Main application in house	U-Value (W/m^2K)
Aluminium (with thermal break)	Window Frame	1.0
Bricks (12 inch)	Building Material	0.31
Concrete (high density – 12 inches thick)	1st floor and roof	0.55
Double glaze window – low-E Argon filled	Window material (New design)	1.9 [34]
Limestone	Façade material	1.26
Metal door (Steel)	Garage door (Old design)	1.2 [32]
Single glaze window	Window material (Old design)	4.8
Travertine	New Ground floor tiles	0.22

Table A.3. Casual gains in Simulation

	Period	Remarks	Sensible Heat (W)	Latent Heat (W)
		Kitchen/Living Area		

Occupancy **(Weekdays/Weekends)**	00:00 – 07:00	Occupants sleeping	0	0
Occupancy **(Weekdays)**	07:00 – 08:00	Occupants in kitchen/Living	70	50
Occupancy **(Weekdays)**	08:00 – 17:00	Occupants at work	0	0
Occupancy **(Weekdays)**	17:00 – 24:00	Occupants in Living/Kitchen	70	50
Occupancy **(Weekends)**	07:00 – 11:00	Occupants in kitchen/Living	70	50
Occupancy **(Weekends)**	11:00 – 14:00	Occupants doing errands	0	0
Occupancy **(Weekends)**	14:00 – 00:00	Occupants most likely to be in Kitchen/Living	70	50
Lighting **(weekdays/Weekends)**	00:00 – 07:00	OFF	0	0
Lighting (300 LUX) **(weekdays/Weekends)**	07:00 – 09:00	ON (8 W/m^2)	42	/
Lighting **(weekdays/Weekends)**	09:00 – 19:00	OFF	0	0
Lighting (300 LUX) **(weekdays/Weekends)**	19:00 – 00:00	ON at (8 W/m^2)	42	/
Others **(Oven/Stove)**	00:00 – 12:00	OFF	0	0
Others **(Oven/Stove)**	12:00-14:00	ON	350[1]	150
Others **(Oven/Stove)**	14:00 – 19:00	OFF	0	0
Others **(Oven/Stove)**	19:00 – 21:00	ON	350	150
Others **(Oven/Stove)**	21:00 – 00:00	OFF	0	0
		Bedrooms		
Occupancy **(Weekdays)**	00:00 – 07:00	Occupants sleeping	70	50
Occupancy **(Weekdays)**	07:00 – 24:00	Occupants not in Bedroom	0	0
Occupancy **(Weekends)**	00:00 – 09:00	Occupants Sleeping	70	50
Occupancy **(Weekends)**	07:00 – 24:00	Occupants not in Bedroom	0	0

Table A.4 Network Flow Criteria

Node	**Internal/External Node**	**Pressure Coefficient Index**

[1] The value assumes the use of either the oven or the stove, thus the rounded value of 700 W was averaged

Kitchen/Living	Internal	-
WC	Internal	-
Corridor GF (Ground floor)	Internal	-
Garage	Internal	-
Corridor FF (First Floor)	Internal	-
Bedroom 1	Internal	-
Bedroom 2	Internal	-
Bedroom 3	Internal	-
Bathroom	Internal	-
Bedroom 1 En-suite	Internal	-
Bedroom 1 walk-in wardrobe	Internal	-
Door_Court (Door in Kitchen/Living Zone)	Boundary Node – Wind induced pressure	5.0 (Semi-Exposed Wall)
Window_Court (Window in Kitchen/Living Zone)	Boundary Node – Wind induced pressure	5.0 (Semi-Exposed Wall)
WC window	Boundary Node – Wind induced pressure	9.0 (Long Sheltered wall)
Entry Door (Entrance door in corridor)	Boundary Node – Wind induced pressure	1.0 (Fully Exposed)
Garage_Door (Door in garage)	Boundary Node – Wind induced pressure	1.0 (Fully Exposed)
Bedroom 1 Window	Boundary Node – Wind induced pressure	5.0 (Semi-Exposed Wall)
Bedroom 2 Window	Boundary Node – Wind induced pressure	5.0 (Semi-Exposed Wall)
Balcony (in bedroom 1)	Boundary Node – Wind induced pressure	1.0 (Fully Exposed)
Window in Bathroom	Boundary Node – Wind induced pressure	5.0 (Semi-Exposed Wall)
Window in en-suite	Boundary Node – Wind induced pressure	1.0 (Fully Exposed)

Table A.5 Modelled Zones

Zone	Location	Base/Floor Area (m^2)
Kitchen/Living	Ground Floor	42.00
WC	Ground Floor	3.75
Corridor_GF	Ground Floor	48.50
Garage	Ground Floor	21.00
Bedroom_1	First Floor	23.10
En-suite	First Floor	5.40
Walk-in wardrobe	First Floor	4.50
Bathroom	First Floor	8.10
Bedroom_2	First Floor	16.80
Bedroom_3	First Floor	12.60
Corridor_FF	First Floor	34.00

B. APPENDIX

Table B.1 Wind velocities and direction for the year 2016. Source:[43]

	North (hr/yr)	North North East (hr/yr)	North East (hr/yr)	East North East (hr/yr)	East (hr/yr)	East South East (hr/yr)	South East (hr/yr)	South South East (hr/yr)	South (hr/yr)	South South West (hr/yr)	South West (hr/yr)	West South West (hr/yr)	West (hr/yr)	West North West (hrs/yr)	North West (hr/yr)	North North West (hr/yr)
0 mph	0	4	1	5	0	4	1	0	10	1	4	0	6	2	4	0
>0 mph	52	57	49	74	41	47	38	36	34	44	64	57	107	70	72	52
>3 mph	92	97	113	151	105	98	90	81	108	90	137	180	280	194	149	92
>7 mph	58	76	118	157	125	118	106	95	10	80	105	183	307	233	120	58
>12 mph	29	54	112	152	134	123	108	93	73	56	66	112	317	279	82	29
>17 mph	13	30	60	103	98	62	50	39	31	28	35	61	287	241	37	13
>24 mph	4	16	28	37	34	19	16	8	5	6	11	31	155	135	13	4
>31 mph	0	3	6	9	6	2	1	1	1	1	3	8	42	32	2	0
>38 mph	0	1	1	1	0	0	0	0	0	0	0	1	6	4	0	0

C. APPENDIX

Excel Results: https://drive.google.com/open?id=0B0_7AqYKq_foWmdjbThTWThMZ2M