



Ethiopian Institute of Architecture, Building Construction and City
Development

Determining Ventilation Orientated Optimum Window Size for
Urban centers of Ethiopia

Matias Deriba Negasa

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School of Graduate Studies

This is to certify that the thesis prepared by Matias Deriba, entitled: Determining Ventilation oriented optimum window size for urban centers of Ethiopia submitted to the graduate studies of Addis Ababa University for the partial fulfilment of the requirements for the Degree of Masters of science in Urban Design and Development complies with the regulations of the University and meets the accepted standards with respect to originality and quality.

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Matias Deriba

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Advisor: Tibebu Assefa (PhD)

November, 2020

Abstract

Natural Ventilation is an effective method for passive cooling, increase indoor air quality and minimize energy consumption of a building. Natural ventilation through window openings is an effective solution to bring air into internal spaces and improve indoor environmental condition. In urban centers, where the density is high and local wind is reduced, the geometry of a building and its opening has a massive role in natural ventilation. The current building codes and regulations of Ethiopia miss detailed guidelines for natural ventilation. On the code and regulation for windows are specified only in relation to the floor area regardless of orientation, height, location and climate. Since the country has different climate zone in different regions, the generalized building code and standard will lead to over or under ventilated rooms in both scenarios creates discomfort. The study attempt to determine ventilation-based window size for urban centers of Ethiopia on different façade orientation to increase the effectiveness of natural ventilation. As wind is the main driving force of natural ventilation, regionalizing of Ethiopia according to wind speed and wind direction (secondary-Inter cardinal direction) is presented in order to study the potential of natural ventilation at different regions in the country. The average wind speed is categorized using the Beaufort's scale of wind speed. The data addresses the urban centers of Ethiopia and the urban centers are selected by density. Both scenarios (single side ventilation and cross-ventilation) are discussed in each zone. Appropriate opening size is determined, using the window orientation with respect to the wind flow direction and also best and worst window orientation is illustrated for each zone. The study verified that, the effectiveness of natural ventilation is associated with wind zone where the urban centers are located.

keywords: Natural ventilation, window size, window orientation, wind map

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Achronyms & Abbreviation

BRE	Building Research Establishment
CIBSE	Chartered Institution of Building Services Engineers
H	Height
HVAC	Heating, Ventilation, and Air Conditioning
IEA	International Energy Agency
ITCZ	Intertropical Convergence Zone
L	Length
NASA	National Aeronautics and Space Administration
NV	Natural Ventilation
OECD	Organization for Economic Co-operation and Development
UFC	Unified Facilities Criteria
UNILA	Federal University of Latin American Integration
W	Width
WFR	Window Floor Ratio
WWR	Window Wall Ratio

CHAPTER ONE

INTRODUCTION

1.1 Background

Natural ventilation is the intentional flow of outdoor air through an enclosure under the influence of wind and thermal pressures through controllable openings. Natural ventilation is a more effective instrument to improve indoor air quality in urban areas, to protect health, to provide thermal comfort and to reduce unnecessary energy consumption (Mat Santamouris, 2005). Natural ventilation in a building means opening a window to let fresh air into a room. The airflow through the opening is due to wind and buoyancy. The wind has a mean and a fluctuating component that may vary over the opening and produce a 'pumping effect'. When the indoor temperature is higher than outdoor, the buoyancy makes the cold air enter at the lower part and the hot air exit at the upper part of the opening (Ghiaus and Roulet, 2005). Wind and stack forces are often combined to design an optimal natural ventilation system. Since the drivers of natural ventilation are inherently variable, natural ventilation has a high variability in effectiveness.

By 2030, 1.1 billion more people will live on Earth bringing the total to about 8.5 billion, (Arsano, 2017). Such an increase in population will result in urban expansion and more pollution, and it will alter the built environment as well as the natural environment. In the urban centers, the city will induce some modifications of the atmospheric boundary layer. For example, moderate to strong winds, and for the same height above ground (20m), a reduction of 20% to 30% in the average wind speed is observed when moving from the countryside into the urban environment (Ghiaus and Allard, 2005).

The size, shape, type and location of the openings, especially the inlets, determine the velocity and pattern of internal airflow. The most common device for natural ventilation is the operable window for which the mechanism involved is primarily wind-driven ventilation, although buoyancy may have a non-negligible effect (Roulet and Ghiaus, 2005). Operable windows are often used to control natural ventilation. They are well adapted to deliver the very large airflow rates needed to evacuate pollutants or to

evacuate heat, particularly for passive cooling. Based on UNILA study, the conditions of natural ventilation were influenced by the size of the windows, as well as by the variation of the angle of wind incidence, which affected significant changes in the values of the pressure coefficients and air change rates per hour. The effect of window size depends on whether or not openings are cross ventilating. If openings are on one surface only, size has little effect on airflow. In cross-ventilated rooms, airflow is determined mainly by the area of the smallest openings, average indoor velocity and number of air changes (UFC, 2004).

To determine the size of windows, it is necessary to obtain a given air exchange rate. The air exchange rates in naturally ventilated buildings depend upon the internal and external geometry of the building and upon the local weather characteristics. In urban canyons where the local wind speed is reduced, the geometry of a building's façade and of its openings plays an increased role. Design decisions for the use of natural ventilation in buildings need an estimation of the appropriate size of the openings and of their location in the façade (Almeida et al, 2005).

In an urban environment, natural ventilation inside buildings is affected by three main geometrical parameters: the canyon geometry, consisting of the ratios of geometric variables such as the height of the buildings (H), as well as the length (L) and the width (W) of the canyon: H/W , L/W and H/L . This study deal with a constant building envelop for all situations to study the efficient opening size. The building configuration regarding potential ventilation paths: single sided ventilation or cross-ventilation; the types of façade geometry and characteristics of the openings (size and location) (Almeida et al., 2005).

Ethiopia lies in the tropical zone. Ethiopian highlands cover most of the country, resulting in cooler climate than other regions on the equator. Most major cities are located in elevated regions over 2000m with mild climate throughout the year. For example, Addis Ababa, the capital city, estimated to have 7204 Natural Ventilation Hours and Bahir Dar in the northwest of the country displays 8136 Natural Ventilation Hours (Chen et al., 2017). Globally, many regions are with abundant potential for utilizing natural ventilation and the majority of Ethiopia lies between 2800 to 8760 hours (Figure 1).

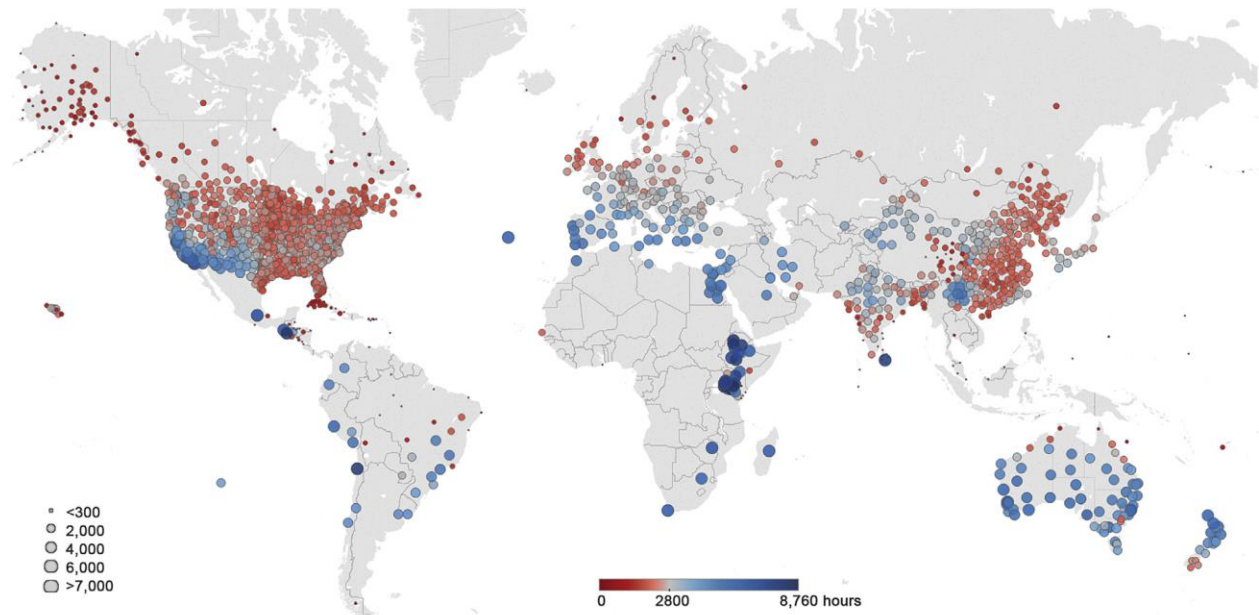


Figure 1: Geographic map of NV hours in 1854 locations. (Source: Y. Chen et al. / Building and Environment, 2017)

1.2 Problem Statement

It is evident that proper ventilation of urban buildings can contribute significantly to reducing the concentration of indoor pollutants and to protecting public health. Since Ethiopia is part of third world, the use of advanced ventilation and filtration techniques is not feasible at all. Thus, natural ventilation may be an effective solution if outdoor air quality is less polluted than indoor air quality. The development of appropriate strategies and techniques to enhance natural ventilation in urban buildings may save millions of lives in developing countries.

In Ethiopia, there is a gap between the actual climatic and environmental context of the country and current codes and regulations. The building code of standards miss detailed guidelines for natural ventilation and the numbers provided shows vagueness. For example on EBCS-II, opening parts of window is specified in relation to the floor area regardless of orientation height local and climate. Ethiopia has different climate zone in different regions but the standard available for buildings natural ventilation is the same. This will lead to over or under ventilated rooms in both case it creates discomfort and health problem. As it is mentioned in different studies, indoor air pollution is responsible for pregnancy-related problems, such as stillbirths, low birth weight, immune system depression and it has been associated with blindness.

Building designers provide openings by giving priority for the aesthetic quality but considering ventilation is also mandatory. Since there is no local standard of size and orientation provided, the designer only refers other countries generalized standard so contextualizing the standard is compulsory.

1.3 Objective

General Objective

- To determine ventilation-based window size for urban centers of Ethiopia on different façade orientation.

Specific Objective

1. To regionalize Ethiopia based on wind speed and wind direction to identify representative zones.
2. To determine the window size for natural ventilation using wind speed and wind direction diagram.

1.4 Research Questions

1. How to regionalize Ethiopia based on natural ventilation?
2. What are the optimum window size and orientation for natural ventilation?

1.5 Significance

Depending on this study, the government can generate an overall optimum opening size for different orientation, climate and building height. Proper implementation of the standard will improve the energy performance of a building. On different studies, it is stated that a proper implementation of opening size and orientation for natural ventilation strategy can minimize up to 78% of energy consumption of a building depending on the local weather and air quality.

Providing optimum ventilation oriented window size for natural ventilation will provide acceptable thermal comfort conditions and reduce health problem for occupants by reducing over and under ventilation of a room. For the occupants the optimum airflow through the opening provided will reduce the embodied energy, capital, maintenance, and operational costs of mechanical equipment and the space needed to accommodate the equipment.

Depending on this study, different architectural, geographical and topographical scenarios can be studied in further detail, such as complex façade, terrain and urban environment. Since the study categorized Ethiopia by wind speed and direction, other wind-oriented studies can be also done depending on this study.

1.6 Scope

This study has determined optimum window size for different reference urban centers that could be a platform for further detailed work in Ethiopia by analyzing ventilation demand. The study deals with the building science which are related to natural ventilation. Even if window is also used for daylighting, this study focuses only on the natural ventilation opening size and orientation. Only building with simple geometry (flat façades) located in an open terrain is discussed on the study because the findings can be generalized to apply to all buildings of same type. All urban centers of Ethiopia is included in the study.

1.7 Limitations

Limited access to full data in micro level is the first limitation of the study. Since the study needs thirty years of wind data in order to encounter the standard, a macro level data from NASA is used. The wind data parameter is only available with point spatial option, and the wind elevation value in meters are required to be at 10m. Lack of previous research studies related to the topic in Ethiopia is the second limitation of the study, so other studies from foreign country with the same climate region is used to provide theoretical and scientific foundation for the research.

1.8 Organization of the Report

This report is organized in seven chapters illustrated in order below.

Chapter one deals about the introduction which contain; the background of the study which describes the know-how and back experience of the research, the driving and initiation of the research is described in problem statement, objectives which describe the desired achievement of the research, research question, significance, scope, limitation and organization of the study, respectively.

Chapter two is literature review which discusses about theoretical review: which describe about the role of natural ventilation, global atmospheric circulation, driving force of natural ventilation, principles of natural ventilation in both single-side cross-ventilation, application of natural ventilation and finally designing for natural ventilation. On the contextual review: the history, potential, application of natural ventilation is discussed with past trends of window sizing.

Chapter three is the material and method of the study. This include the study area description, types of data which describe the data used for the study, methods of data collection including the material used to collect the data, research design which describe the flow of the research in graphical way, and sampling. the analysis, in this section the collected wind speed and wind direction data is analyzed by using graph, chart and table. Window sizing and orientation with respect to the wind flow angle is analyzed for different scenarios.

Chapter four is the result part, the output of the analyzed data is illustrated in detail based on the information gathered.

Chapter five is discussion part, discusses the result part with respect to the reviewed literature and studies.

Chapter six is conclusion, findings and recommendation: summarizes the key findings and outcomes of the research.

CHAPTER TWO

LITERATURE REVIEW

2.1 Theoretical Review

2.1.1 The Role of Ventilation

Fresh air is required to achieve a healthy, fresh, and comfortable indoor environment for people to work and live in. Natural ventilation can ensure the supply of adequate breathing air, adequate ventilation of contaminants, adequate thermal conditioning and moisture dissipation, and contribute to well-being through a connection to the dynamics of nature (Yang, 2012). The purpose of ventilation is to eliminate airborne contaminants, which are generated both by human activity and by the building itself. These contaminants are bad odors, moisture; which increases the risk of mold growth, carbon dioxide gas; which may induce lethargy in high concentrations, dust; aerosols and toxic gases resulting from human activity, as well as from the materials of the building, and excessive heat (Ghiaus and Allard, 2005).

Buildings are required to protect their occupants from the external environment and to provide them with a good indoor environment. A building that is well adapted to its climate protects its occupants against the extreme conditions observed outdoors without creating uncomfortable internal conditions.

2.1.2 Natural Ventilation

Natural ventilation, as the name implies, is a system using natural forces to supply fresh air for comfort and heat dissipation. The term natural ventilation is used to indicate the intentional airflow through windows, doors or other openings designed for the purpose, obtained without the use of fans; it is created by pressure differences caused by the wind and/or by temperature differences between the inside and the outside. If the temperature in the indoor space exceeds 26 °C or relative humidity is quite high, natural ventilation can improve the thermal comfort. In hot and humid climates, cross ventilation is the

simplest strategy to adopt if the indoor temperature is almost the same as the outdoor temperature. Givoni assumes that the maximum allowed indoor air speed is about 2 m/s, thus ventilation maintains comfort up to an outdoor temperature limit of 32 °C. Natural Ventilation approach relies on the natural forces of wind and buoyancy to deliver fresh air to indoor spaces. For sustainable building design in tropical climate the natural ventilation zone is illustrated in (Figure 2).

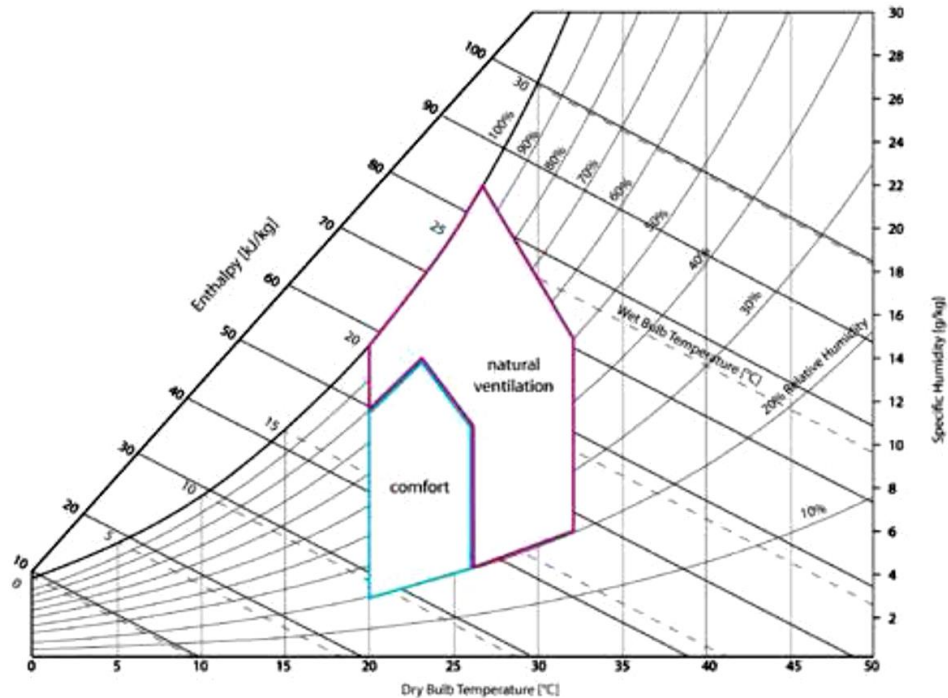


Figure 2: Natural Ventilation Zone (Source: Sustainable Building Design for Tropical Climates, 2015)

Benefits of Natural Ventilation

Natural ventilation has several benefits: low running cost, zero energy consumption, low maintenance and lower initial cost. It is healthier, and the way it connects with the outside is seen as a psychological benefit. The primary reason for using natural ventilation over mechanical ventilation is energy efficiency. Because natural ventilation does not require energy use through motorized fans, there is less energy use. The effectiveness of natural ventilation is determined by the prevailing outdoor conditions: microclimate (wind speed, temperature, humidity and surrounding topography) and the building itself (orientation, number of windows or openings, size and location).

Natural Ventilation Driving Forces

Natural ventilation is provided from two sources: thermal buoyancy and wind. Wind driven ventilation, the air moves from higher (positive) pressure regions to the lower (negative) pressure regions. This phenomenon is based on Bernoulli's principle, which uses pressure differences to move air. The warm air is less dense than cool air so it rises and creates a difference in pressure which in turn induces air movement, This phenomenon is called "the thermal buoyancy" and is sometimes referred to as "the stack effect".

The magnitude and pattern of natural air movement through a building depends on the strength and direction of these natural driving forces and the resistance of the flow path. Stack ventilation, can operate when no wind pressure is available. The absence of wind can occur at certain times, due to its variability, or in certain sites, due to blocking effect of other buildings or vegetation. It can also operate in deep plan buildings where the distance from openings in the perimeter, and the presence of partitions, make wind-driven cross ventilation impractical (Bhatia, 2012). The design of natural ventilation system often relies on both these driving forces. The dominating natural driving force has consequences for the shape and layout of the building. The detailed airflow around a building is illustrated in (Figure 3).

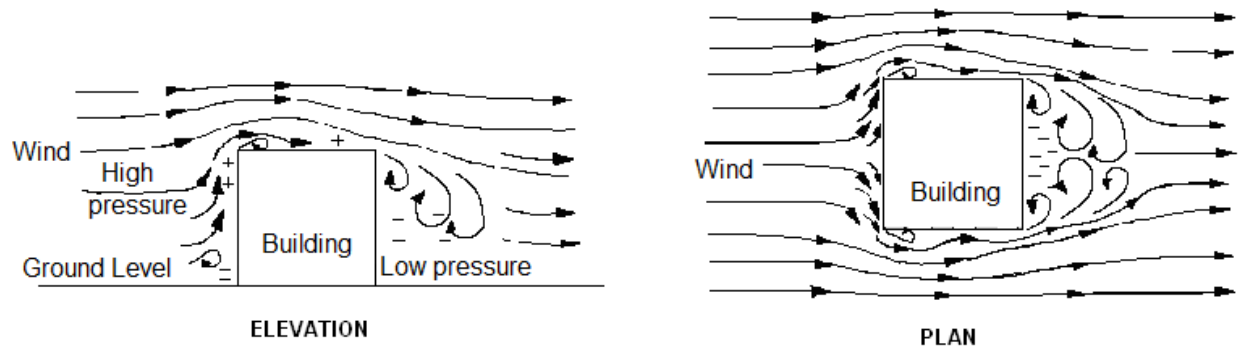


Figure 3: Detail of Airflow around a building (Source: Design options for HVAC distribution systems, 2012)

The air movement in a building is a dependent on the pressure differential between the outlets and inlets, which in turn is dependent on the wind speed, wind direction and building shape. Wind speed increases with height and is lower towards the ground due

to frictional drag. The building geometry, relative position and size of openings; building location in relation to surroundings; and the terrain geographical location of the building, create wind flow changes affecting building pressures.

Principle of Natural Ventilation

The ventilation principles used in the building to exploit the natural driving forces are classified as Single-sided ventilation, Cross-ventilation and stack ventilation.

a. Single-Sided Ventilation

Single sided ventilation relies on airflow through openings on only one side of an enclosed space. The air enters from one opening and leaves from the same opening or from another opening in the same wall. With single ventilation opening in the room, the main driving force for natural ventilation is wind turbulence (Bhatia, 2012). Compared to other strategies, lower ventilation rates are generated and the depth of penetration of the airflow into the space is limited (Figure 4). According to ASHRAE standard, single sided ventilation is generally effective for room depths not more than 2.5 times the height of the room and the ventilation opening area should be between 5% to 10% of the room's floor area.

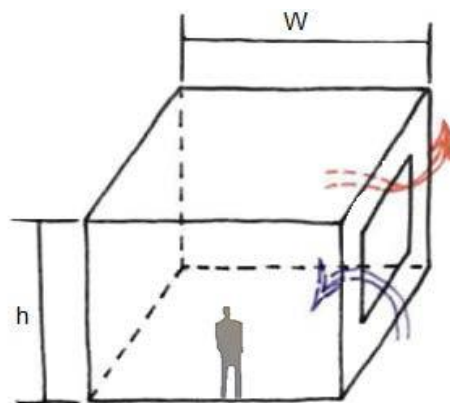


Figure 4: Single-side ventilation (Source: Design options for HVAC distribution systems, 2012)

When windows are limited to only one surface, Ventilation usually be weak, and it is independent to wind detection. The average internal wind speed will not change significantly with increasing window size. UFC states that, one-sided ventilation can be

made effective when two openings are placed on the windward face, the wind angle is oblique (20 to 70 degree), the windows are as far apart as possible.

b. Cross-Ventilation

Cross ventilation relies on airflow between ventilation openings on opposite sides of a space. Simply, the air enters from one opening (in the windward wall) and travels across the space to leave from another opening in the opposite side (in the leeward wall). As the air moves across a cross-ventilated space, it picks up heat and pollutants (Bhatia, 2012). Cross ventilation can be considered as the most effective technique that can grant a consistent large airflow with deep air penetration across the ventilated space (Figure 5). The airflow in the cross ventilation is a wind driven airflow, unless a difference in height between the inlet and outlet openings within the same wall is provided. According to ASHRAE standard, Cross ventilation is the most suitable technique for ventilating deep-plan buildings. The depth of the room can be up to 5 times the height.

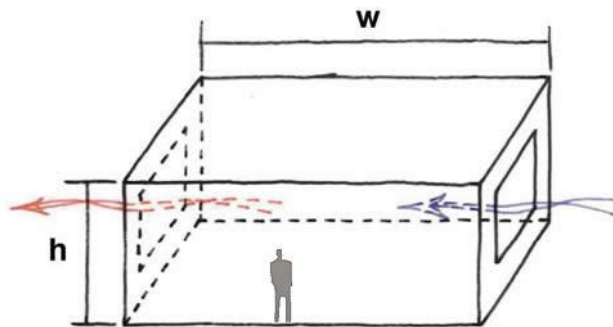


Figure 5: Cross-Ventilation (Source: Design options for HVAC distribution systems, 2012)

Cross Ventilation provides the maximum interior velocities and the best overall air distribution pattern. Openings in both positive and negative pressure zones are mandatory for cross ventilation. For windows on adjacent walls, the overall room air distribution is 10% to 20% higher average velocities when the wind incidence angle is perpendicular to the building face. For windows on opposite walls, oblique wind incidence angles give 20% to 30% higher average velocities than perpendicular winds (UFC, 2004).

c. Stack Ventilation

Stack ventilation is driven through the building by thermal buoyancy. The warm air inside the building is less dense than cooler air outside, and thus will try to escape from openings high up in the building envelope. Since this study mainly deals with wind driven natural ventilation, stack ventilation is not discussed.

d. Building Orientation

The building orientation with respect to wind direction significantly affects natural ventilation performance. According to ASHRAE, the optimum angle, which provides the best air circulation inside spaces, could be obtained by orienting the air inlet 45° to the prevailing wind. Inlet openings facing the incoming wind at 90° provides the maximum airflow.

2.1.3 Application of Natural Ventilation

The urban environment has drawbacks for the application of natural ventilation, for example; lower wind speed, higher temperatures due to the effect of the urban heat island, noise and pollution (Georgakis and Santamouris, 2005).

World urban population has increased rapidly. According to UNFPA, in the 1950, the number of urban resident were not more than 200 million but by the end of the century the total number reached 3 billion and it is expected to be 5 billion in 2025. Ethiopian central Statistics Agency project the urban population to be 42.3 million by the year 2037.

Urbanization has a dramatic effect on energy consumption. As reported by IBGE (1993), a 1 per cent increase in the per capita gross national product (GNP) leads to an almost equal (1.03 per cent) increase in energy consumption. However, an increase of 1 per cent in the urban population increases energy consumption by 2.2 percent (Christian and Francis 2005). Comparison of the energy consumption per capita for the inner and outer parts of cities shows that the consumption in the inner is considerably higher.

Using alternative energy source like renewable source could provide the necessary energy to the residents of the urban in addition to minimizing the over consumption of energy. Natural Ventilation is one of these technologies. Natural ventilation is more effective instrument to improve indoor air quality in urban areas, to protect health, to provide thermal comfort and to reduce unnecessary energy consumption. The energy cost of a naturally ventilated building is 40% lower than that of air-conditioned building (sacht, 2017).

The indoor environment in urban center buildings are affected by the concentration of harmful pollutants in the buildings. Human activity, outdoor pollution and the presence of materials that emit different compounds are the source of indoor air pollution. According to WHO, the concentration of indoor pollutants may be two to five times higher than outdoor pollutants. According to United Nations Centre for Human Settlements, indoor air quality is inadequate in 30% of the buildings around the world (LRC, 1993). The people that occupy buildings produce carbon dioxide (CO₂), odors and moisture. Combustion appliances such as fireplaces, furnaces, spot heaters, cook stoves, and water heaters generate CO₂, CO, various nitrogen- and sulfur containing by-products (NO_x and SO_x), moisture, particulates, etc. *Building Materials and Furnishings* Particle board, fiberglass, asbestos, caulks, paints, gypsum joint compound, solder, fabrics, etc., may emit (by "outgassing" or "off gassing") volatile organic compounds (VOC's, including formaldehyde), particulates, and heavy metals such as lead and mercury, found mostly in older construction (Barley, 2001). Latin America, Asia and Africa have shown that indoor air pollution is responsible for pregnancy-related problems, such as stillbirths and low birth weight. It has also been associated with blindness (attributed to 18% of cases in India) and immune system depression (Santamouris, 2005).

A mechanical ventilation system uses one or more electrical blowers, and sometimes a system of ductwork, to move air in and out of a home. Natural ventilation has the potential to reduce the energy cost required for mechanical ventilation and cooling of a building. Building energy uses account for approximately 40% of total primary energy use in developed countries (Russell, 2005). Among building services, energy use for the building heating, ventilation and air conditioning (HVAC) systems is over 50% of total energy

consumption in the building sector in many developed countries (Kaur 2011). Similar trends observed in the developing countries as standards of living are improving. Energy use for cooling buildings has doubled between 2000 and 2018, led by a combination of warmer temperatures and population and economic growth, according to the International Energy Agency (IEA). The IEA's 2018 report states that the number of AC units worldwide is predicted to increase from 1.6 billion to 5.6 billion by the middle of the century. As a result, the greenhouse-gas emissions from coal and natural-gas plants generating electricity to power the units will nearly double, from 1.25 billion tons in 2016 to 2.28 billion tons in 2050.

2.1.4 Global Atmospheric Circulation System

Solar energy is the driving force of atmospheric circulation, which heats the surface and atmosphere with different intensities at the equator, middle latitudes, and poles. The rotation of earth on its axis and unequal arrangement of land and water masses also contribute to atmospheric circulation.

The horizontal motion of air in attempts to equalize lateral differences in atmospheric pressure (and consequently other atmospheric properties such as temperature and humidity as well) is called as wind. In this tendency to reach equilibrium or stability in one part of the atmosphere invariably creates new differences elsewhere; the result is blowing of wind is a never-ending process considering the entire atmosphere over the surface of the earth as a whole continuum (Nanda, 2018). Wind is a vector quantity as it has both magnitude and direction which means it is characterized by speed and direction. Some wind movement are confined in a small locality and other appear to be global. The global wind belts is illustrated in Figure 6.

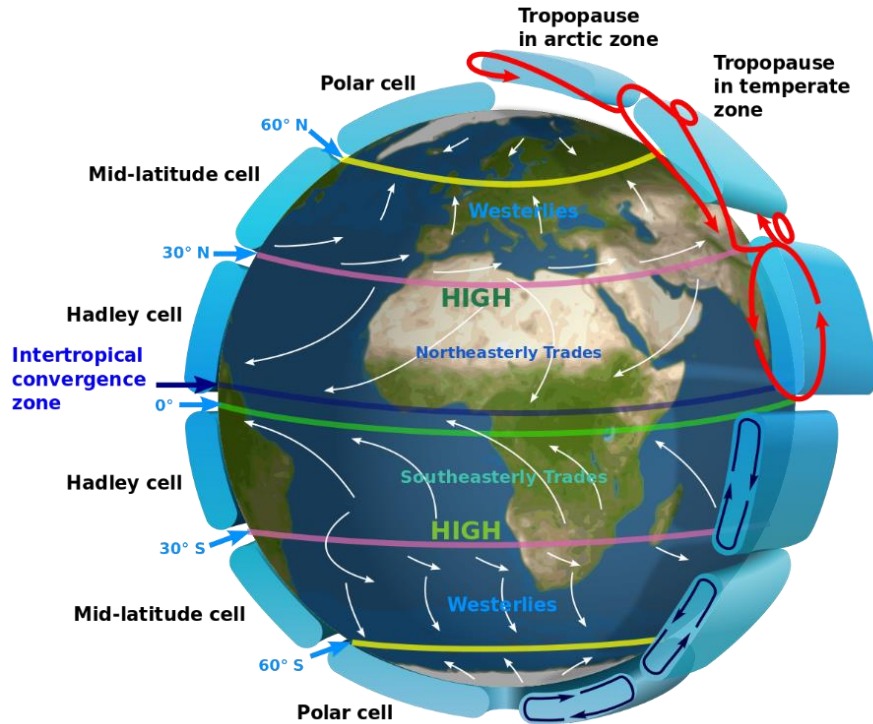


Figure 6: Global wind belts (Source: Dynamic Earth, 2003)

2.1.5 History

Vernacular buildings are historical examples of passive systems: they respond to the climatic context using the available natural resources to create healthy and comfortable spaces for occupants. Before the expansive use of active building systems for heating, cooling, and ventilation, buildings were constructed in ways that would regulate the interior climate or temperature based on their overall form, the size of openings (windows, doors), and type of building envelope. Thermal comfort and natural ventilation have a long history in the built environment. Around 400 BC, Socrates had some thoughts on the climatic suitability of houses and on how to build to ensure thermal comfort. Vitruvius (1st century BC) also wrote about the need to consider climate in building design for reasons of health and comfort. This, however, had very little influence on the practice of architecture (Arsano, 2017).

The tradition of ventilation, which incorporates a range of design responses to climate, has its origins in Egypt, where from the 13th century BC. Portray buildings with a traditional wind catcher used to help ventilate the interior (Fathy, 1986). This approach subsequently

spread eastwards as part of the Islamic tradition through the Middle East and Iran to north India (with the Moghul empire), and westwards across North Africa to southern Spain with the Moors (Phan, 2019). Wall painting from the tomb of Nebamun. Egyptian Dynasty 18, about 1475 BC. & Section through the Qā'a of Muhib Ad-Din Ash-Shāf'i Al- Muwaqqi, showing how the malqaf and wind-escape produce internal air movement (Figure 7).

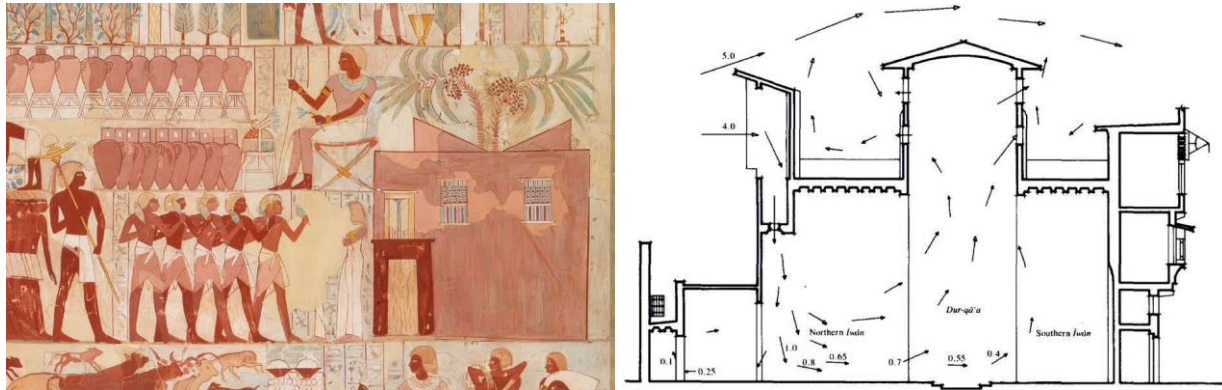


Figure 7: Traditional wind-scape method in Egypt in 1475 BC. (Source: R. Schiano-Phan, 2019)

Vernacular architecture blends buildings into their specific settings, so that there is a natural harmony between the climate, architecture, and people. Vernacular architecture learned from the environmental variations of place relating to local variations in temperature, humidity, sun, wind, rain, earthquakes, and storms (Clements, 2012). Vernacular architecture also adapted to ensure indoor air quality through natural ventilation through the careful design and placement of openings.

2.1.6 Design of optimal Openings

The opening size controls both the ventilation rate and air velocity within the interiors. The general rule of maximizing the natural ventilation effectiveness is to have inlet and outlet openings as large as possible. According to ASHRAE, highest flow per unit area of openings is obtained when the inlet is small and the outlet is large by at least 25%, and the inlet window height is limited to 1m and the inlet width is up to two-thirds of the wall width (Figure 8).

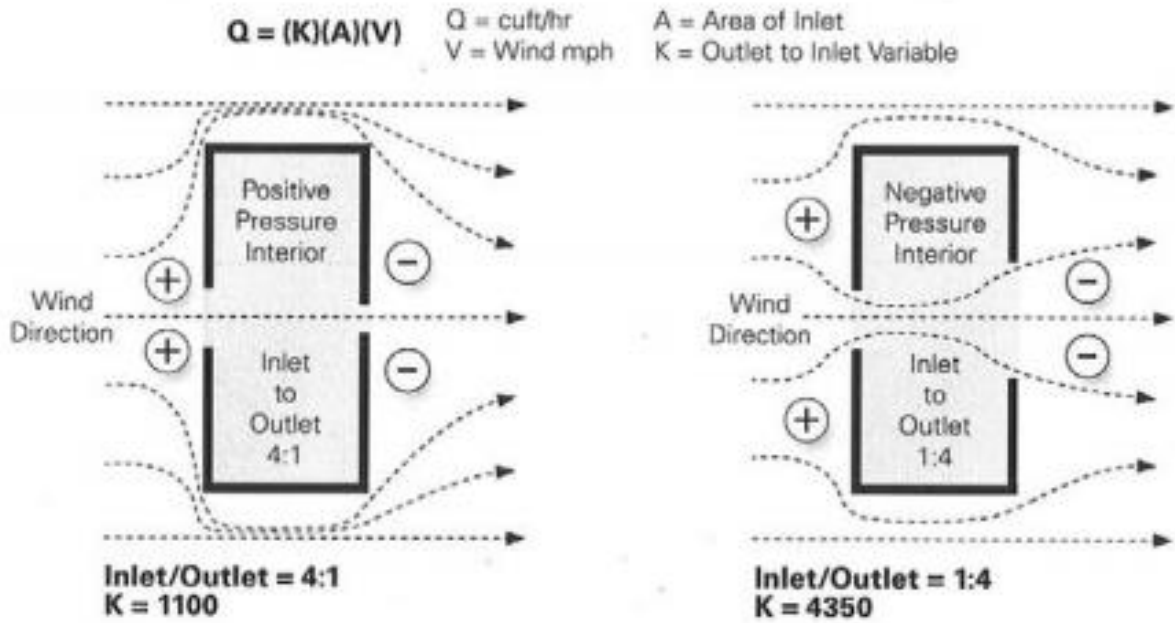


Figure 8: Inlet to outlet relation of opening (Source: Design options for HVAC distribution systems, 2012)

The effect of window size depends on whether or not openings are cross ventilating. If openings are on one surface only, size has little effect on airflow. In cross ventilated rooms, airflow is determined mainly by the area of the smallest openings (Guyer, 2013). Average indoor velocity and number of air changes are highest when inlet area is equal to or slightly less than outlet area as in the Equation 1

Outlet area/inlet area = 1.25.....Equation 1

Ventilation is more efficient for a greater number of incidence angles when inlets are larger than the outlets. If concentrated flow in a restricted area of the room is desired, the inlets may be sized smaller than the outlets and placed immediately adjacent to the living space to be ventilated (Figure 9). In general, use the largest area of openings possible with inlet area equal to or slightly less than outlet area.

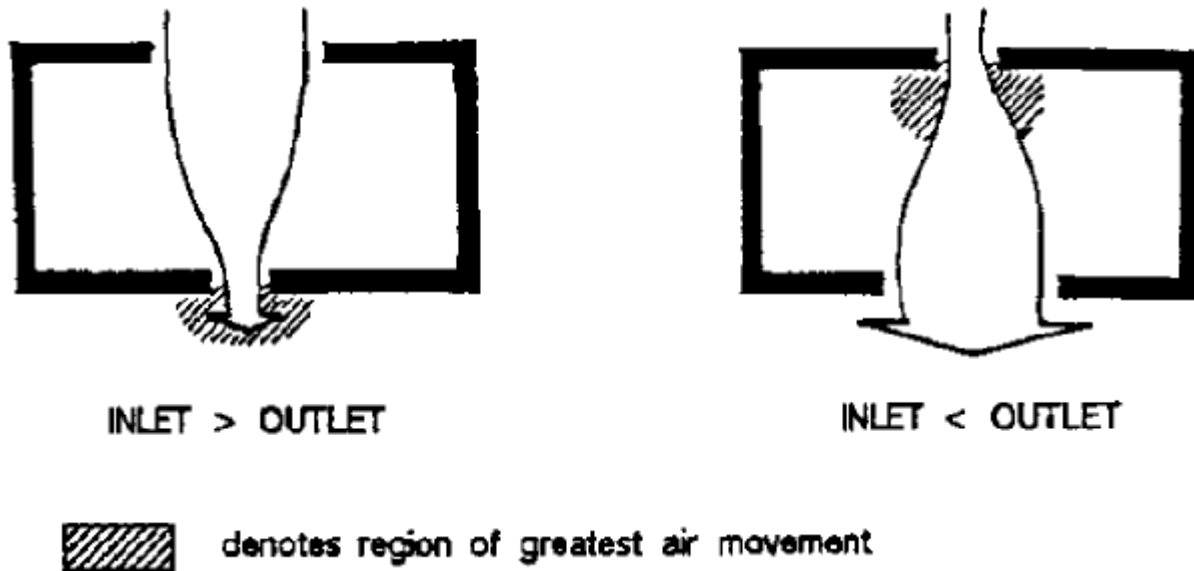


Figure 9: The effect of relative opening size on airflow (Source: Guyer, 2013)

In urban canyons, where the local wind speed is relatively low, the geometry of a building's façade and of its openings plays a bigger role. Design decisions for the use of natural ventilation in buildings need an estimation of the appropriate size of the openings and of their location in the façade. The study verified that, conditions of natural ventilation are influenced by the size of the windows, (Helenice and Marieli, 2017). The rate of interior airflow is determined by the magnitude of the pressure difference across the building and the resistance to airflow of the openings. UFC state that; the size, shape, type and location of the openings, especially the inlets, determine the velocity and pattern of internal airflow. Designing opening for ventilation should consider factors; predominant external wind speed and direction, Building envelope, and Location and type of inlet and outlet.

Indoor airspeeds, even under the most favorable conditions, are only 30% to 40% of the free exterior wind speed in cross-ventilated spaces, 5% to 15% of the free exterior wind speed in rooms with openings in one wall only and 3% to 5% in rooms with one opening (Figure 10).

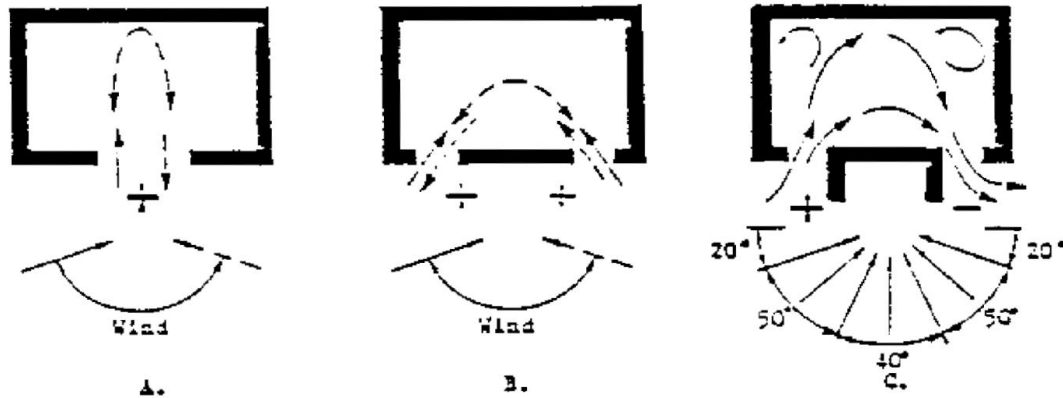


Figure 10: Ventilation in rooms with openings in one wall (Source: Unified Facilities criteria, 2004)

- A. Worst case: one opening. Ventilation is dependent upon pulses (fluctuation) of the wind.
- B. Better: two windows placed as far as possible and facing obliquely into the wind. Ventilation is better because there is greater difference in pressure between the two openings.
- C. Best: two openings placed far apart with appropriate location wing walls facing obliquity into the wind. Wing walls improve ventilation by creating positive and negative pressure zones that drive airflow.

For wind-driven ventilation, outlet height has little impact on interior airflow, but inlet height has a great effect on the airflow pattern in the room. Positive pressures built up on the windward face of the building can direct the airflow up to the ceiling or down to the floor of the room. These positive pressures are related to the area of the windward face (UFC, 2004). Thus, a window located high on the wall directs airflow up to the ceiling because the positive pressure built up on the building face is larger below the window than above it.

The effect of window size depends on whether or not openings are cross ventilating. If openings are on one surface only, size has little effect on airflow. In cross-ventilated rooms, airflow is determined mainly by the area of the smallest openings; average indoor velocity and number of air changes is highest when inlet area is equal to or slightly less than outlet area. The air flow pattern due to the wind depends on the relative position of the openings. The best conditions are created when the outlet opening is higher and wider than the inlet (Figure 11) (the ideal is to have them of equal area).

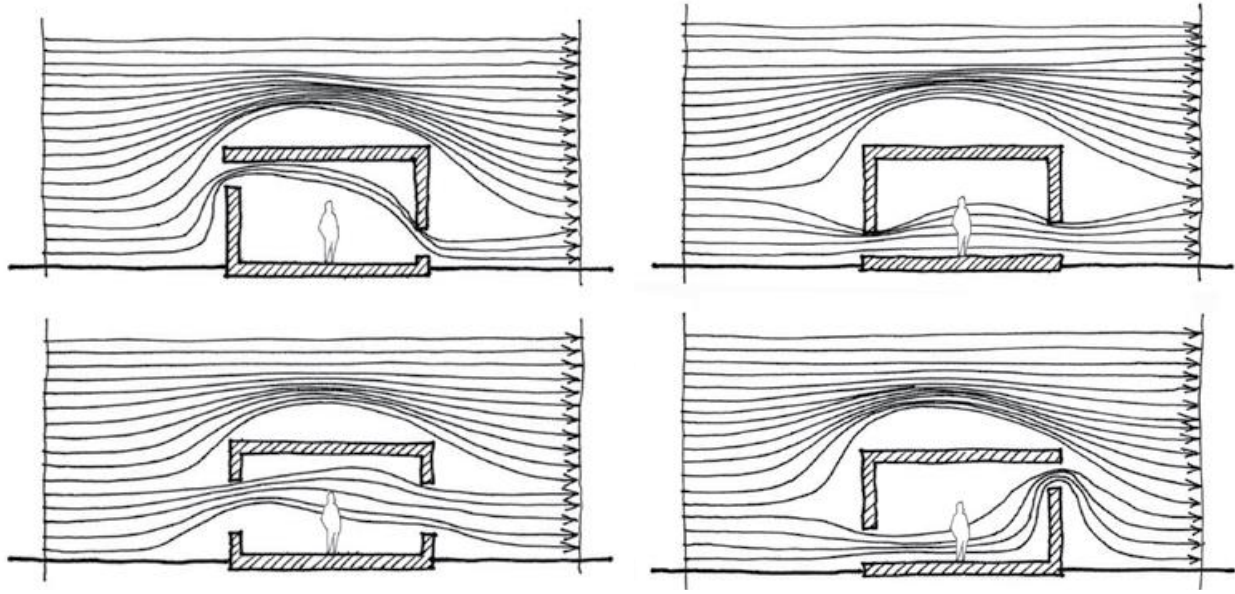


Figure 11: Airflow pattern, according to the relative position of the openings (Source: Sustainable Building Design for Tropical Climates ,2015)

For an elongated building without openings, the largest pressure differences (which drive cross-ventilation) occur when the building is perpendicular to the prevailing wind. However, this orientation does not necessarily result in the best average interior velocity rates or airflow distribution. For bodily cooling, the goal is to achieve the highest average room velocity in which air movement occurs in all occupied parts of the room. When windows are in adjacent walls, the optimum ventilation occurs with the long building face perpendicular to the wind, but a shift of 20 to 30 degrees from perpendicular will not seriously impair the building's interior ventilation. This allows a range of orientations for resolving possible conflicts with the optimum solar orientation (Guyer, 2013).

Wind approaching at an incidence angle of 45 degrees results in interior velocities that are 15 to 20 percent lower than when the wind approaches perpendicular to the face. When windows are in opposite walls, a 45-degree incidence angle gives the maximum average indoor air velocity and provides better distribution of indoor air movement. Wind approaching at 90 degrees is 15 to 20 percent less effective. Wind parallel to the ventilation face produces ventilation depending entirely on fluctuations in the wind and is therefore very uncertain (Figure 12).

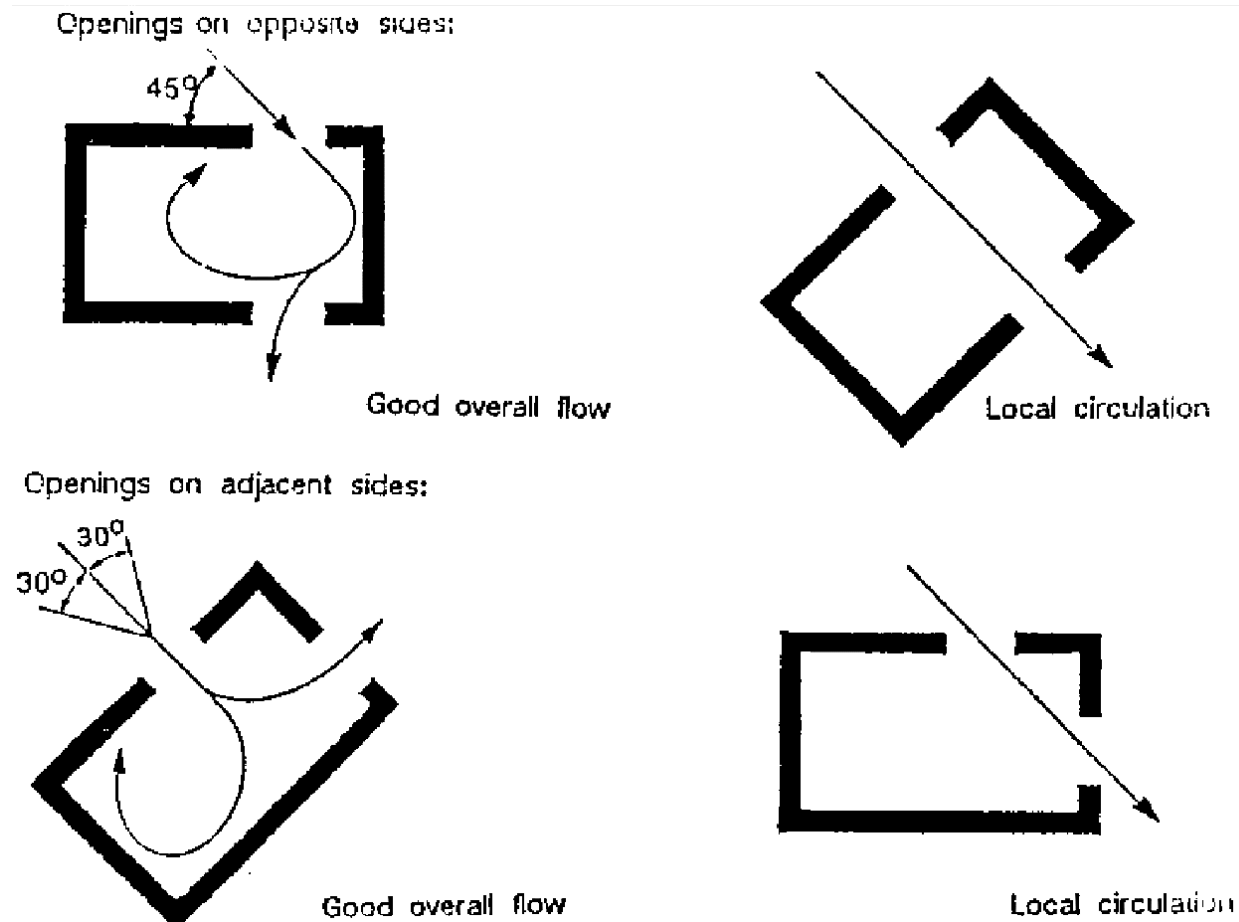


Figure 12: Effect of wind incidence angle on interior airflow (Source: Guyer, 2013).

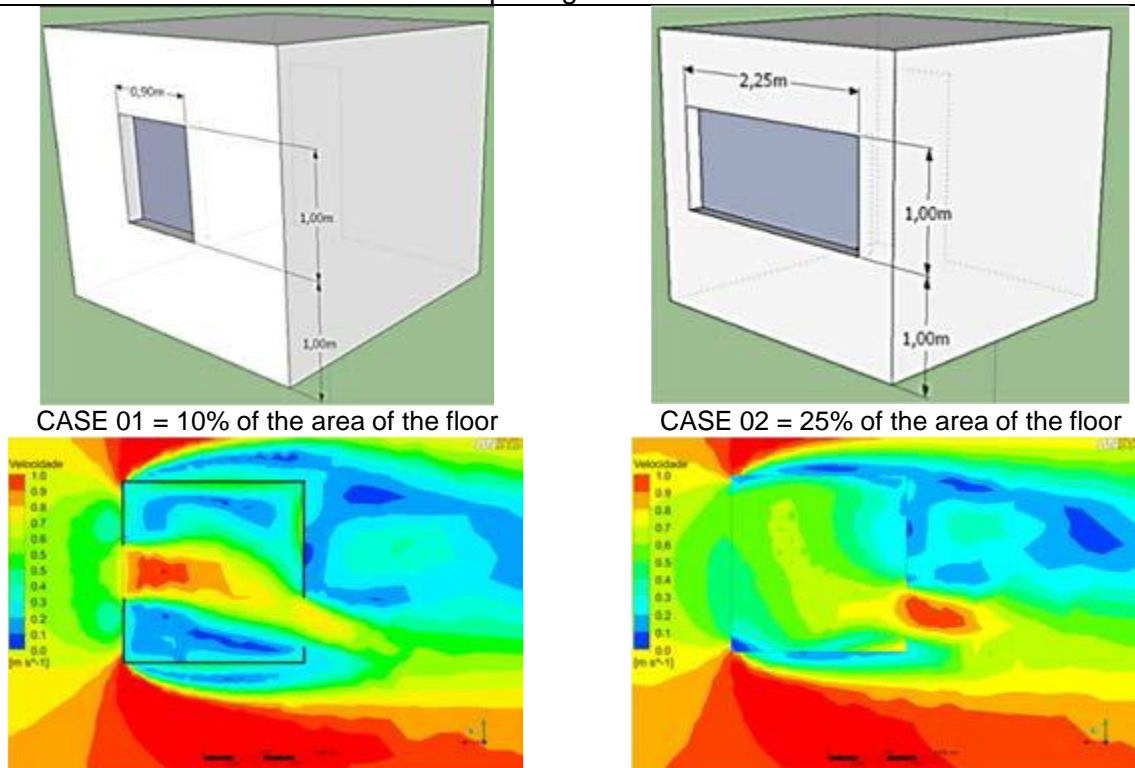
As the wind blows onto and around buildings, it creates regions in which the static pressure is above or below that of the undisturbed air stream. Positive pressure on the windward side forces air into the building, and negative pressure on the leeward side pulls it out of the building. Pressures on the other sides are negative or positive depending on the wind incidence angle and the building shape. The rate of interior airflow is determined by the magnitude of the pressure difference across the building and the resistance to airflow of the openings. The size, shape, type and location of the openings, especially the inlets, determine the velocity and pattern of internal airflow.

When designing and placing windows and openings for ventilation, the following factors must be considered: predominant external wind and directions when the winds occur. Construction of the building envelope and landscaping may hinder or facilitate natural ventilation of the interior spaces. Location and type of inlets has the largest effect on the airflow pattern through the space, Location and outlets type has little effect on airflow

pattern. Number of air changes per hour has little to do with body cooling; the airflow velocity and distribution pattern are more important, and changes in indoor airflow direction tend to retard airspeed.

It was verified that, the conditions of natural ventilation were influenced by the variation of the angle of wind incidence (Sacht, 2017), which affected significant changes in the values of the pressure coefficients and air change rates per hour. Regarding the distribution of the airflow in the internal environment, the best performances were recorded when the wind moved through the window at an angle between 0° and 45° . According to the study, the highest rates were reached when the wind moved obliquely in the building (45°). The worst performance occurs when the wind moved parallel to the openings (90°), where the internal airflow has reduced velocities. In Table 1 below the two different dimension of windows with respect to wind speed and the incident angle are given.

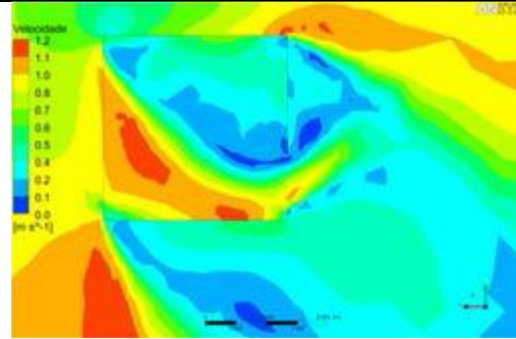
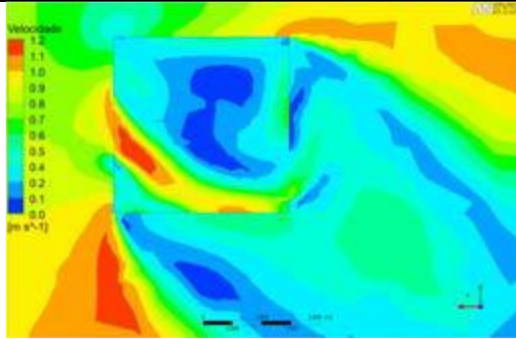
Table 1: Ventilation rate in two different opening size



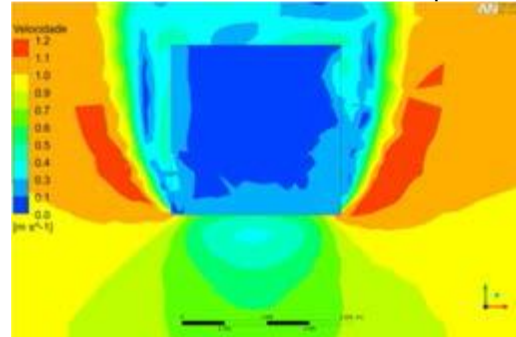
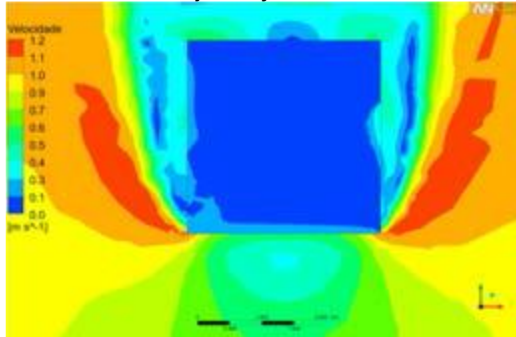
CASE 01 = 10% of the area of the floor

CASE 02 = 25% of the area of the floor

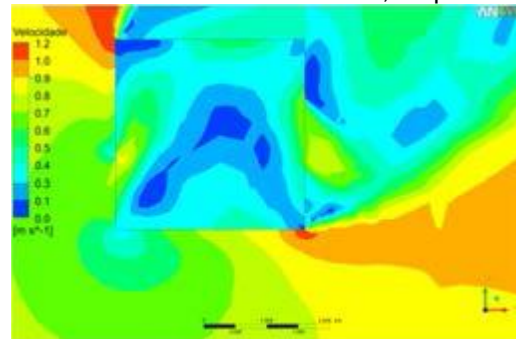
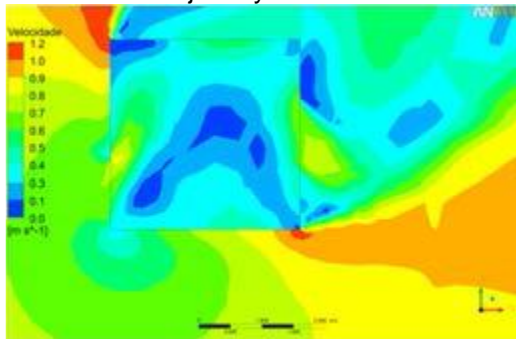
Trajectory of the airflow in the internal environment for the 0° incidence angle of external winds for C01 and C02, respectively.



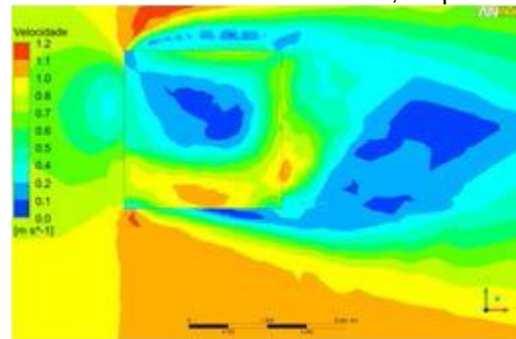
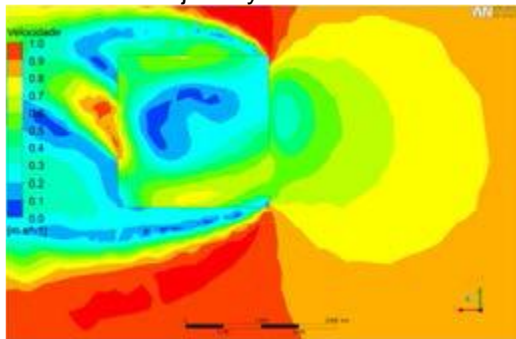
Indoor airflow trajectory for the 45° incidence angle of external winds for C01 and C02, respectively



Indoor airflow trajectory for the 90° incidence angle of external winds for C01 and C02, respectively.



Indoor airflow trajectory for the 135° incidence angle of external winds for C01 and C02, respectively.



Indoor airflow trajectory for the 180° incidence angle of external winds for C01 and C02, respectively.
 (Source: Windows Size and the performance of natural ventilation, 2017)

The performance of natural ventilation depends greatly on the direction and speed of wind with respect to the opening quadrants (Awbi, 2002). In all cases examined in the ventilation rate increased with wind speed and slightly decreased with changes in the wind direction (Figure 13).

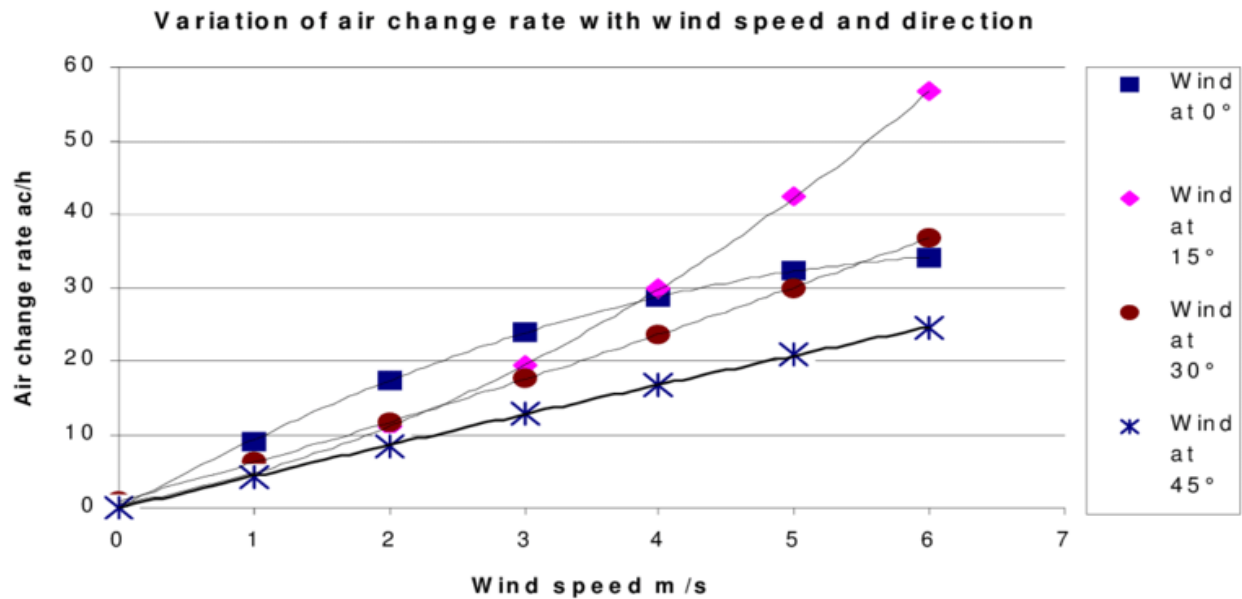
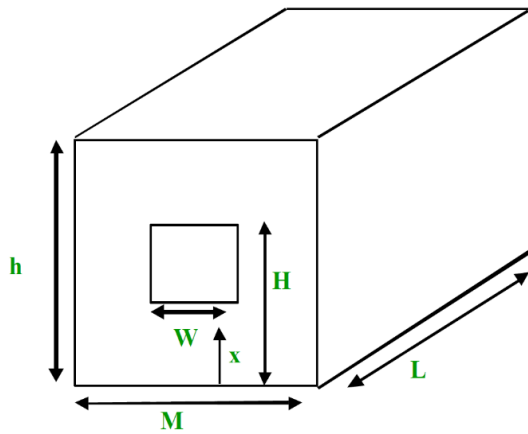


Figure 13: The variation of ventilation rate with wind and wind direction (Source: Full-scale model wind catcher performance evaluation using a wind tunnel, 2002)

URBVENT - Natural ventilation in urban areas - potential assessment and optimal façades design, simulated a number of scenarios in relation to natural ventilation. The main objective of the work package is to develop a design methodology and performance criteria for best practice design of naturally ventilated buildings. The goal is to optimize the façade of urban buildings to better exploit natural resources and maximize natural ventilation performance, giving credit for energy conservation, improved indoor air quality and best use of renewable energy sources. One part of the work task is developing of methodology for optimum openings design. Form their studies selected scenario is discussed here. Small offices and apartment, typically having a single-sided ventilation. Flat façades without obstacles because façade with obstacles such as balconies overhangs or other elements create complex wind patterns and pressure distributions on the opening, so it should be studied deeply and individually.

The URBVENT simulation considered six geometric variables related to room and opening dimensions were considered. All these variables were changed allowing for different combinations between them all. This has created thousands of different architectural scenarios that provide a deep insight into the magnitude of airflows under different circumstances. For the single-sided ventilation cases, simulations have been performed with the AIOLOS software to evaluate the natural potential. More than 1.5 million values were produced. Due to the magnitude of this number, these results had to be grouped in three hundred EXCEL files, in order to be manageable. In each one of these files, for a certain volume, and for the defined climatic data, it is possible to find the air changes and the airflow rates in the room for the different combinations considered. The variation of the dimensions are stated in (Table 2).



M – Width of the zone;
 L – Length of the zone;
 h – Height of the zone;
 H – Height of the opening top of the window;
 W – Width of the window;
 x – Height of the opening bottom of the window.

Figure 14: Scenario created to perform the single-sided simulations (Source: URBVENT, 2003)

Table 2: Variations of the dimensions considered in the simulations

M(m)	L(m)	h(m)	X(m)	H(m)	W(m)
3 - 5	3 - 5	2.8 - 5	0.1 - 2.4	0.6 - 3	0.2 - 4

(Source: URBVENT, 2003)

Using the experience gained through the specific experiments, a theoretical model to calculate the wind speed at any point in a canyon is developed. The overall method is incorporated in a software tool developed under the MATLAB Code (URBVENT, 2003). To calculate the optimum opening of naturally ventilated buildings located in urban canyons is developed. The overall work is based on the development of a recurrent neural network model that calculates the airflow in natural ventilated rooms in buildings located

in urban canyon under: specific climate conditions, canyon characteristics, openings of buildings and building geometry. So regionalizing Ethiopia In to different category is mandatory for the study.

In all these studies, only summer conditions have been simulated. It is assumed that, in winter, when outdoor temperatures are cool, occupants will always limit natural ventilation to minimum hygienic rates to reduce their heating bills. Therefore, the interior temperature of the simulated room was kept constant at 25°C. For the exterior environment, the climatic data that were used are listed below in (table 3). It covers a range of external temperatures and wind velocities (normal component relative to the window, the only one of interest for single-sided ventilation). Simulations have been carried out with combinations of each temperature and each wind velocity, for a total of 320 cases for each geometry.

Table 3: Climatic data file used in the simulation

T_{ext}	26	27	28	29	30	31	32	33	34	35	36	37	38	39	40	41
T_d	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16
u	0.5	1	1.5	2	2.5	3	3.5	4	4.5	5	5.5	6	6.5	7	7.5	8

(Source: URBVENT, 2003)

Where,

T_{ext} – External Temperature (°C):

T_d – Difference between external and interior temperature. The interior temperature kept constant at 25 °C;

u – Wind speed (m/s)

The study have been carried out for a base scenario of a room with a volume of 56m³ obtained with the following dimensions: h = 2.8 m, M = 5 m and L = 4 m. The window characteristics were as follows: x = 1 m, H = 2 m and W = 2 m. The temperature difference between the outside and the inside environment (DT) and the wind velocity influence the air change rate presented below in (Figure 14 and 15).

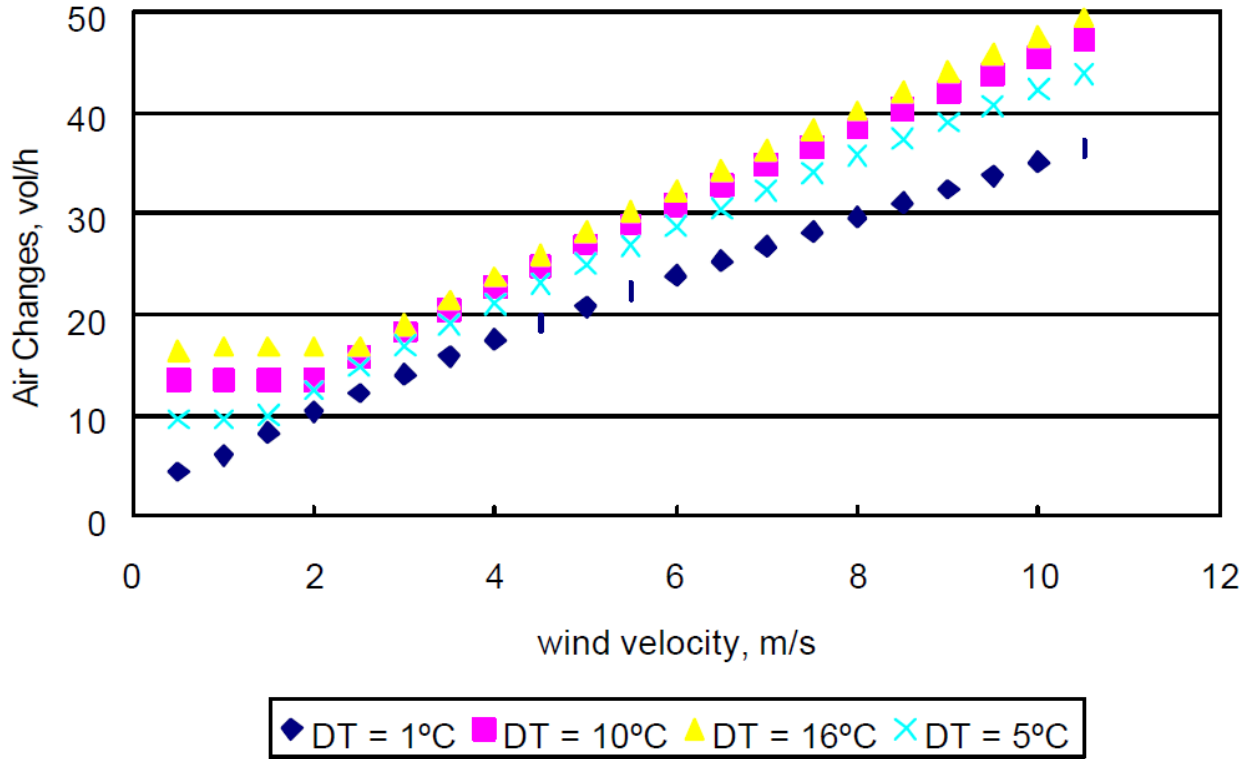


Figure 15: Influence of the wind velocity for different temperature differences (Source: URBVENT, 2003)

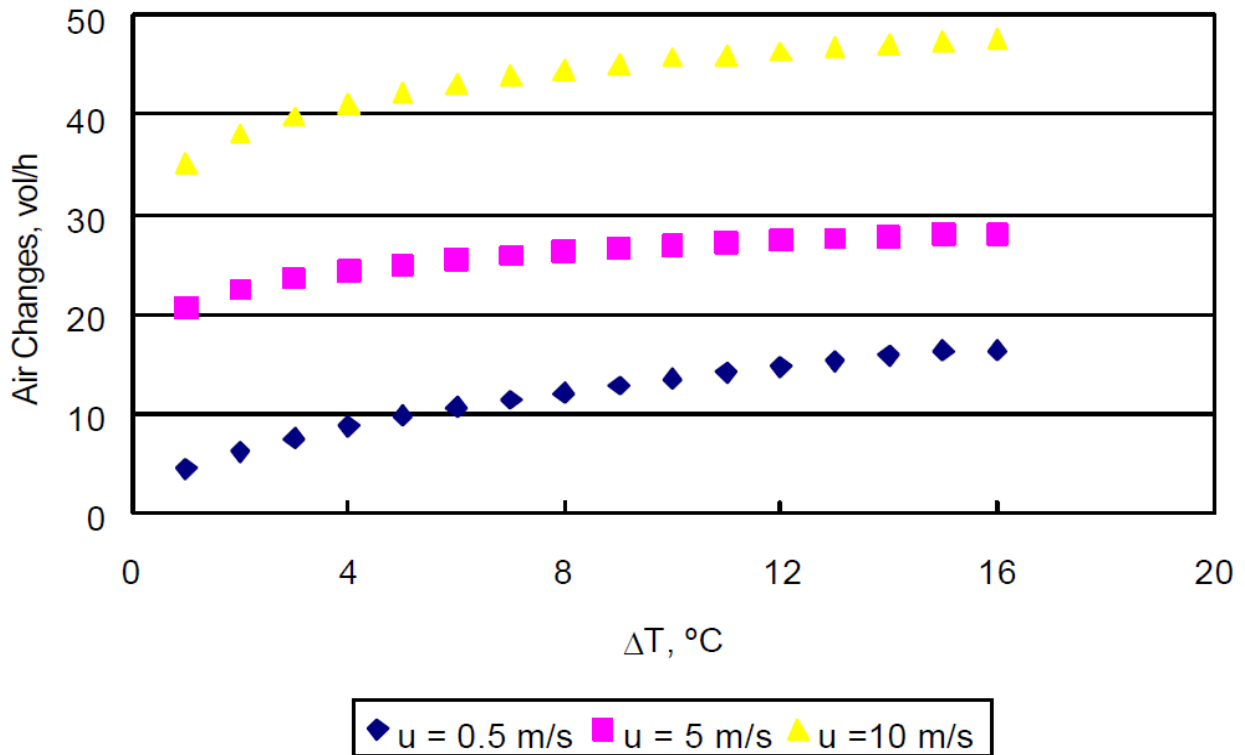


Figure 16: Influence of the temperature difference for different wind velocities (Source: URBVENT, 2003)

As it is visible in both (Figures 14 and 15), and as expected, as the temperature difference increases the air changes inside the room also increase. However, the impact of the temperature difference on the exchange rate is lower as the temperature difference gets larger or, stated the other way round; the influence of the temperature difference is larger when the wind velocity is lower. The influence of the geometric characteristics and of the location of the window for different wind velocities and temperature differences presented below.

The wind velocity has more impact than the temperature difference on the air exchange rate (Figure 16). It also shows a linear variation of the air change values width of the window, which is clearly in line with the expectations(Figure 17). The influence of the height of the top of the window (H) on the air exchange rate for different wind velocities and temperature differences (Figure 18). As expected, as the height increases the ACH values also increase as the window area also increases and the stack effect becomes more intense.

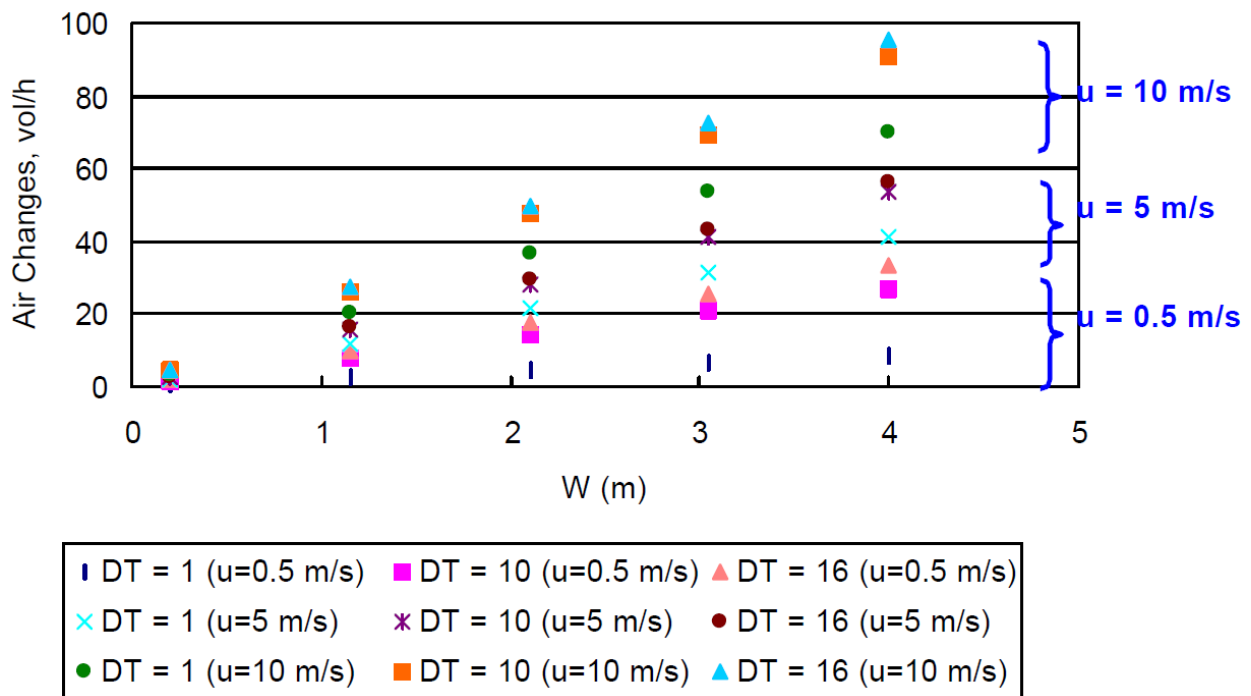


Figure 17: Influence of the width of the window for different wind velocities and temperature differences (Source: URBVENT, 2003)

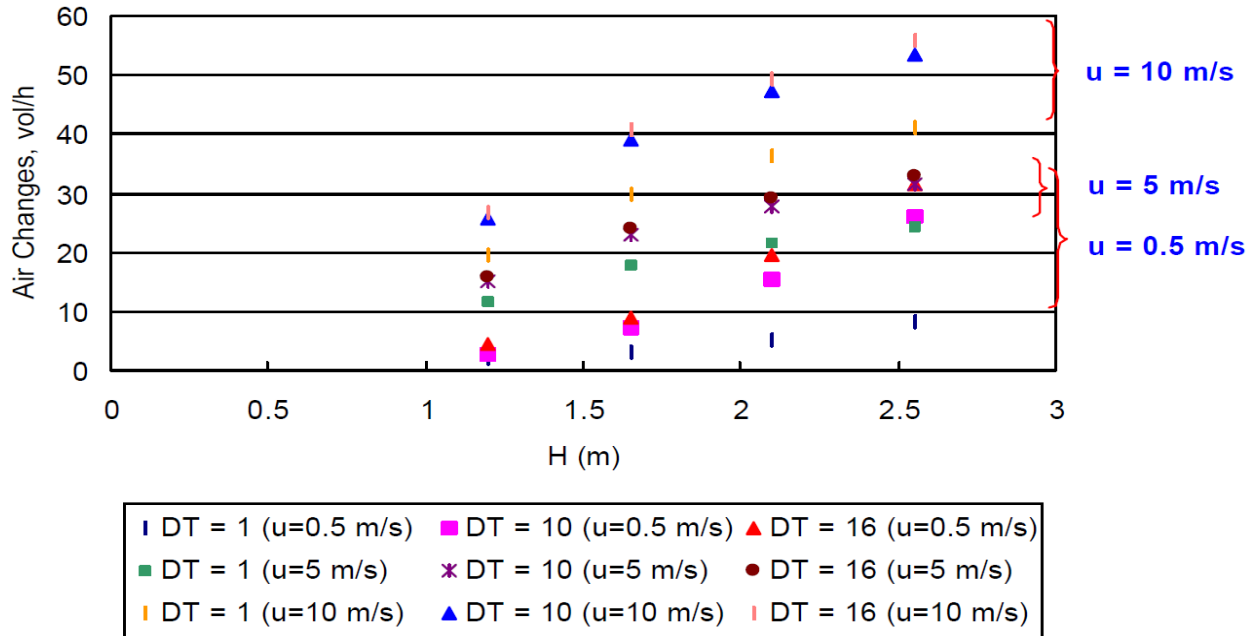


Figure 18: Influence of the height of the window for different wind velocities and temperature difference (Source: URBVENT, 2003)

The influence of the height of the opening bottom (x) on the air exchange rate for different wind velocities and temperature differences (Figure 19). Here the tendency is the opposite of what is seen in the previous figure: as x increases, the air exchange values become lower.

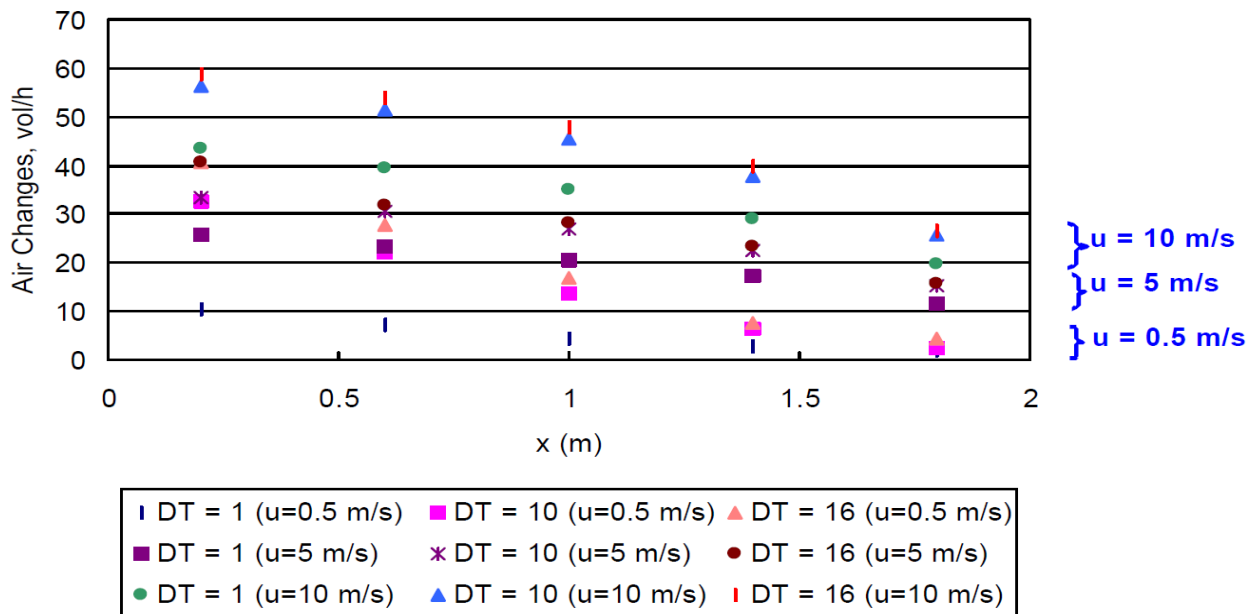


Figure 19: Influence of the height of the bottom for different wind velocities and temperature differences (Source: URBVENT, 2003).

By integrating Matlab tool to integrate the mathematical computing, visualization, and a powerful language to provide a flexible environment for technical computing. In addition, it contains the Neural Network Toolbox, which provides a complete set of functions and a graphical user interface for the design, implementation, visualization, and simulation of neural networks. It supports the most commonly used supervised and unsupervised network architectures and a comprehensive set of training and learning functions. Each network “netx” is a feed-forward backpropagation network that has as inputs the values of external temperature, the wind velocity, the room volume, the height of the opening bottom of the window, the height of the opening top of the window and the value of the Air Change Rate per hour, and that after been trained according to correspondent values of air change per hour for the rooms, can simulate new inputs and predict the width of the window for the single sided ventilated room (Figure 20).

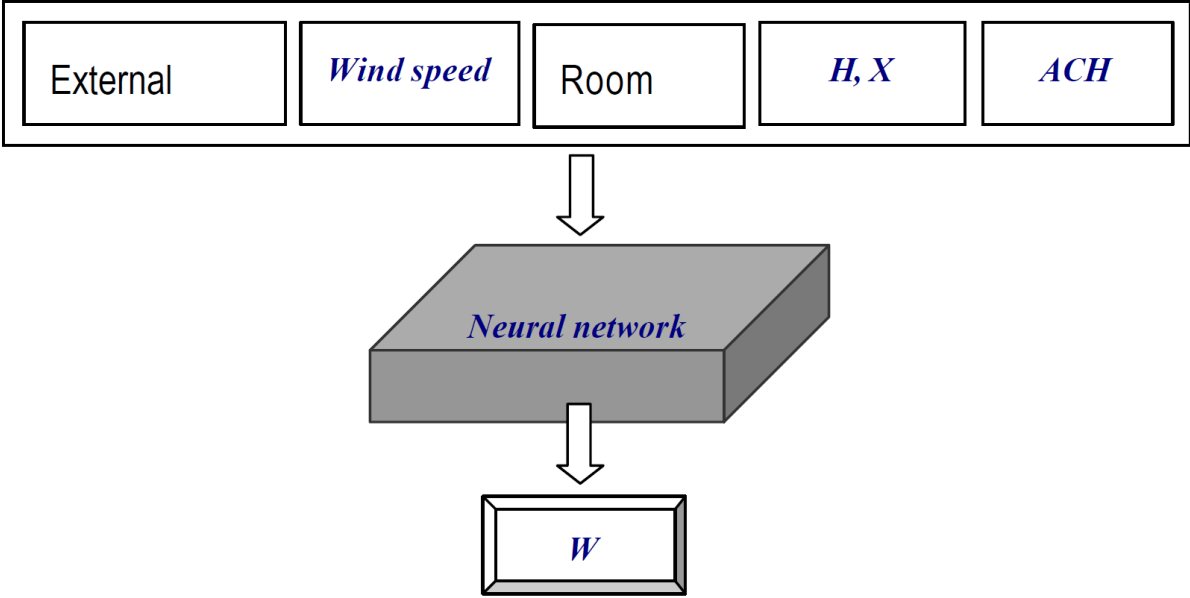


Figure 20: Architecture of the model of calculation of W for single sided ventilation (Source: URBVENT, 2003)

Using the experimental data regarding the airflow in naturally ventilated buildings, the developed models have been validated. It is found that the proposed model to calculate the airflow in naturally ventilated buildings located in urban environment as well as the model to calculate the optimum opening are very accurate and can be used to design naturally ventilated buildings in dense urban environments (URBVENT, 2003).

To estimate the size of the openings (opposite) in the case of cross ventilation, the following (Equation 3) is used:

$$V = KAv \dots \dots \dots \text{Equation 2}$$

$$A = V/Kv \dots \dots \dots \text{Equation 3}$$

Where: V = air flow rate [m^3/s];

K = coefficient of effectiveness;

A = net free area of inlet openings, equal to outlet [m^2];

v = outdoor wind speed [m/s].

(Source: Sustainable building design for tropical climate, 2015)

The coefficient of effectiveness depends upon the direction of the wind relative to the opening, and on the ratio between the areas of the two openings. It is maximum when the wind blows directly onto the opening and it increases with the relative size of the larger opening. For opposite openings of equal area, $K = 0.6$ for wind perpendicular to opening (or 0°) and $K = 0.3$ for wind at 45° . Changes in wind direction up to 30° on either side of the normal to the window wall have little effect on the values of K . For wind directions outside these limits, the value of K may be considered to change linearly with wind direction.

The airflow rate can also be obtained using the (Figure 21) (wind 0° to opening) and (wind at 45° to opening) in (Figure 22), providing the airflow rate per square meter through the smaller opening (coincident with the air velocity in m/s) with different wind speed.

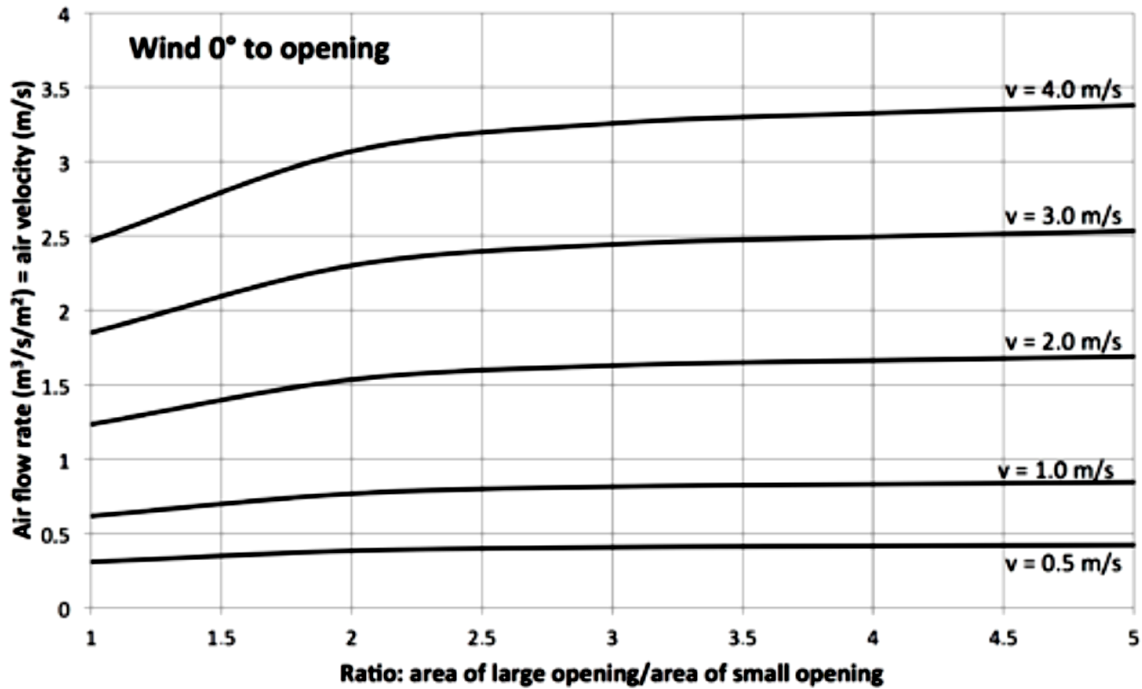


Figure 21: Airflow rate per square meter through the smaller opening (or air velocity in m/s) with different wind speed – wind incident at 0° (Source: sustainable building design for tropical climates, 2015)

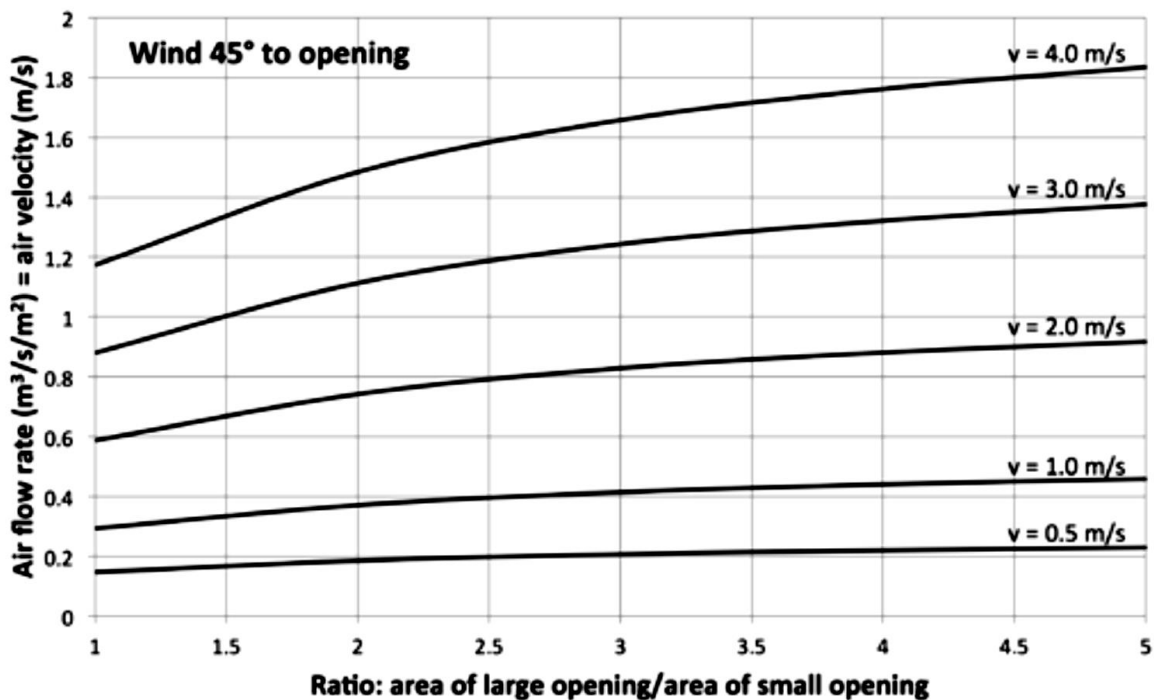


Figure 22: Airflow rate per square meter through the smaller opening (or air velocity in m/s) with different wind speed – wind incident at 45° (Source: sustainable building design for tropical climates, 2015)

According to the study of sustainable building design of tropical climates, a compromise between the absence of information about air velocity and the detailed knowledge of the values of air velocity in each part of the internal space is an evaluation of the average wind velocity. From the average wind velocity, it is possible to derive, as a first approximation, an indication of the effect of the airflow on comfort. The relationship between the area of the openings and the internal air velocity as a percentage of external wind speed. For a cross ventilated room with centered opposite openings, is plotted on the chart below, for different values of inlet area expressed as % of total (inlet + outlet) net fenestration, to take into account the effect of different inlet and outlet sizes (Figure 23).

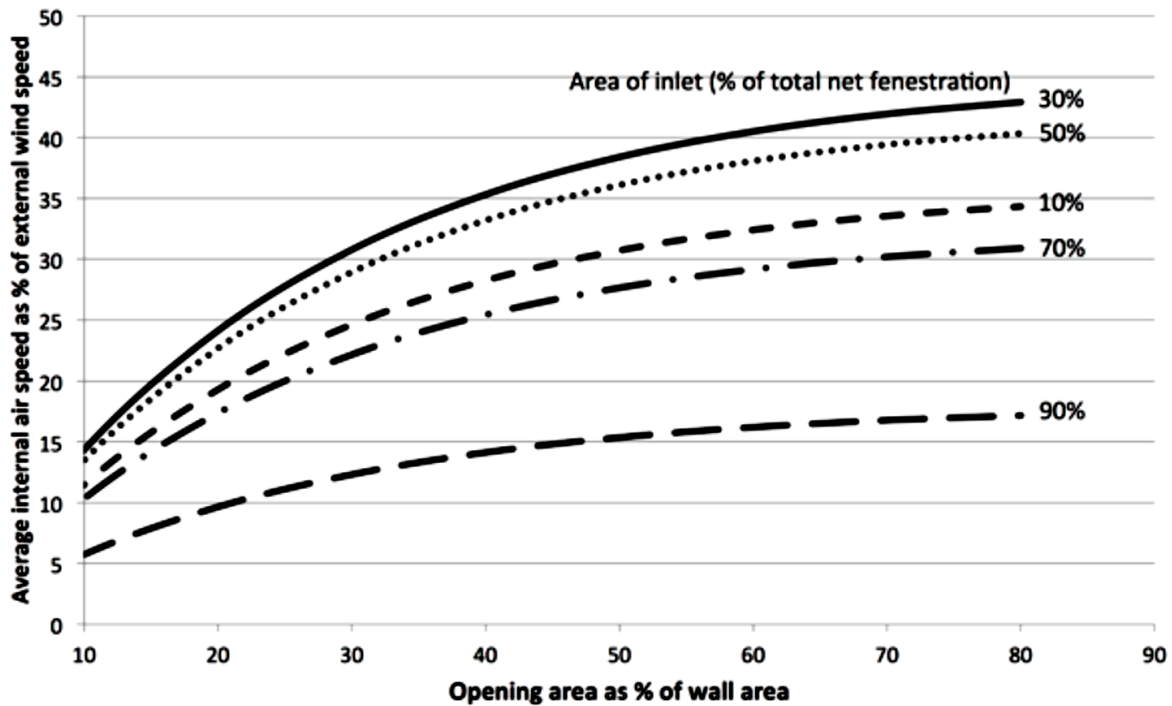


Figure 23: average internal air speed for different areas of the openings for cross *ventilation* (Source: sustainable building design for tropical climates, 2015)

The values of internal air speed deriving change if the location of windows is changed, i.e., if they are not centered and opposite. For a given external wind velocity, the value of the average internal air velocity must be corrected according to Table 4.

Table 4: Effect of window location on indoor air motion

change in%

orientation → window location ↓	wind ↓ 0°	45° wind		
[]	0	0	[]	0
[]	-10	+40	[]	-10
[]	-10	-15	[]	+40
[]	-15	0	[]	-10
[]	-15	0	[]	-60

(Source: sustainable building design for tropical climates, 2015)

2.2 Contextual Review

2.2.1 Potential of Natural Ventilation

Ethiopia located at the Northern hemisphere the trade wind blow predominantly from the northeast. Trade winds are the powerful prevailing winds that blow across the tropics. According to National Geographic, trade winds are generally very predictable. The trade wind and the Local wind has a great impact on Wind drive natural ventilation. As both wind types can be predicted it is mandatory to study both in order to design naturally ventilated building. For natural ventilation to be effective there has to be a close relationship between the architecture and the air circulation system. This includes the Opening design and Orientation.

Outdoor air temperature and humidity of most Ethiopian regions are in a comfortable range, providing potential for natural ventilation through the year. Nevertheless, the Ethiopian code of standards, opening parts of windows are not stated in relation to opening height and orientation. The potential of direct ventilation map shows Ethiopia has a dominance potential of high and low ventilation (Figure 24).

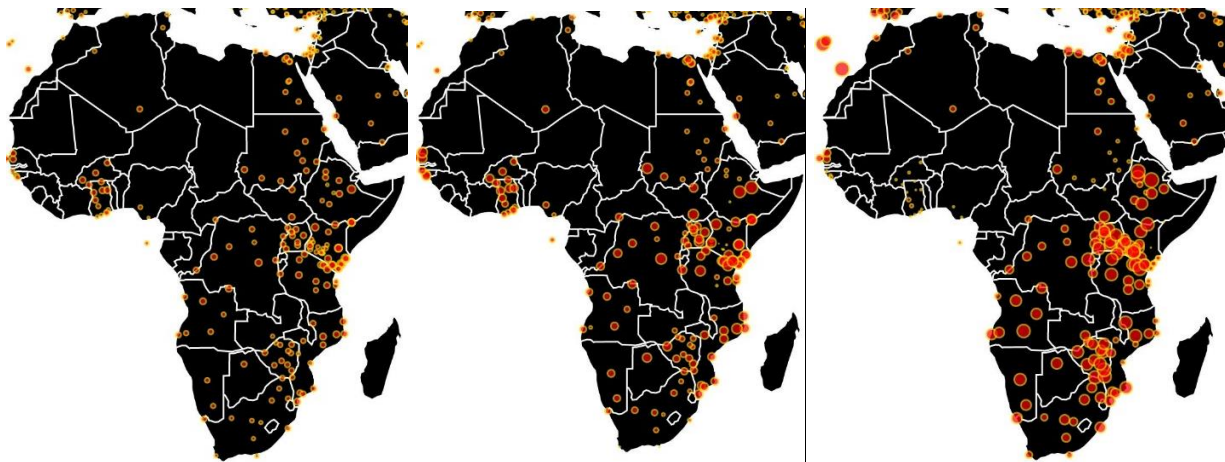


Figure 24: Map showing natural ventilation prediction Potential of direct ventilation, Potential of high ventilation and potential of low ventilation respectively (source: Chen, 2017).

2.2.2 Application of Natural Ventilation in Ethiopia

There is a limited study about natural ventilation including all cities of Ethiopia. In Addis Ababa, the capital of Ethiopia outdoor air temperature and humidity are in a comfortable

range providing great potential for natural ventilation during daytime all throughout the year. It is conducive to provide night flushing during relatively hot times of the year. East and West openings have greater potential for good natural ventilation than North and South openings (Figure 25) (Yacob, 2014).

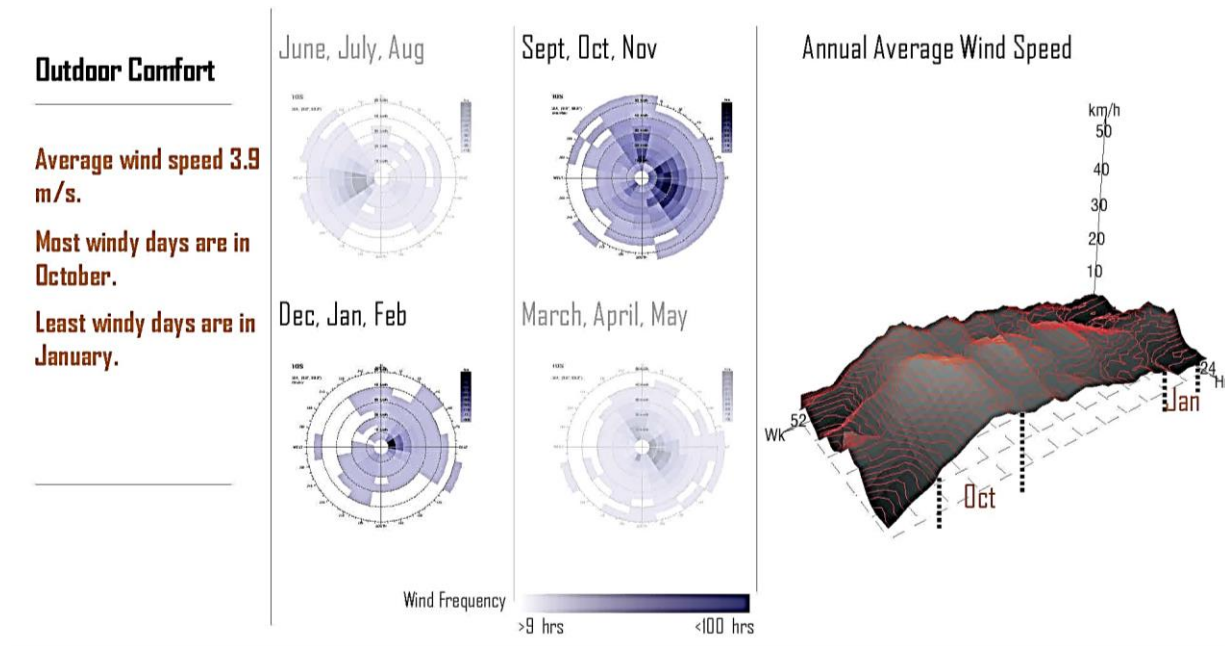


Figure 25: Wind condition in Addis Ababa (Source: Climate responsive building guidelines, 2006)

According to 2015 Ethiopian urbanization review, the rate of urbanization will be about 5.4% a year. Energy is the most important engine in the urban environment; it defines the quality of urban life and global environment. In developing countries like Ethiopia, the cost of energy is higher than the developed countries. Citizens in these countries spend 12% of their income on energy service (OECD, 2002).

2.2.3 History

In Ethiopia, the integration of openings in a building is existed since 8th century BC (Fig 26). The well-known multi story building in Yeha. Yeha is a town in the central zone of the northern Tigray Region, which served as the capital of the pre-Aksumite Kingdom Damat.

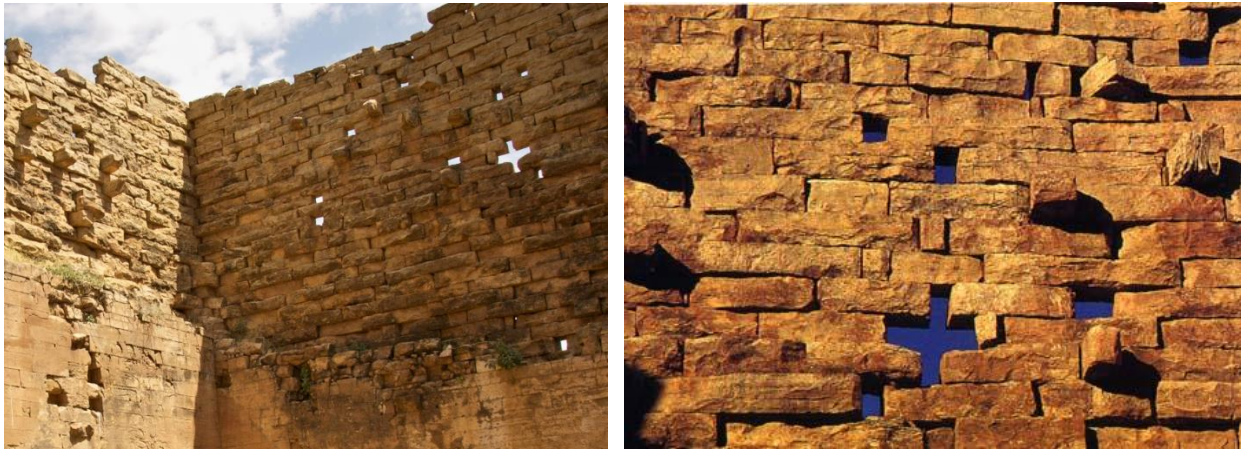


Figure 26: The ruin of the temple at Yeha, showing the opening in 8th century BC (Source: www.selamta.net, March 2020)

The Ethiopian Architecture continued to introduce opening even in Rock-Hewn Architecture around the country. The most famous examples are the 11 monolithic churches of Lalibela, carved out of the red volcanic tuff found around the town.

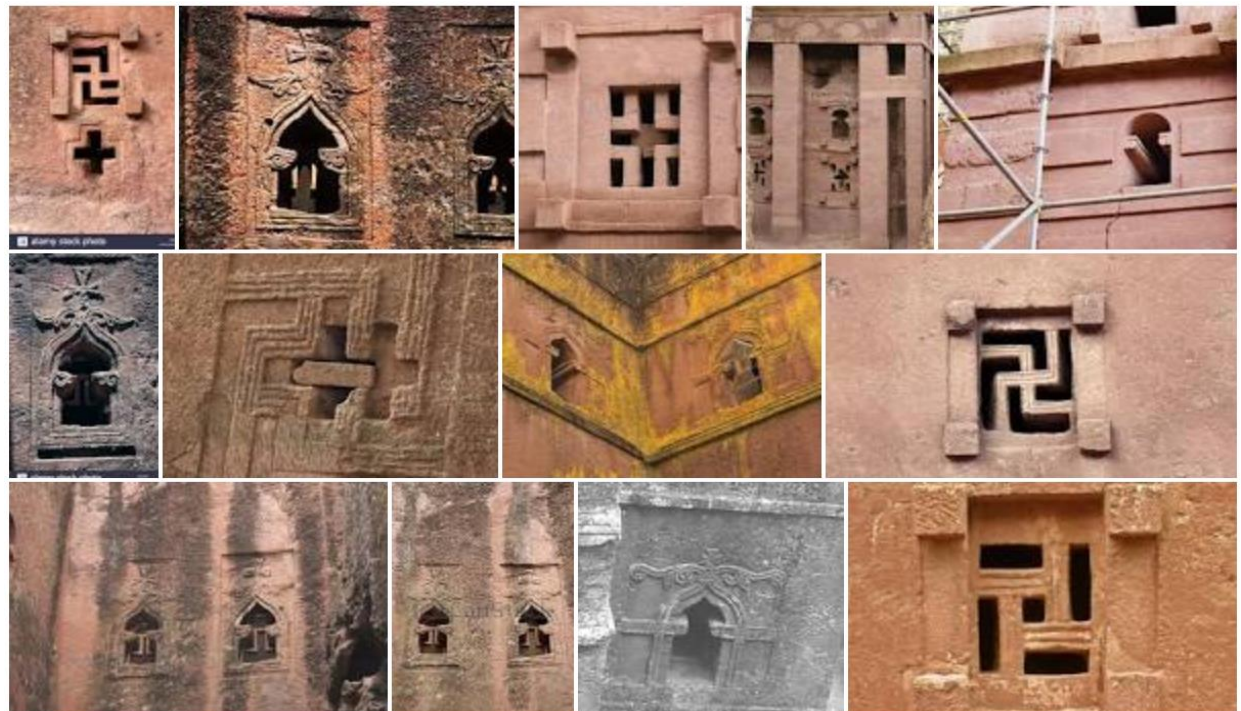


Figure 27: Openings of Lalibela Rock-Hewn churches (Source: www.selamta.net, March 2020)

CHAPTER THREE

MATERIAL AND METHODS

2.1 Study Area Description

Ethiopia is located in the North Eastern part of the African continent between 3°N and 15°N Latitude or 33°E and 48°E Longitude. Ethiopia is in the tropical zone laying between the Equator and the Tropic of Cancer (Figure 28). The country is among the largest countries of Africa and characterized by a wide variety of landscapes, with marked contrasts in relief and altitudes ranging from about 155 m below sea level to about 4,533 m above sea level.



Figure 28: Location map of Ethiopian

The climate of Ethiopia is therefore mainly controlled by the seasonal migration of the Intertropical Convergence Zone (ITCZ) and associated atmospheric circulations as well as by the complex topography of the country (Fazzini et al, 2016). In Ethiopia, the wind

regime is influenced by barometric synoptical variations associated with the position of the ITCZ. Winds are not strong because the Horn of Africa is not a cyclone-genetic area and temperatures are rather uniform throughout the whole year. It is evident that in the central northern part of the country, in a few sites of the Eritrean coast and the Sudan lowlands, winds from the northern quadrant dominate, whereas in the southern areas, winds from the second and the third quadrants prevail throughout the whole year. On the margin of the Somali Plateau, western winds prevail, whereas in the far southwest of Ethiopia southwestern winds are more common. On the highlands, the annual frequency of days with calms and light breezes amounts to 12–18 % of the total (Fazzini et al, 2016).

2.2 Methods of Data Collection

Bioclimatic chart is used to determine the wind speed that will create comfort, choosing the size and arrangement of windows that best approximates the proposed room design will be the next step. The methods are detailed in (Table 5).

Table 5: Tools of Data Collection

No	Specific Objective	Data Type	Collection Method	Instrument	Analysis
1	To regionalize Ethiopia based on wind speed and wind direction to identify representative zones.	Wind speed and Direction at 10 and 50 meter	30 years Daily recorded Wind speed and direction at 10 and 50 meter From NASA	Satellite weather data collector	The Wind speed and direction is used to categorize Ethiopian cities and towns to a certain category.
2	To determine the window size for natural ventilation using wind speed and wind direction diagram.	Wind Ross, Air velocity rate, cross-sectional area, Air flow rate, Building location,	Wind direction and speed diagram from NASA	Window sizing Procedure	Determining required total window inlet and outlet areas based on specified interior air velocity from climate analysis, examine and calculate required open effective window area.

2.3 Research Design

The research design illustrates the overall strategy that are used to integrate the difference components of the study in logical way, to address the research problem. It also include the method and procedures used in collecting and analyzing measures of variables specified in the problem statement (Figure 29).

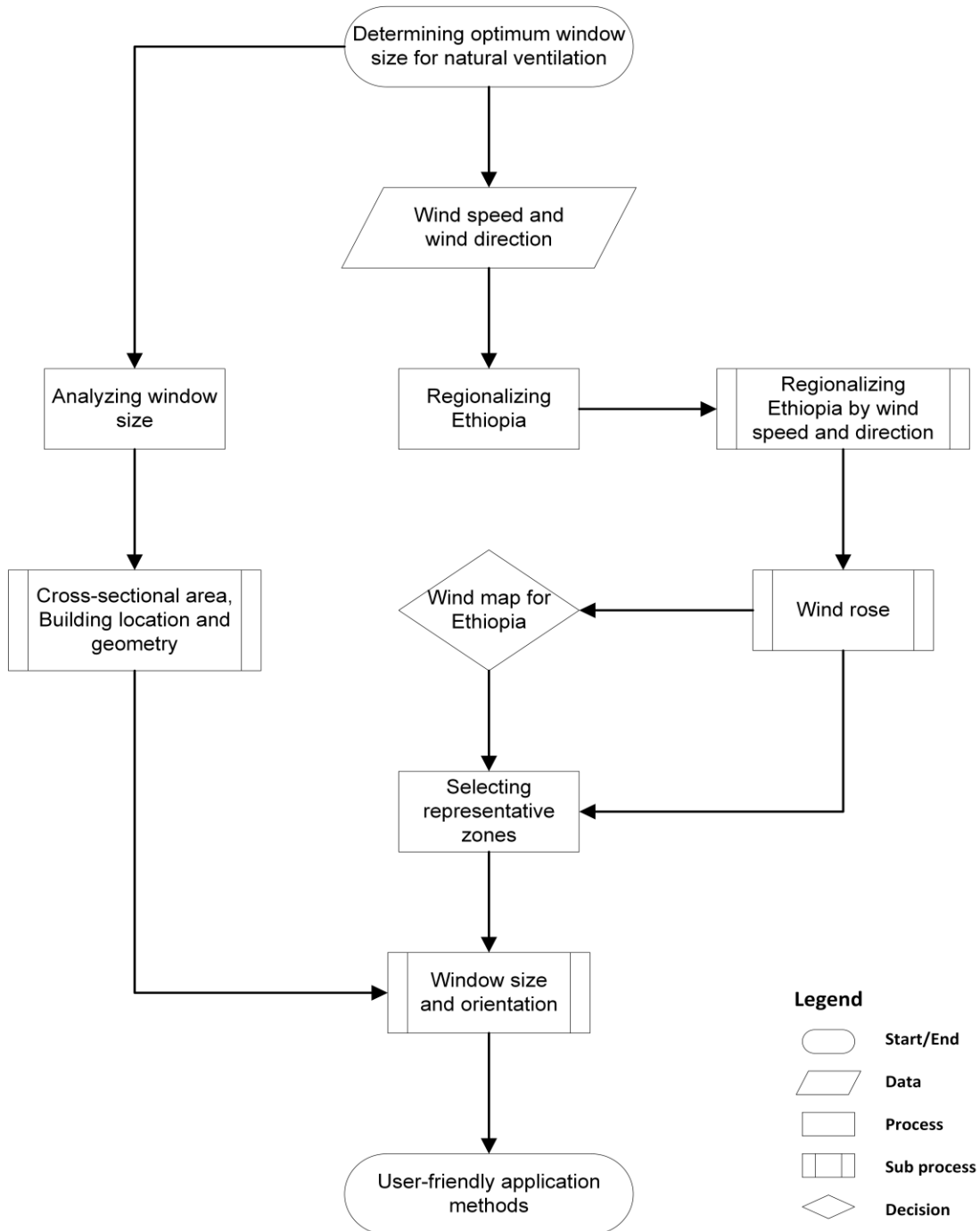


Figure 29: Research Design

2.4 Sampling

The urban centers of Ethiopia are selected depending on density (Figure 30) which include administrative districts. The urban centers are categorized according to the wind data collected for select representative urban centers. After identifying representative cities, their wind speed and wind direction were collected with the cross-sectional area of a simple geometry. Then the optimum size that fit for the area have been determined.

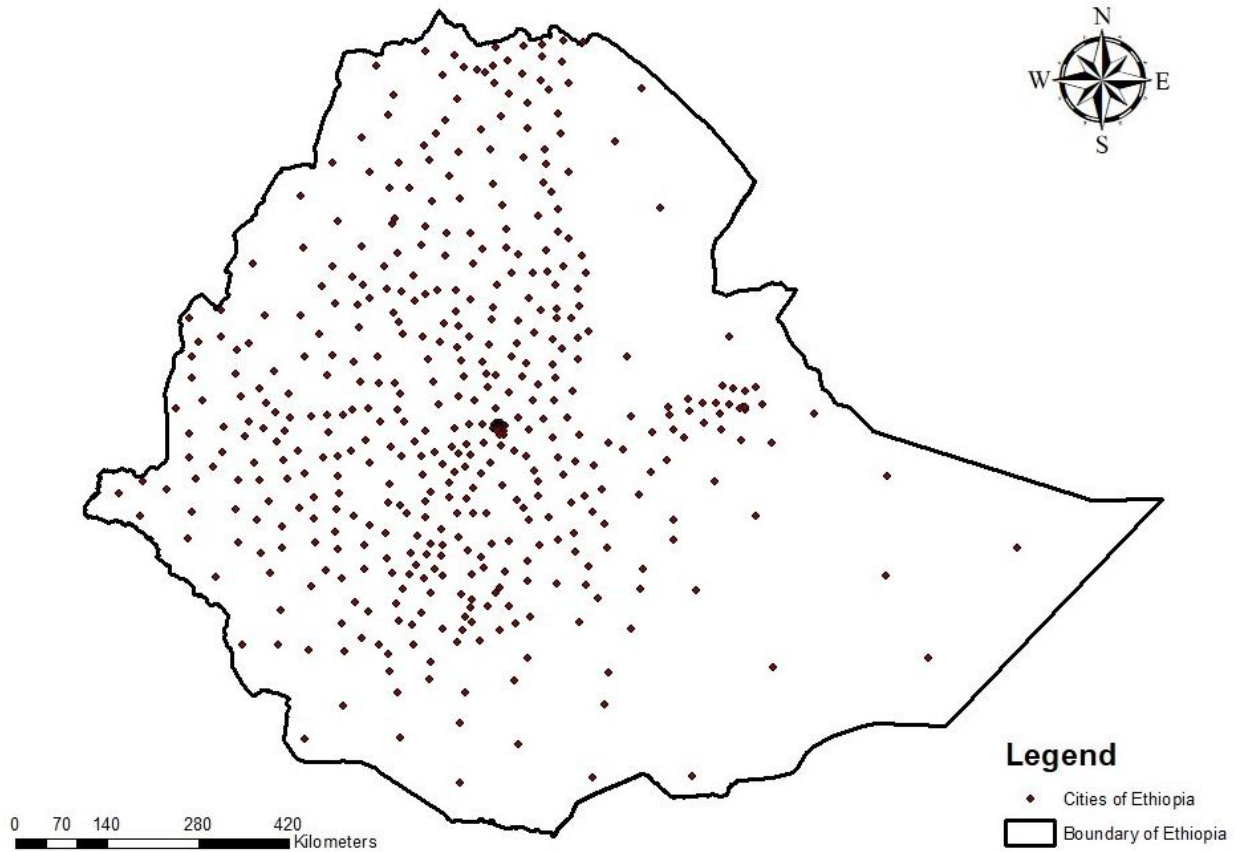


Figure 30: Location of Ethiopian Cities (Source: EthioGIS, June 2019)

2.5 Data analysis

2.5.1 Regionalizing Ethiopia

To regionalize Ethiopia based on Ventilation access, different sources of climatic data that have wind speed and detection at different levels are explored and compared. The MARRA-2 is chosen because it presents 30 years of data. The daily means wind are taken from NASA(MARRA-2) and represents estimates at 10m and 50m above the local surface over a 0.5° latitude x 0.5° longitude grid. Wind direction at a given height in meters as the meteorological convention. The meteorological convention gives the direction from which the wind originates and wind direction is measured in degree clockwise from due north. To calculate wind speed at different height Equation 4 has been used, for correction factors as a function of the height and roughness of the ground (Table 6) is used.

$$\frac{V_z}{V_{10}} = KZ^\alpha \dots\dots\dots\text{Equation 4}$$

Where: V_z = Wind speed at height Z (m/s)

V_{10} =Wind speed at 10m (m/s)

K and α are two coefficient that vary depend on the types of ground

(Source: Kolendowicz, 2007)

Table 6: Correction factors as a function of the height and roughness of the ground

Terrain	α	K
Open countryside, flatland	0.17	0.68
Low-density urban periphery	0.20	0.52
Urban area	0.25	0.35
Downtown	0.33	0.21

(Source: Sustainable Building Design for Tropical Climates, 2015)

Average wind speed is categorized by using the Beaufort’s scale. In addition, the study region are classified according to the sustainable building design for tropical climates. The Beaufort’s scale is a system originally developed by Admiral Beaufort (1805) and subsequently revised by other works giving an approximate estimate of wind speed, (Table 7).

Table 7: Beaufort scale of wind speed

Beaufort No.	Wind speed(m/s)	Description	Land condition	Comfort
0	0–0.5	Calm	Smoke rises vertically	No noticeable wind
1	0.5–1.5	Light air	Smoke drifts	
2	1.6–3.3	Light breeze	Leaves rustle	Wind felt on face
3	3.4–5.4	Gentle breeze	Wind extends flags	Hair disturbed, clothing flaps
4	5.5–7.9	Moderate breeze	Small branches in motion, raises dust and loose paper	Hair disarranged
5	8.0–10.7	Fresh breeze	Small trees in leaf begin to sway	Force of wind felt on body
6	10.8–13.8	Strong breeze	Whistling in telegraph wires, large branches in motion	Umbrellas used with difficulty Difficult to walk steadily Noise in ears
7	13.9–17.1	Near gale	Whole trees in motion	Inconvenience in walking
8	17.2–20.7	Gale	Twigs broken from trees	Progress impeded Balance difficult in gusts
9	20.8–24.4	Strong gale	Slight structural damage (chimney pots and slates)	People blown over in gusts
10	24.4–28.5	Storm	Seldom experienced inland. Trees up-rooted, considerable structural damage	

(Source: Kolendowicz, 2007)

Secondary-Inter Cardinal direction is another method used to classify the regions by wind direction. The secondary-Inter Cardinal direction is classified in to 16 direction as shown in (Figure 31).

Cardinal Direction	Degree Direction
N	348.75 - 11.25
NNE	11.25 - 33.75
NE	33.75 - 56.25
ENE	56.25 - 78.75
E	78.75 - 101.25
ESE	101.25 - 123.75
SE	123.75 - 146.25
SSE	146.25 - 168.75
S	168.75 - 191.25
SSW	191.25 - 213.75
SW	213.75 - 236.25
WSW	236.25 - 258.75
W	258.75 - 281.25
WNW	281.25 - 303.75
NW	303.75 - 326.25
NNW	326.25 - 348.75

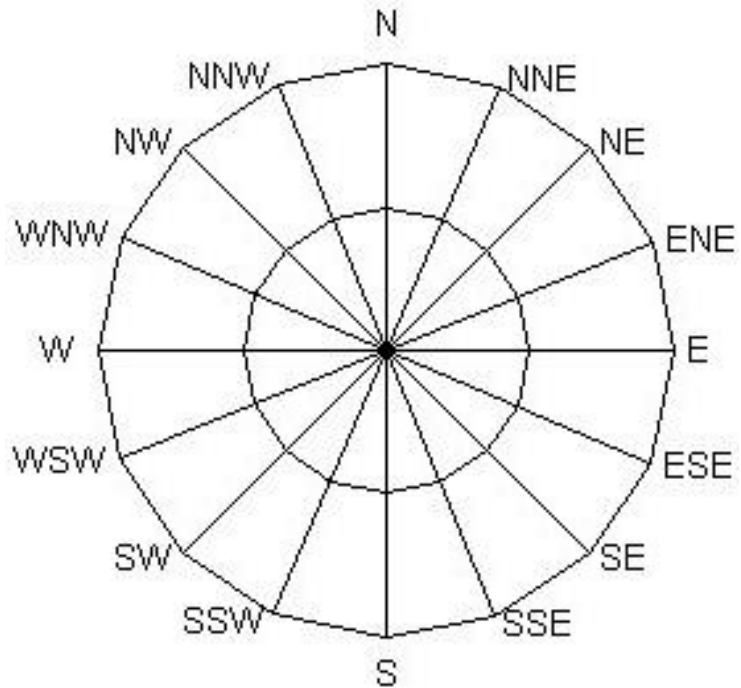


Figure 31: Wind direction and degrees (source: Torres, 1999)

According to sustainable building design for tropical climate, (Aste, 2015), additional regionalization for cross ventilation when the openings are in opposite direction of the airflow is obtained using the graph (Figure 19 and 20) which is classified in to 11 category. 0.0 to 0.5m/s, 0.51m/s to 1.0m/s, 1.01m/s to 2.0m/s, 2.01m/s to 3.0m/s, 3.01m/s to 4.0m/s and above 4.0m/s.

To determine the window size for identified cardinal direction using ventilation and wind direction diagram different studies are used. For the category generated by overlaying wind speed and direction, a simple geometry room with different orientation and height has been studied in both single-sided and cross-ventilation scenarios.

By using (Equation 2) for cross-ventilation the appropriate opening size is determined, for a same room size in a different opening orientation. The airflow rate is obtained using the graph (figure 19 and 20) “K”. Depending up on the direction of wind relative to the opening and on the ratio of the two opening. The opening orientation at the selected cardinal direction is studied in seven category for both 90^0 and 45^0 wind flow angle and then appropriate equation have been proposed for each category.

To determine the appropriate size of window to obtain a required airflow rate, two scenario is studied. When the inlet and outlet windows are equal and when there is different inlet and outlet window size. URBVENT, Natural Ventilation in Urban areas potential assessment and optimal façade design evaluated the simulation of single-sided ventilation by using AIOLOS software. The URBVENT work package 2 created a database of natural ventilation rates that can be used to train a fuzzy logic predictor. In this sense, a large number of different situations studied. Nevertheless, due to unavailability of the data local strategy is studied.

The airflow rate is mandatory to develop a user-friendly method for determining optimum window size for the room. The airflow rate is calculated in cubic feet per minute (CFM) by using the room volume and typical air change rate. Determining the CFM of a room is mathematical process of figuring the room’s cubic area as well as the rate at which it is desire the air to circulate throughout the room. After finding the CFM of the room, it should be changed to cubic meter per second in order to calculate the optimum window size with the wind flow direction and speed.

2.5.2 Window sizing for natural ventilation

Window size for cross ventilation

When the inlet and outlet windows are equal, the wind speed at the height of the window is calculated using (Equation 4) with the reference height of 10m and correction factors given in (Table 4). By assuming that inlet window size is equal to outlet window size (Figure 32). When the air flow angle is at 45° “K” is equal to 0.3 (a). when the airflow angle is perpendicular to the window the value of “K” is 0.6.

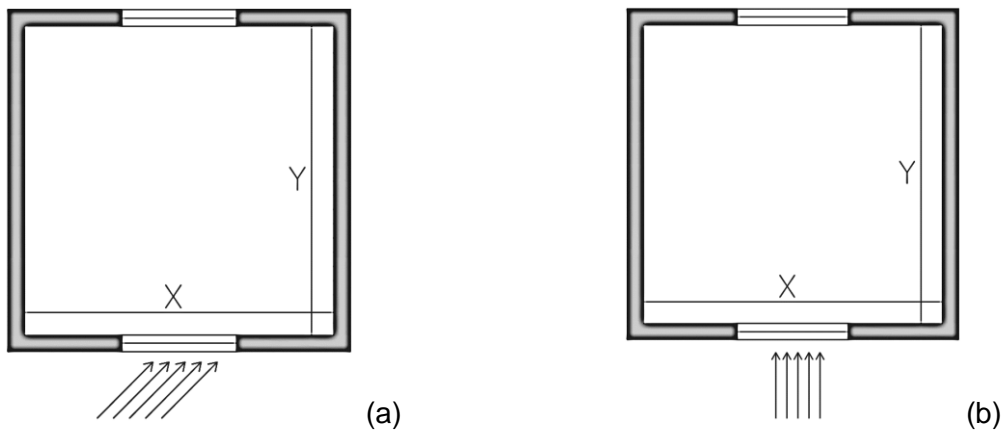


Figure 32: Plan of the room with equal windows size at an angle of 45° (a) and 90° (b) respectively

To determine the effect of a different ratio between inlet and outlet window area (Figure 33), the same calculation is used with the ratio of the windows. By using the graph of (Figure 21 and 22), the airflow rate is estimated. Tracing the graph using the ratio between the inlet and outlet to get the airflow rate.

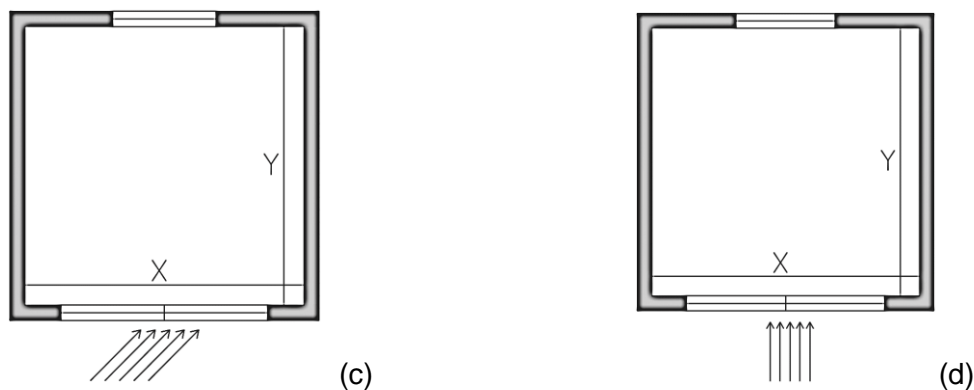


Figure 33: Plan of the room with different windows size at an angle of 45° (a) and 90° (b) respectively

The desired total airflow rate must be divided by values that can be read on the Y-axis, for example (Figure 34) in order to obtain the outlet opening area needed (that corresponds to the “smaller” area).

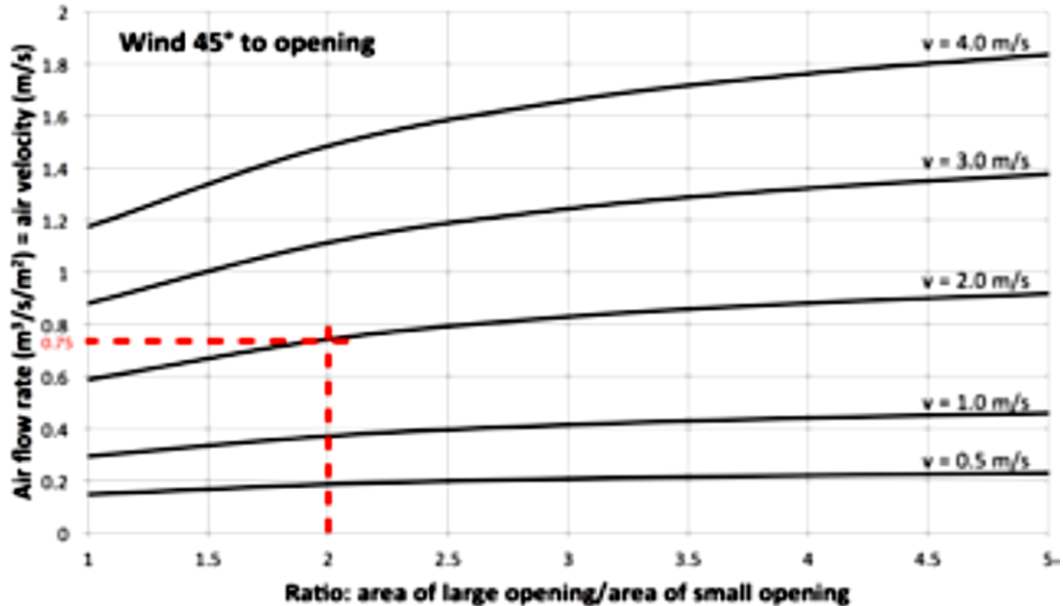


Figure 34: Airflow rate per square meter through the smaller opening (or air velocity in m/s) with different wind speed – wind incident at 45° (Source: sustainable building design for tropical climates, 2015)

Window size for single-side ventilation

Average internal wind speed will not change significantly with increasing window size of a single window (Figure 35a). As one-sided ventilation can be made effective when: Two openings are placed on the windward face (Figure 35b) and the wind angle is oblique (20 to 70 degrees) as in (Figure 35c). The windows are as far apart as possible, and If deflectors such as wing walls are used.

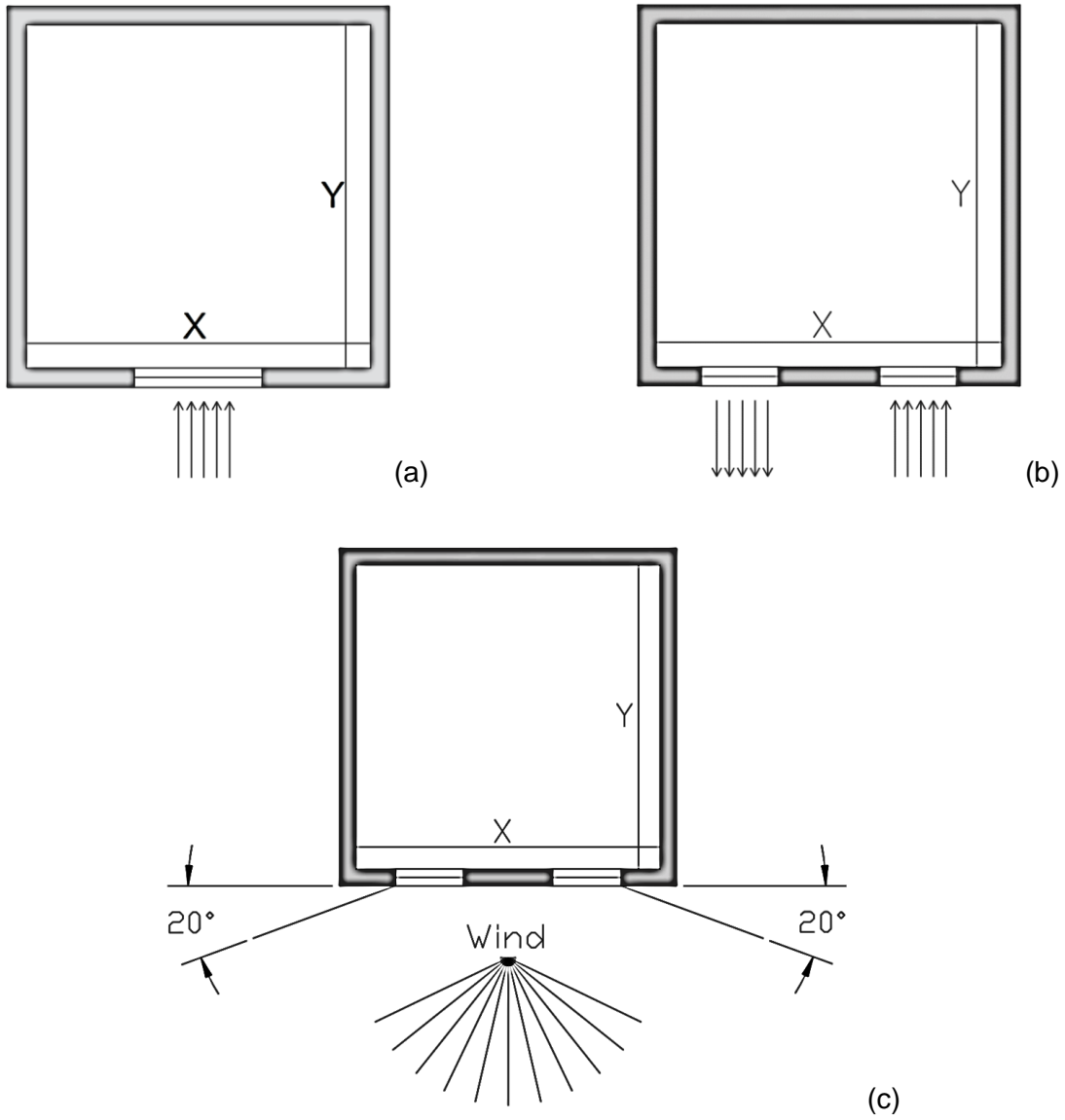


Figure 35: Ventilation in rooms with openings in one wall

CHAPTER FOUR

RESULT

4.1 Regionalizing Ethiopia by wind speed and direction

The prepared average wind speed parameter for the urban centers of Ethiopia, area coverage analysis is performed by using the Beaufort's scale of wind speed. The mapping is done using ArcMap 10.5, which is the component of Esri's ArcGIS suit of geospatial processing program. It include special libraries for data mapping on available geographical and wind data. It is also used to pre-analyze the data on maps. The wind speed that is collected from urban centers of Ethiopia is represented in the map. It is clear from (Figure 36) that the regions 90% wind speed is in between 1.6m/s to 5.4m/s. The annual average wind speed data of the overall area shows that 50% of light breeze, 40% Gentle breeze and 2% of light air at the height of 10m (Figure 37). The mean wind speed zone at 10m is classified in to three. Zone 1: is from 0.6m/s - 1.5 m/s, Zone 2: is from 1.6m/s – 3.3m/s, Zone 3: 3.4m/s – 5.4m/s.

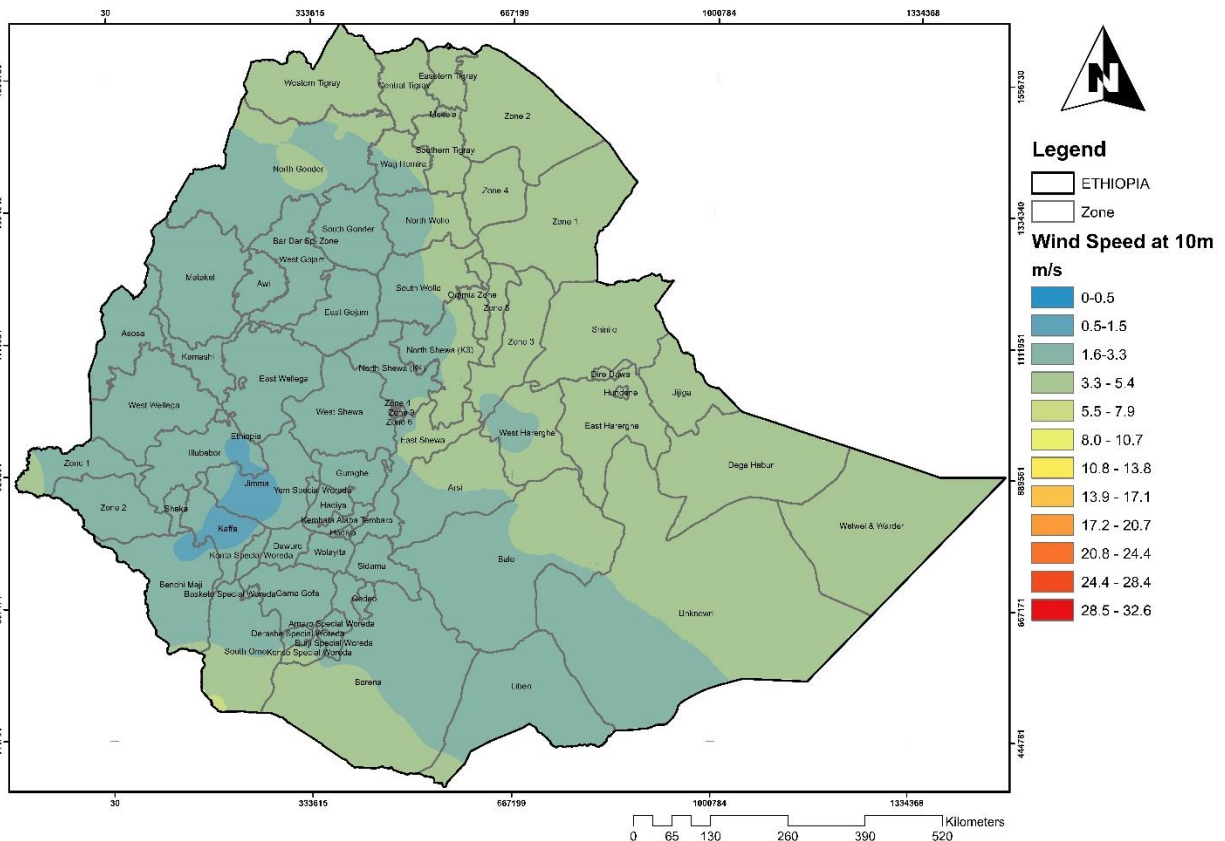


Figure 36: Regionalized map by Beaufort's scale of wind speed at 10m

According to the Beaufort's scale, the annual average wind speed data of the overall area of Ethiopia shows that 50% of Light breeze, 40% Gentle breeze and 2% of Light air at 10m (Figure 37). So on land, the wind is felt on exposed skin, and leaves and smaller twigs are in constant motion. According to (Adler, 2007), more than 98% of the wind speed in Ethiopia desirable for natural ventilation effective design.

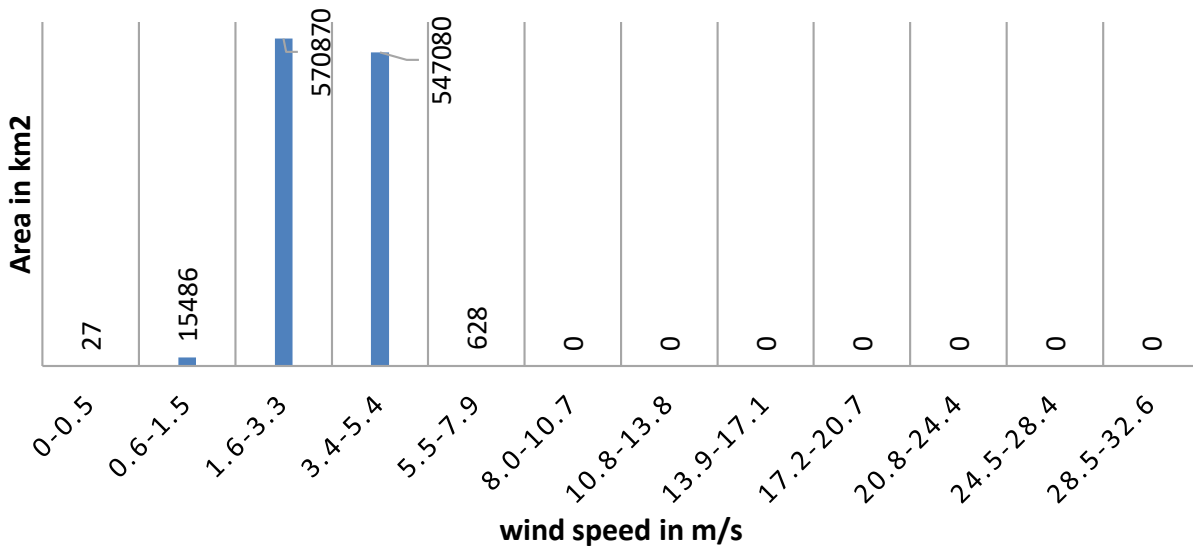


Figure 37: Area coverage by Beaufort's scale of annual wind speed at 10m of Ethiopia

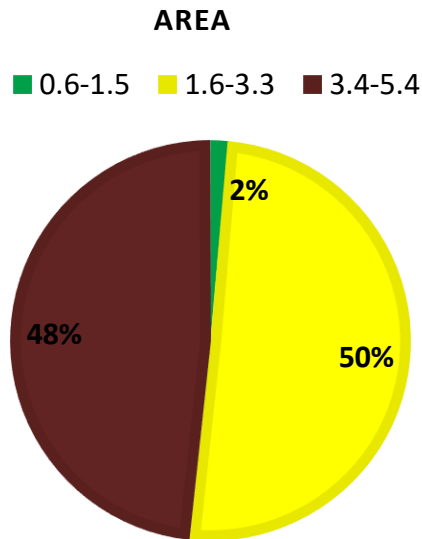


Figure 38: Regionalized area coverage by Beaufort's scale of wind speed at 10m

Wind speed at 50m is used to regionalized the second map which appears to be a slight difference from the map at 10m height. The dominant wind speed is between 3.4m/s and 5.4m/s, which covers more than 750,000 km² (Figure 39). Of the overall area of Ethiopia shows that 29% of light breeze, 69% gentle breeze and 2% of moderate breeze at the height of 50m (Figure 40).

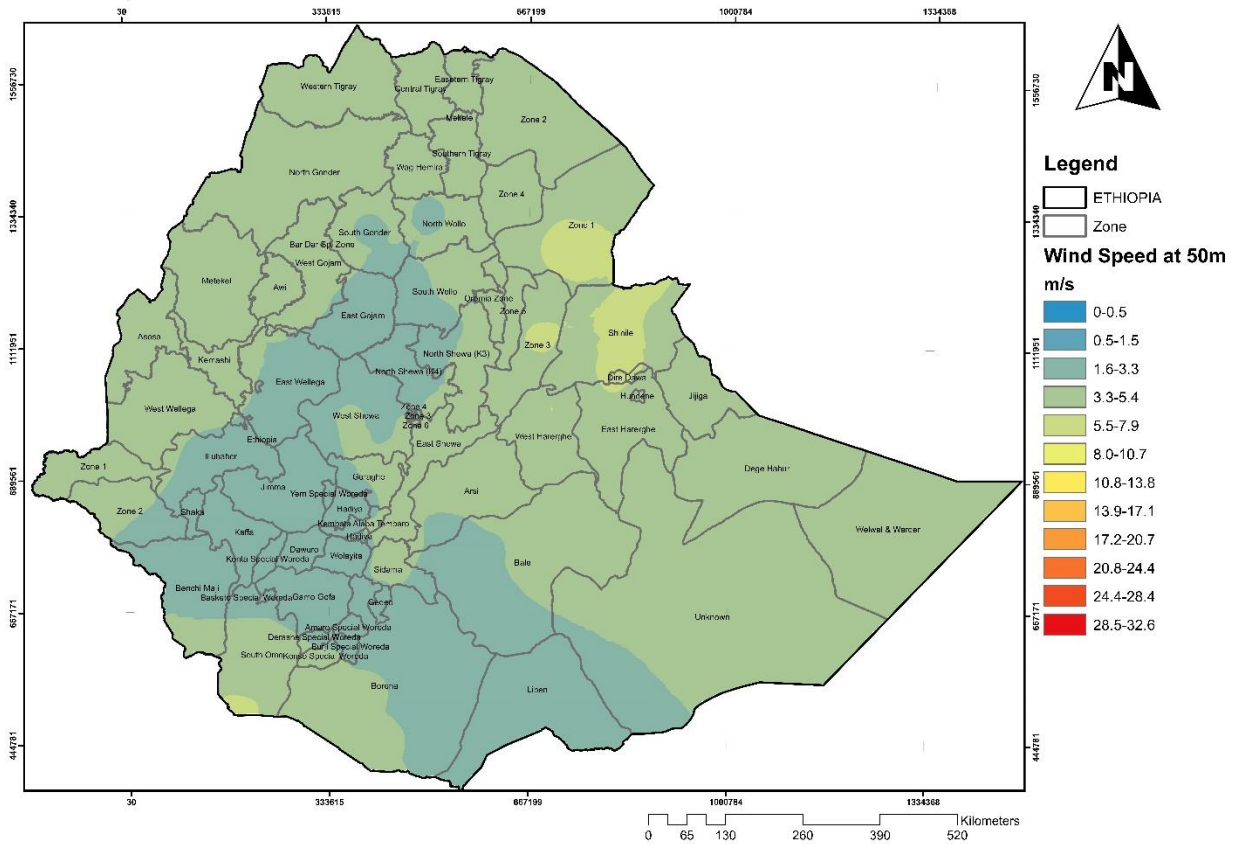


Figure 39: Regionalized map by Beaufort's scale of wind speed at 50m

According to the Beaufort's scale, the annually average wind speed data at 50m shows a little difference from the wind data at 10m. Of the overall area of Ethiopia shows that 29% of Light breeze, 69% Gentle breeze and 2% of Moderate breeze at 50m (Figure 41). So on land the wind is felt on exposed skin, and leaves and smaller twigs are in constant motion.

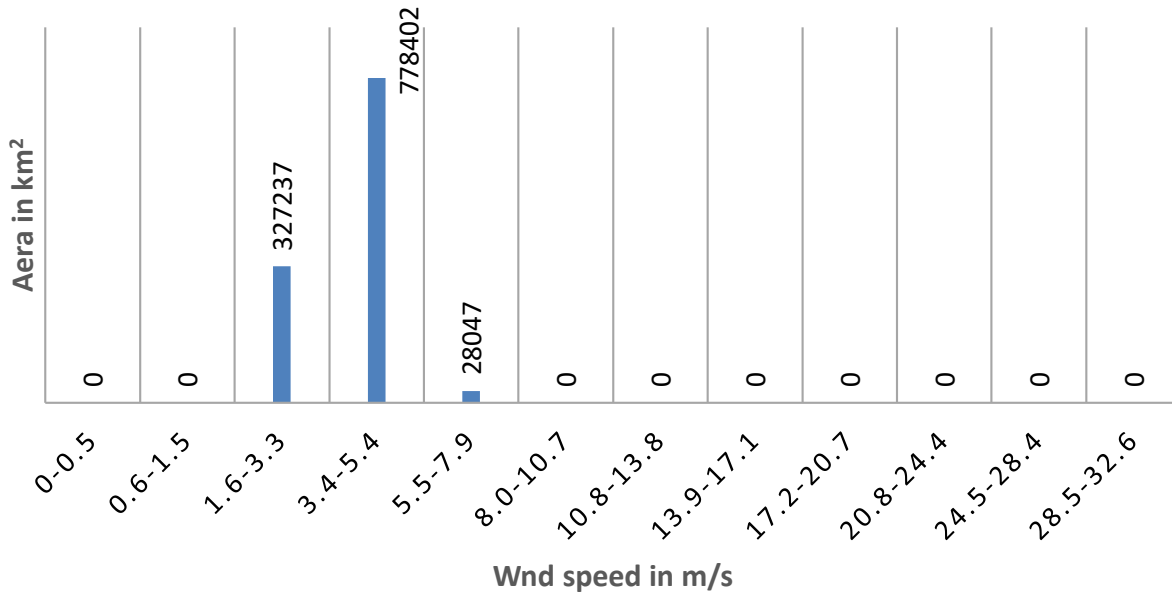


Figure 40: Area coverage by Beaufort's scale of Annual wind speed at 50m of Ethiopia

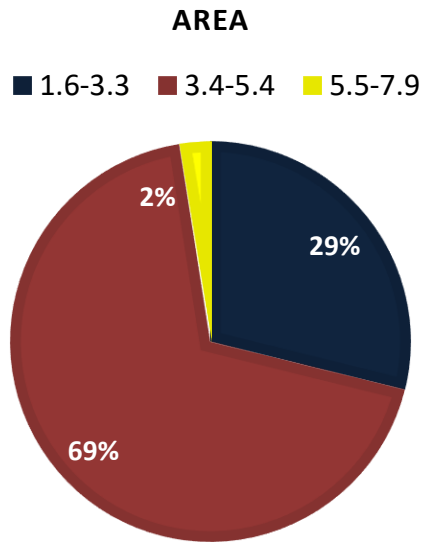


Figure 41: Regionalized area coverage by Beaufort's scale of wind speed at 50m

The mean wind speed zone at 50m is classified in to three. Zone 2: is from 1.6m/s – 3.3m/s, Zone 3: 3.4m/s – 5.4m/s and Zone 4: 5.5m/s – 7.9m/s,

Wind direction is another means that is used to regionalize Ethiopia. From the collected wind direction data of the urban centers of the country is categorized depending on the wind flow direction. According to the map generated, the dominating wind direction of the

country is from southeast it covers more than 500,000km² of the region (Figure 42). The wind flow from the direction of southeast covers 45% of the overall wind direction. 24%, 15% and 14% flow from the direction of East-southeast, South-southeast and south respectively (Figure 45a). Therefore, the overall wind direction flow from between the cardinal direction of East and South.

The map of wind direction at 50m is almost the same as the map of wind direction at 10m, as shown in figure 36 and 39. The dominating wind direction of the country is from southeast, it covers more than 550,000km² of the overall wind direction (Figure 43) which is 49% of the region. The rest 21%, 15% and 13% wind flow from the direction of East-southeast, South-southeast and south, respectively (Figure 45b).

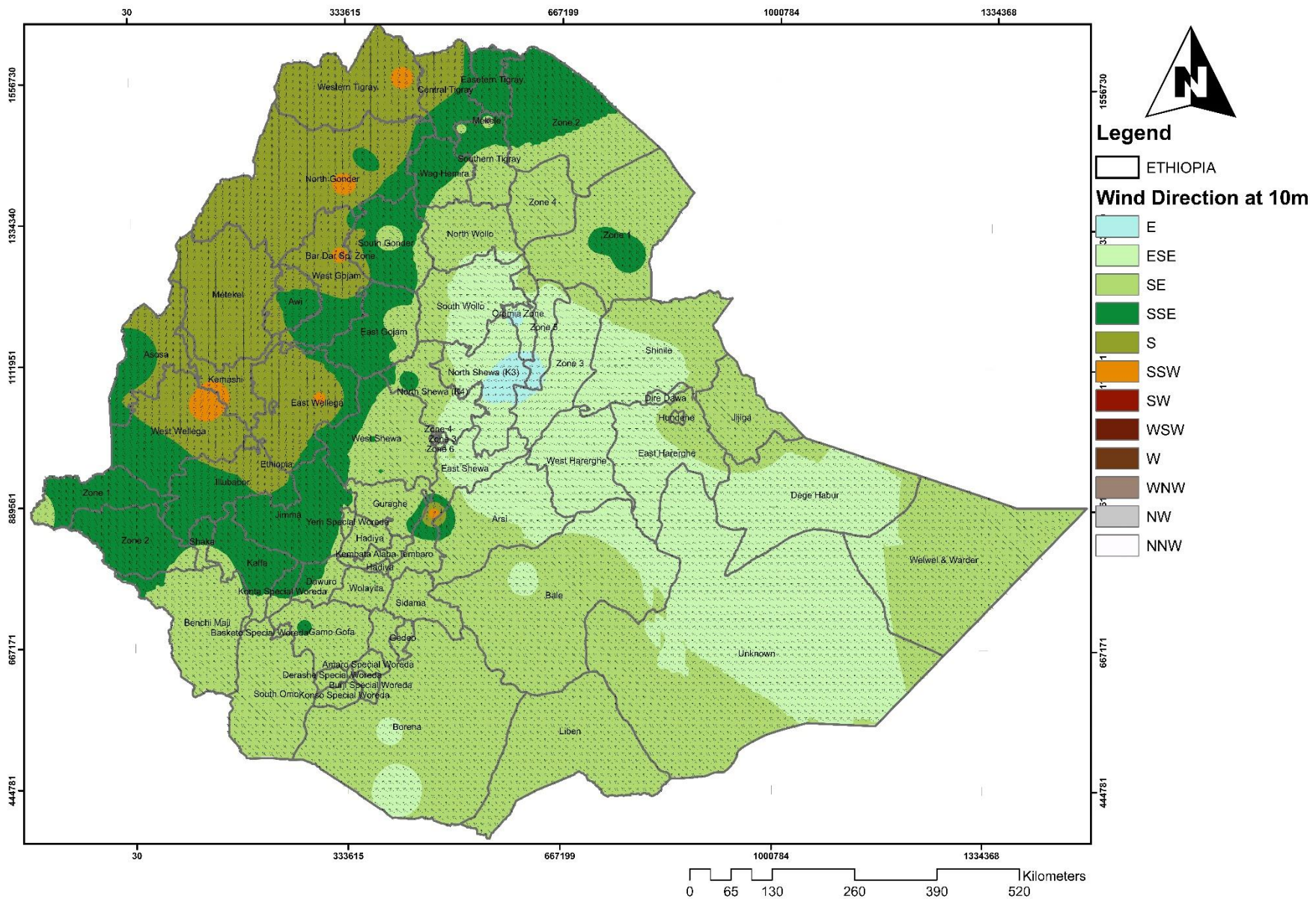


Figure 42: Regionalized map by wind direction at 10m of Ethiopia

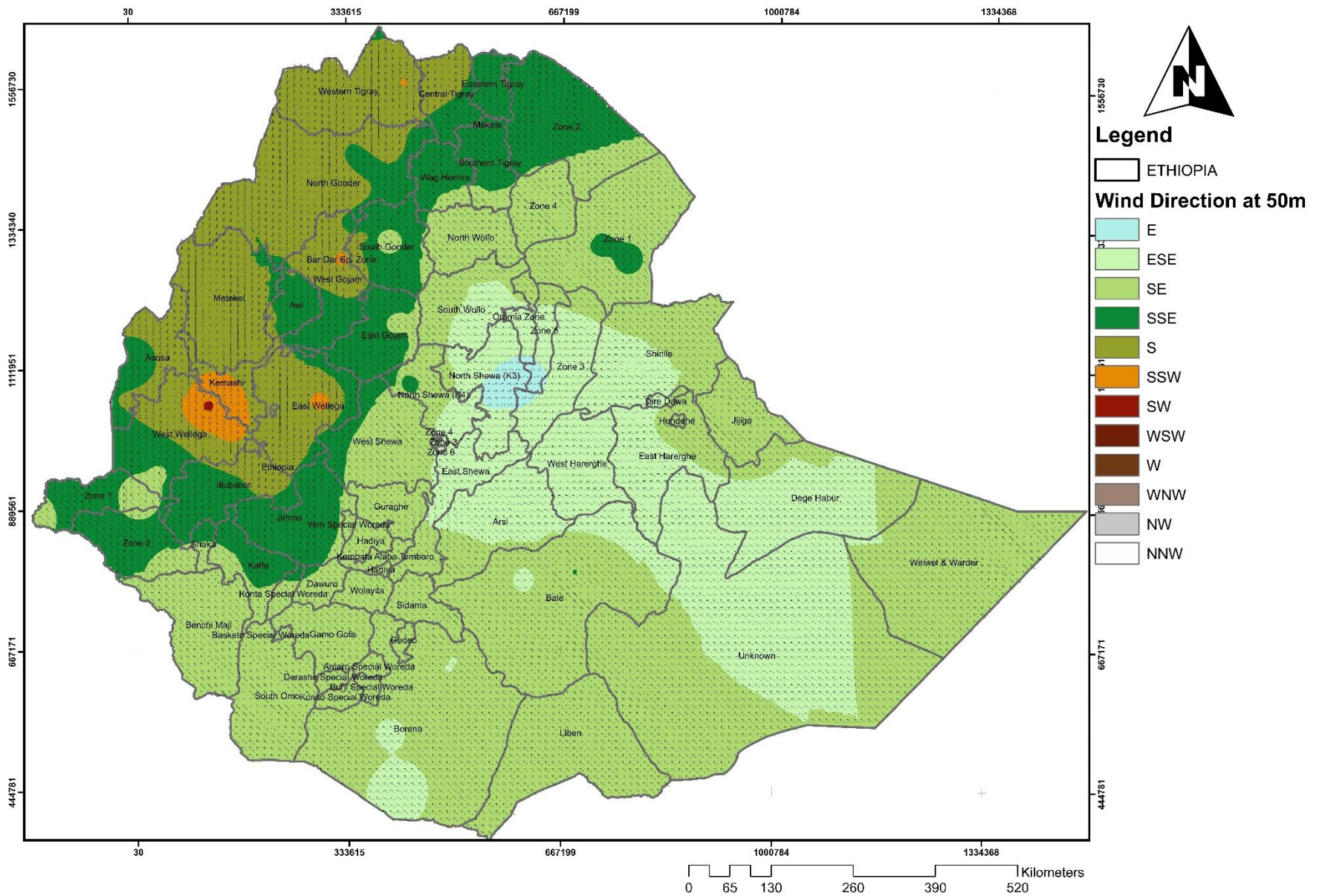


Figure 43: Regionalized map by wind direction at 50m

To investigate the effect of wind flow angle on natural ventilation wind direction is studied on the selected cardinal direction. Sixteen cardinal direction is evaluated at the height of 10m. The wind flow direction of Ethiopia is between the cardinal direction of E and SSW. The dominant wind flow direction at the height of 10m is from southeast to the northeast, it covers more than 500,000 km² of the region (Figure 44). The dominant wind flow direction at 50m is the same as at 10m but it covers more than 550,000km² (Figure 45).

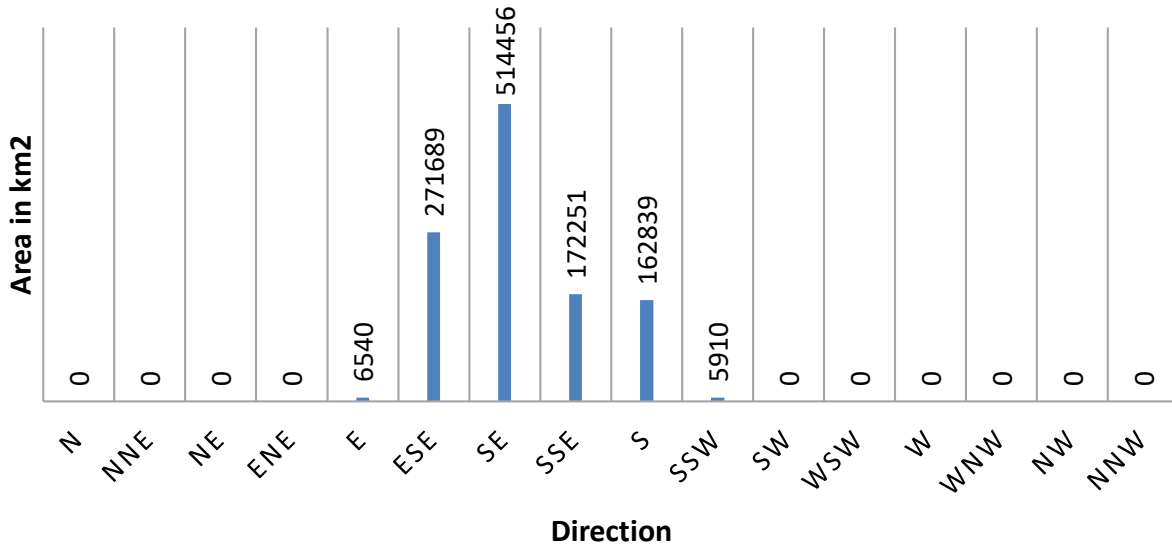


Figure 44: Area coverage of wind direction at 10m

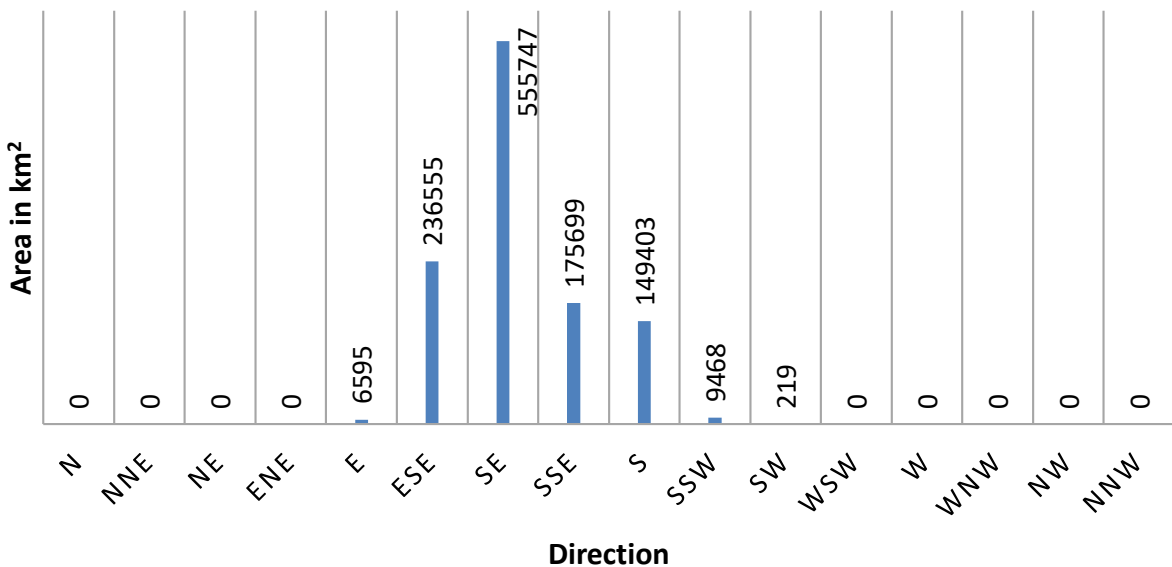


Figure 45: Area coverage of Wind Direction at 50m of Ethiopia

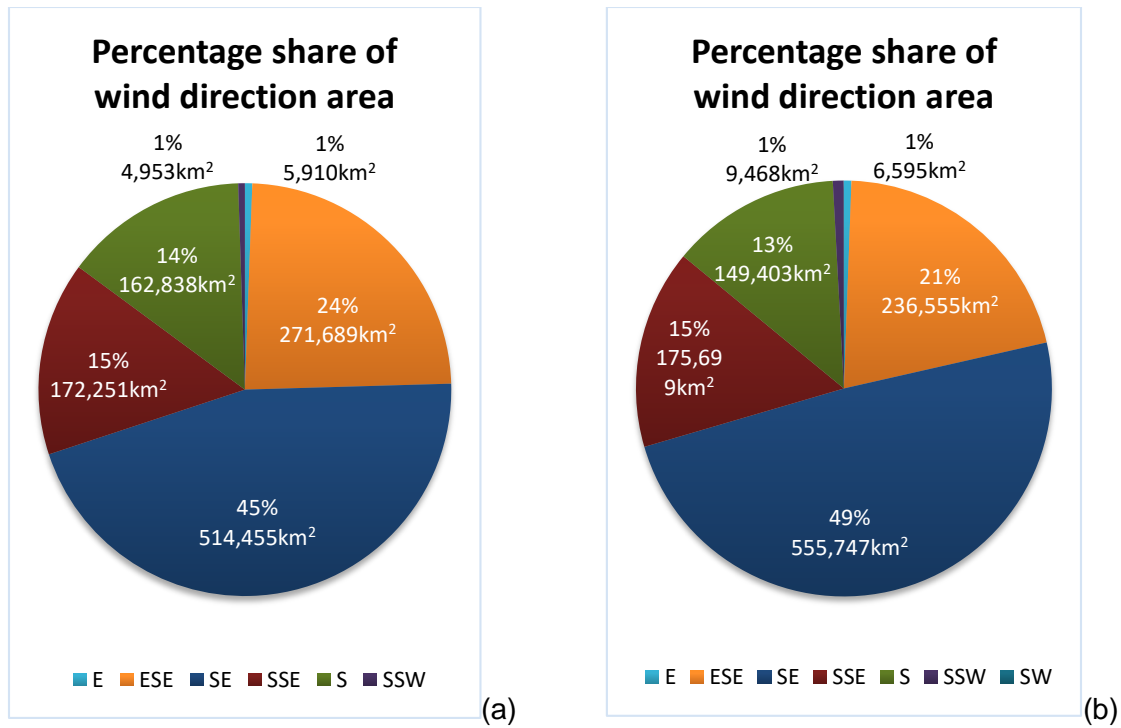


Figure 46: Area coverage of the regionalized map by wind direction at 10m and 50m

The wind direction is classified in to five major zones these are; Zone 1: wind direction from ESE, zone 2: wind direction from SE, zone 3: wind direction from SSE, zone 4: wind direction from S, and zone 5: wind direction from East, it is summarized in figure 47 below.

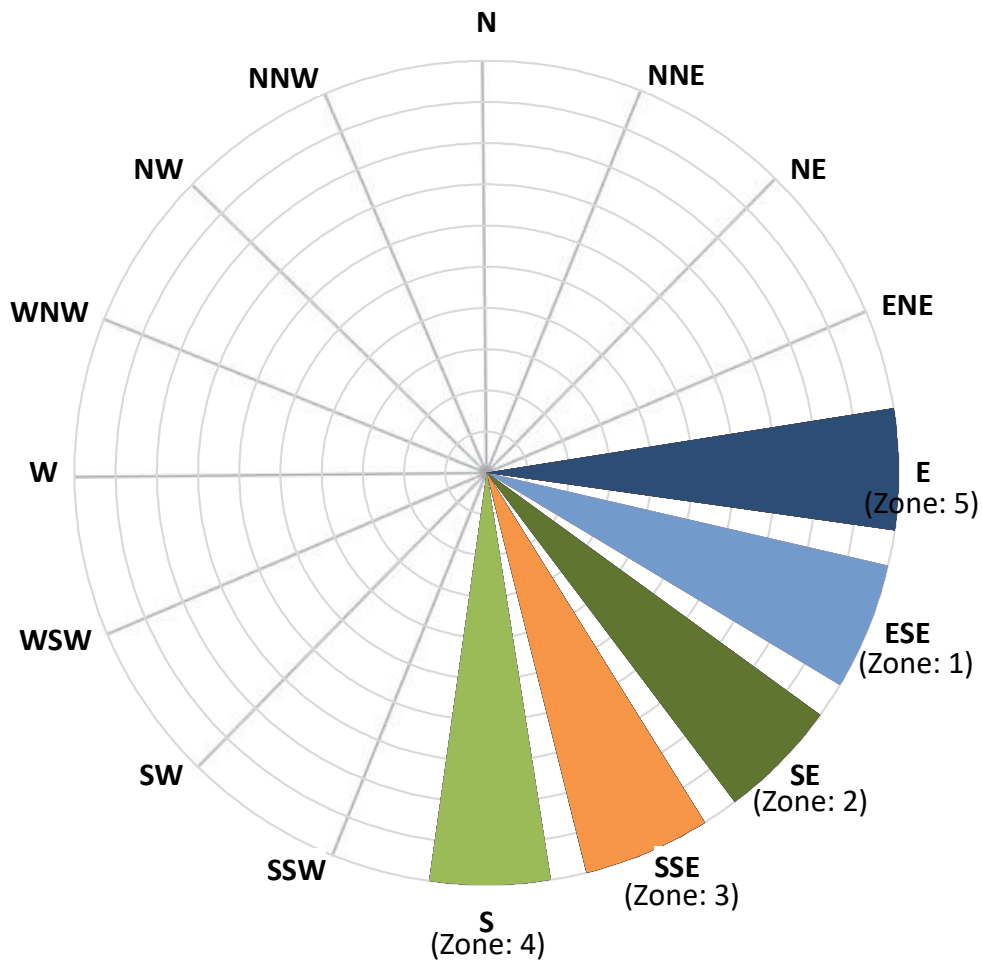


Figure 47: Dominant wind flow direction with respective zones of Ethiopia

The parameters, which characterize wind (Speed, Direction and frequency) of the different urban centers in Ethiopia, are given in (Figure 48) by using thirty years of wind data. The wind rose illustrates the frequency of winds blowing from particular direction. It shows the percentage of time the wind blows from sixteen compass points or the air in calm condition. Each notch represents five percent of the time, and the center represent the percentage of calmness.

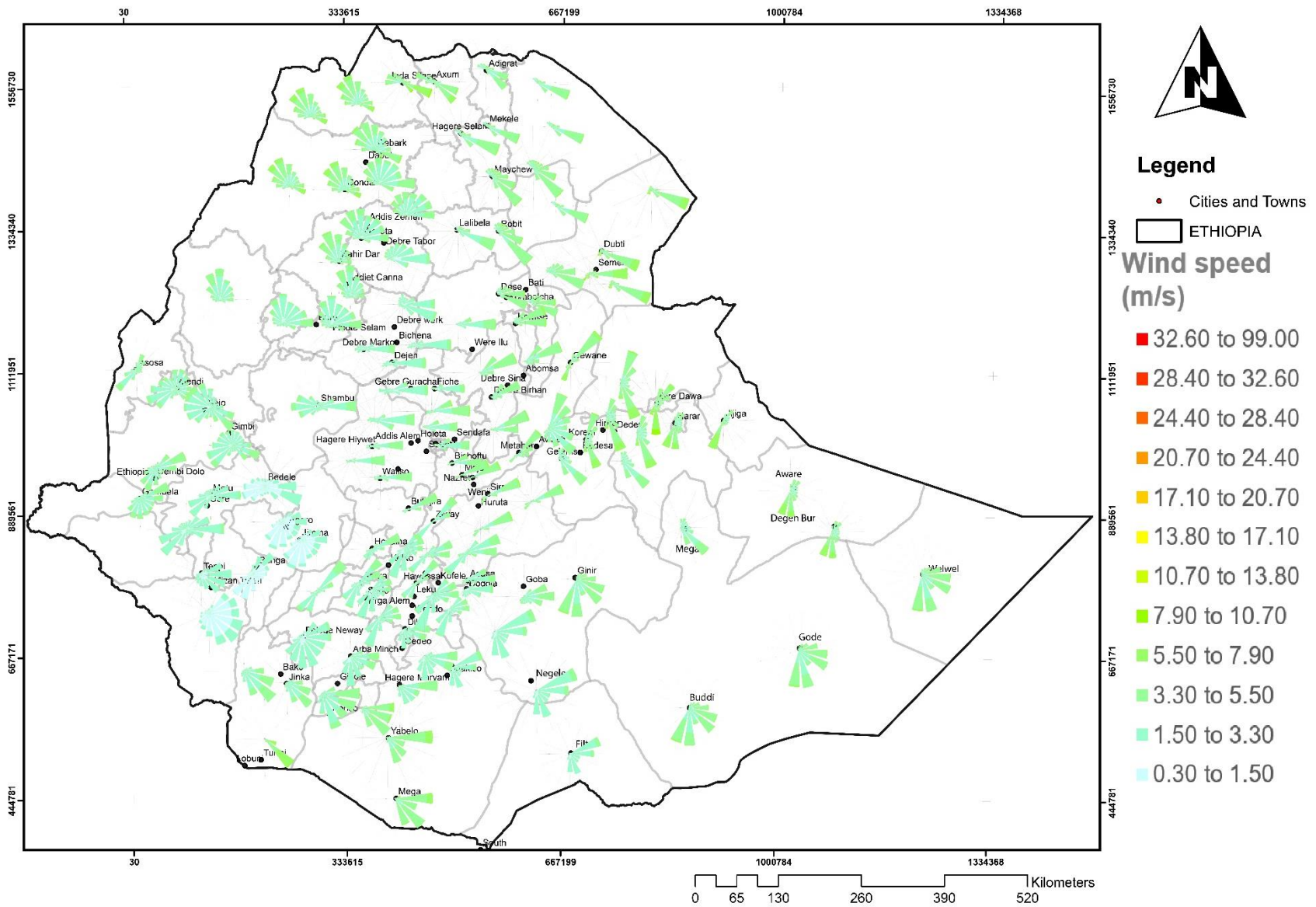


Figure 48: Annual mean wind rose diagram of Ethiopia

To check the validation of the data which is used to generate the wind rose, it is cross checked with another source of data. The Iowa Environmental Mesonet (IEM) is used. For cross checking the wind rose is generated based on archived data. Three urban centers such as Addis Ababa, Bahir Dar and Dire Dawa were identified for the case of local data depending on the availability of data. The wind rose diagram of Addis Ababa generated from IEM is illustrated in (Figure 49) for the month of March, April, may and June.

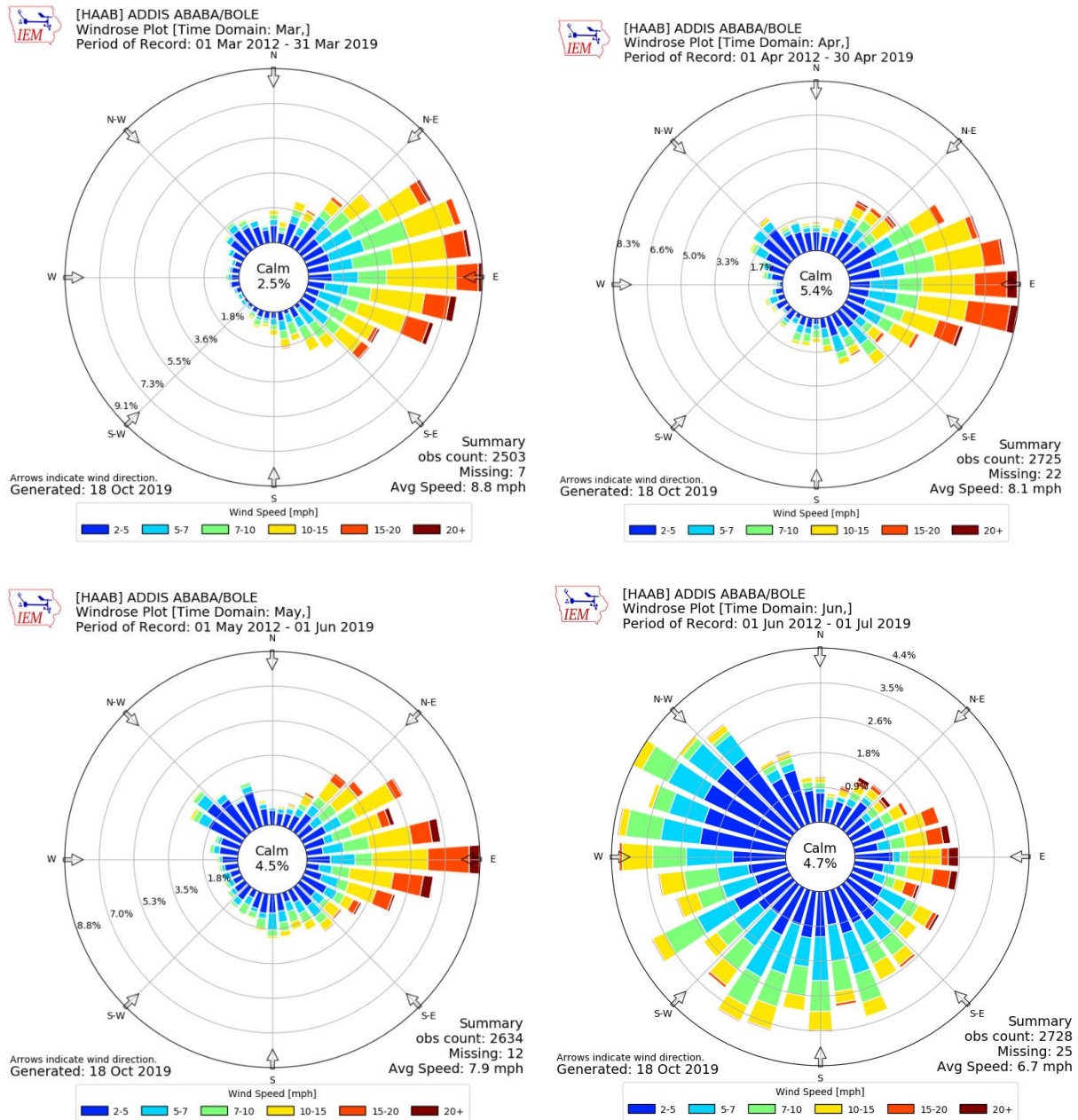


Figure 49: Wind rose diagram of Addis Ababa for the month of March, April, May and June.

Wind rose diagram of Bahir Dar is illustrated in (Figure 50) for the data available months of January, February March, April, May and June respectively. The diagram is generated from the data collected for a time of one year.

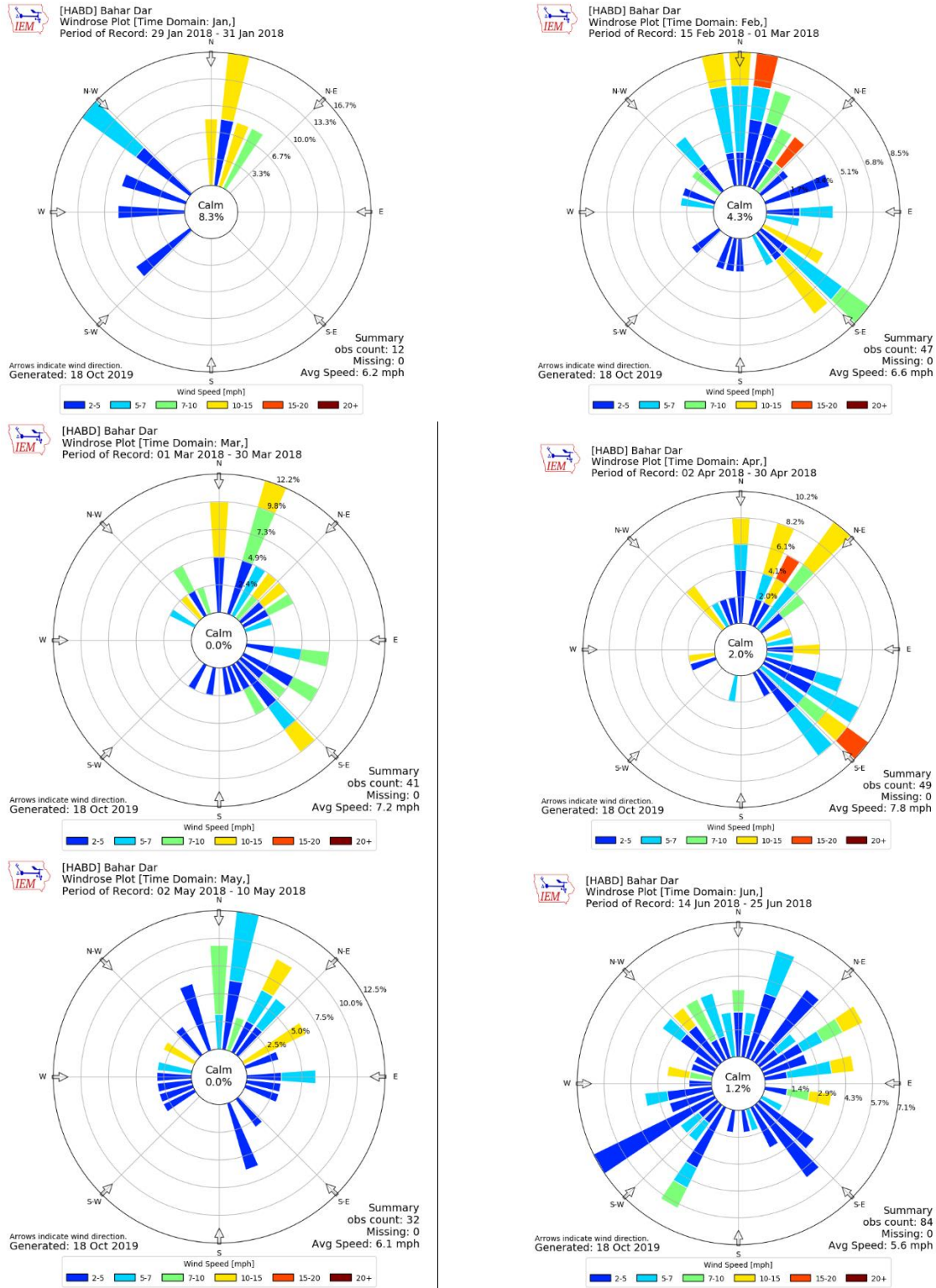


Figure 50: Wind rose diagram of Bahir Dar for the months from January to June

Wind rose diagram of Dire Dawa is illustrated in (Figure 51) for the months of January, February, March, April, May and June respectively.

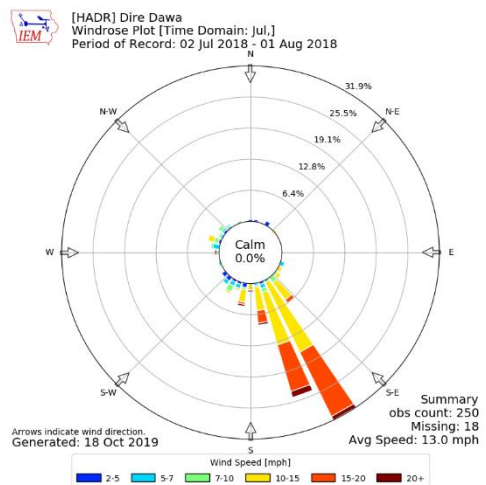
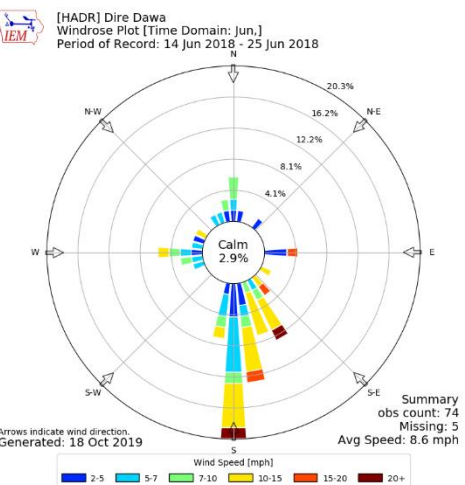
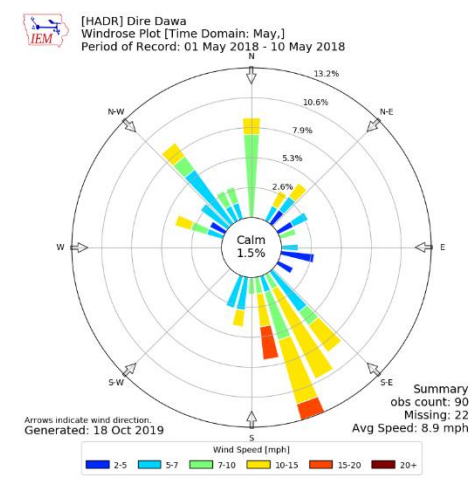
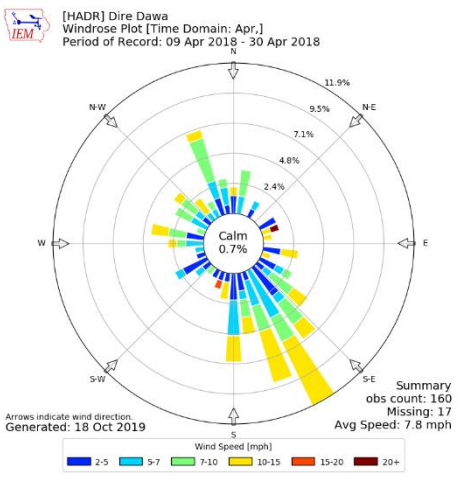
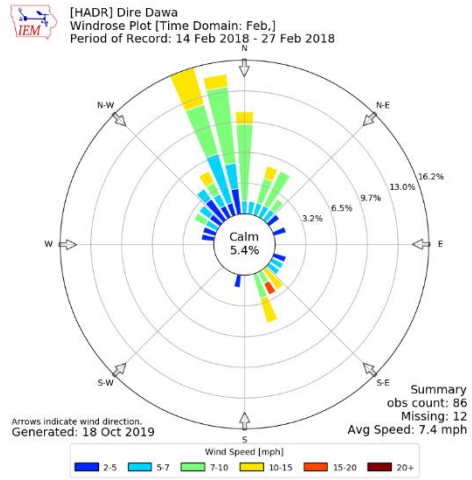
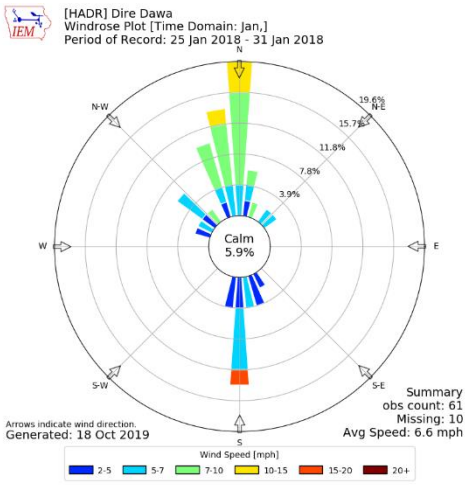


Figure 51: Wind rose diagram of Dire Dawa for the months from January, February, April, May, June and July.

As the main objective of the study is optimum window size for natural ventilation, it is important to use new scale to classify the wind speed data. According to Sustainable building design for tropical climate (Aste N., 2015), for cross-ventilation when the openings are in opposite direction the airflow rate can be obtained using the graphs classified: 0-0 to 0.5m/s, 0.51m/s to 1.0m/s, 1.01m/s to 2.0m/s, 2.01m/s to 3.0m/s, 3.01m/s to 4.0m/s and above 4.0m/s (Figure 19 and 20). Mapping of Ethiopia in (Figure 51) shows the classification of wind speed for cross-Ventilation depending on sustainable building design.

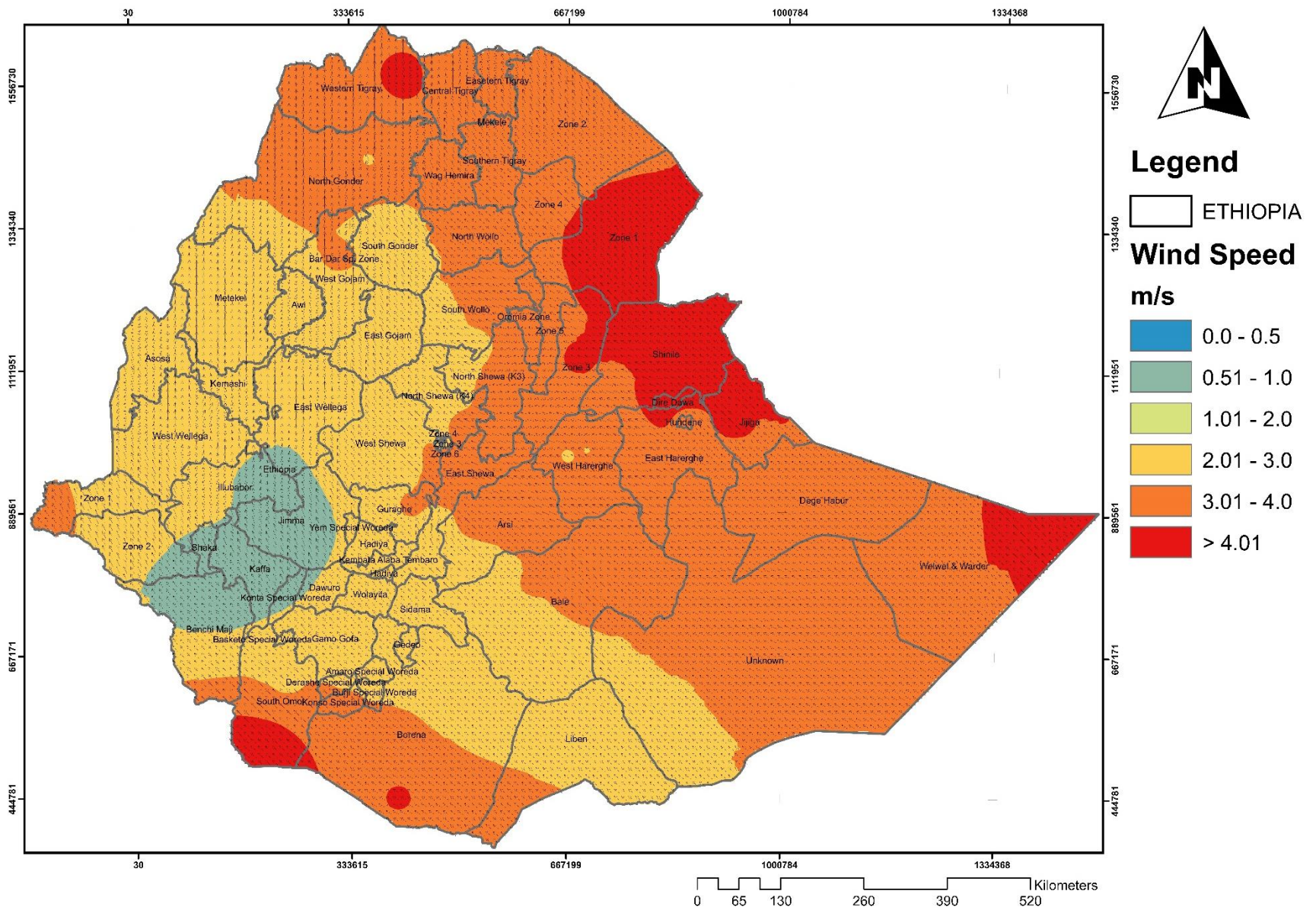


Figure 52: Regionalized map by wind Speed using sustainable building design strategy of Ethiopia

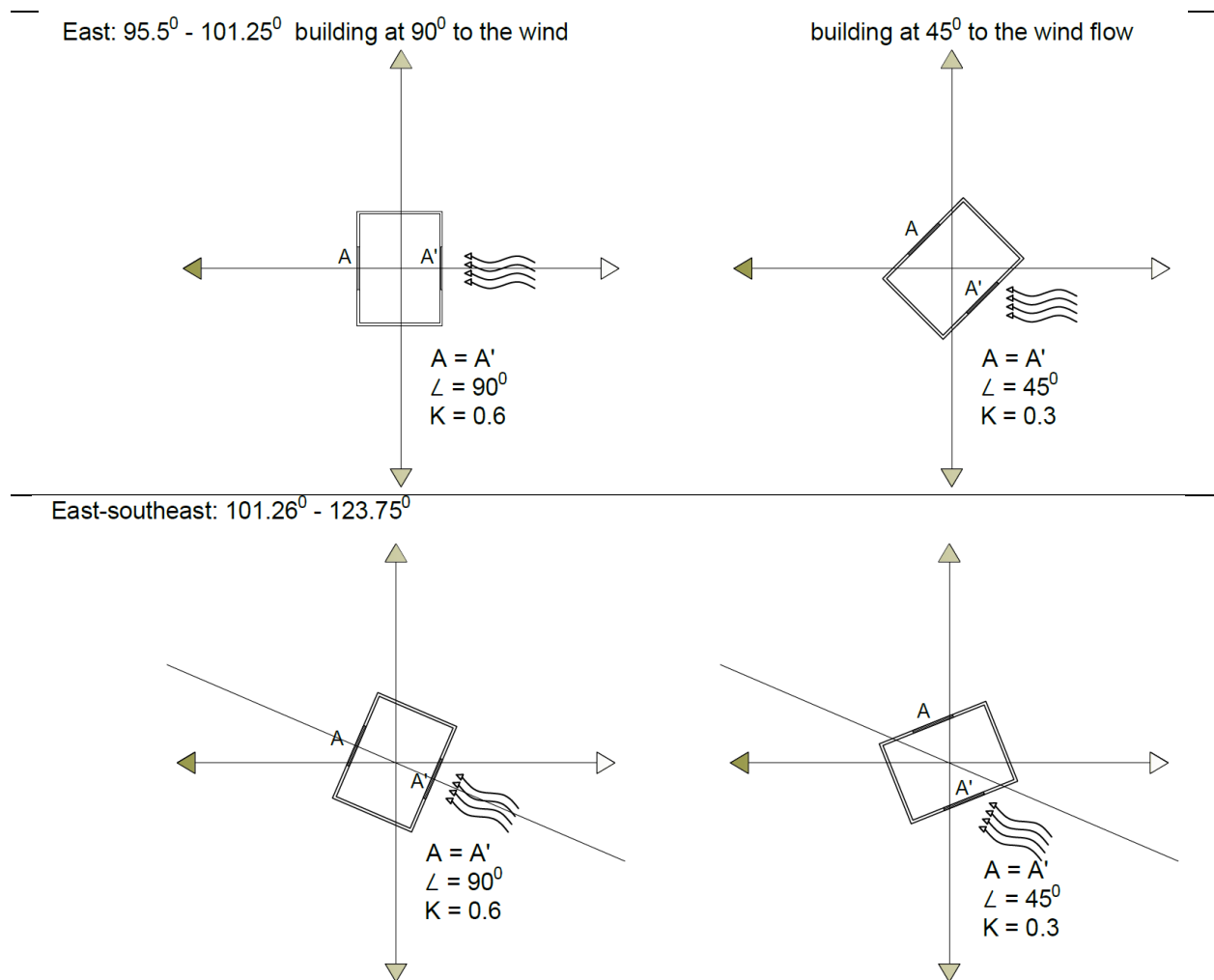
4.2 Size of window

4.2.1 Window size and orientation for cross ventilation

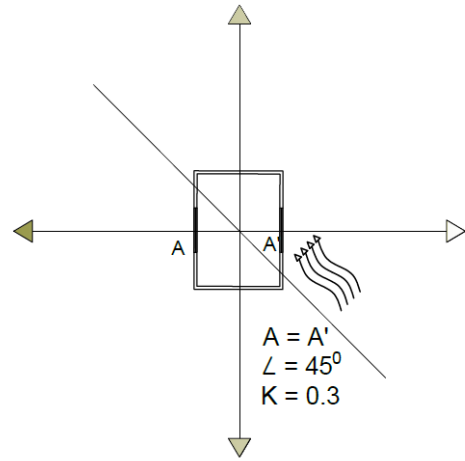
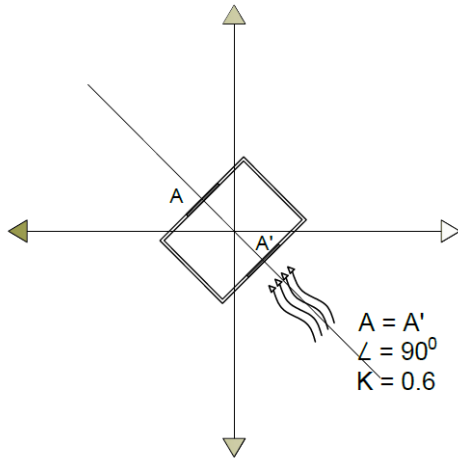
The airflow rate is maximum when the wind flows directly on to the opening. Changes on the window direction up to thirty degree to the either side have a little effect on the value of “K”. The Value of “K” are described in table 9 in relation to the wind angle and inlet to outlet ratio. “K” is the coefficient of effectiveness.

As the coefficient of effectiveness depends upon the direction of the wind relative to the opening and on the ratio between the two openings seven cardinal direction is selected by using the regionalized map. On each cardinal direction there is two airflow angle, the one which is perpendicular to the window and the other with 45° .

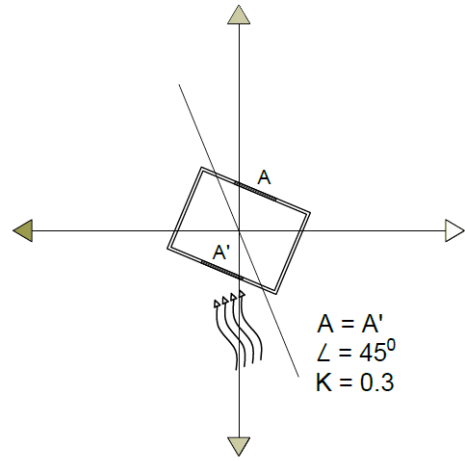
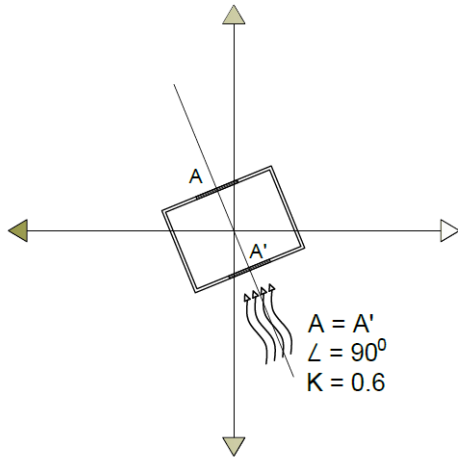
Table 8: Opening orientation at different angle with relation to Wind Direction



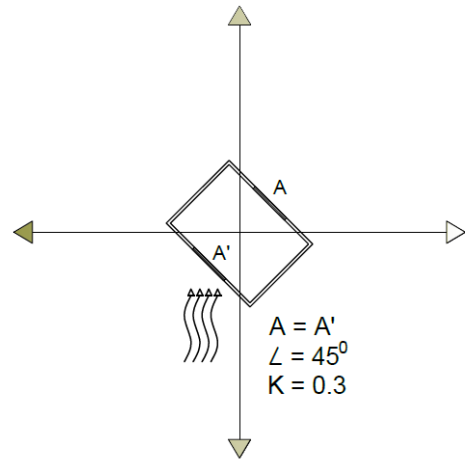
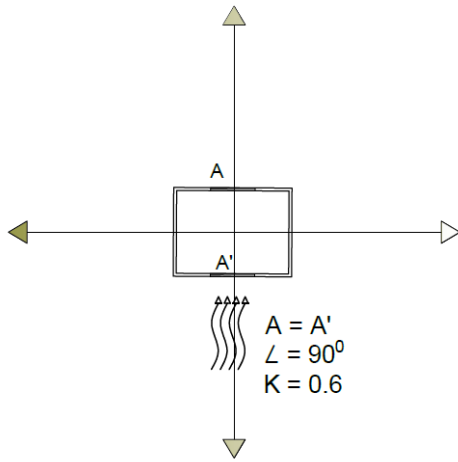
Southeast: $123.76^{\circ} - 146.25^{\circ}$



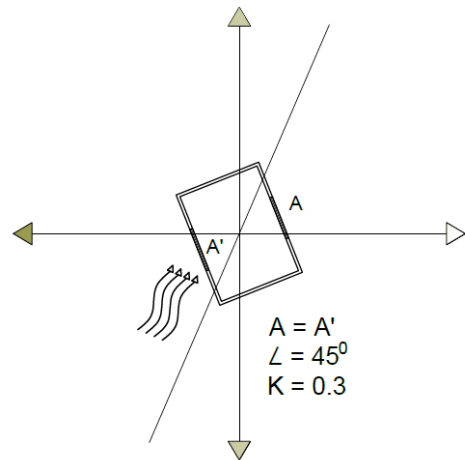
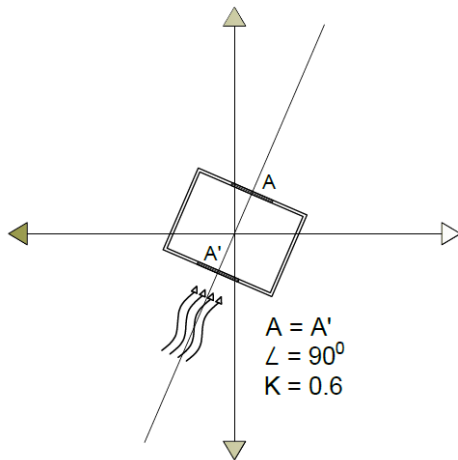
South-southeast: $146.26^{\circ} - 168.75^{\circ}$



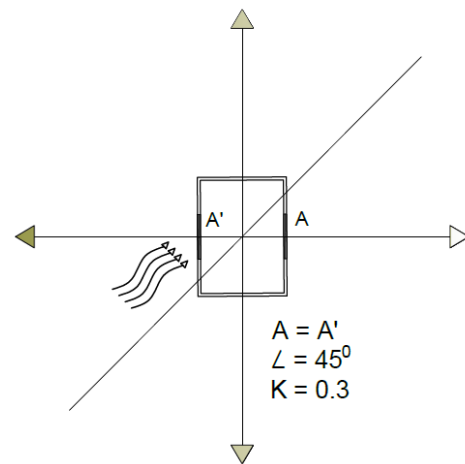
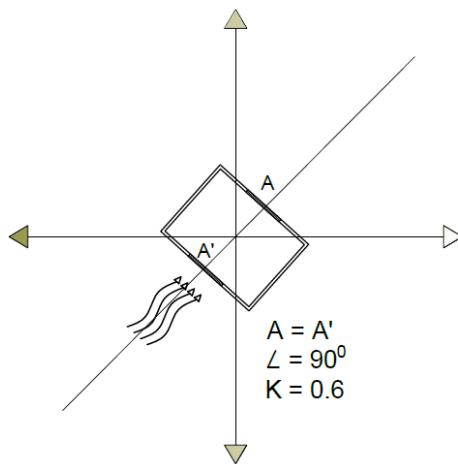
South: $168.76^{\circ} - 191.25^{\circ}$



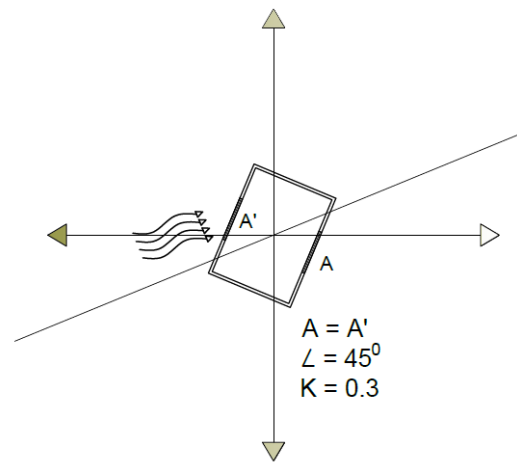
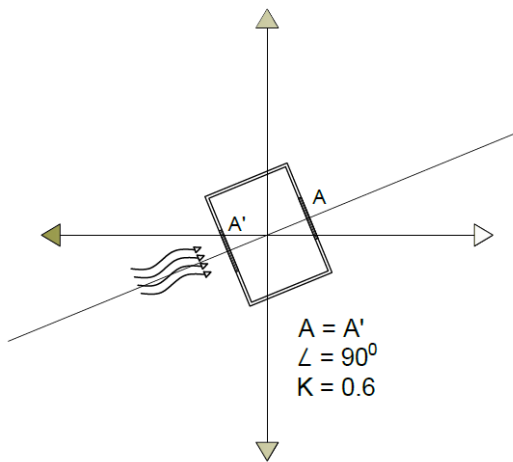
South-southwest: $191.26^{\circ} - 213.75^{\circ}$



Southwest: $213.75^{\circ} - 236.25^{\circ}$



West-southwest: $236.26^{\circ} - 258.75^{\circ}$



Where:

A = area of inlet

A' = area of outlet

α = airflow angle

K = coefficient of effectiveness

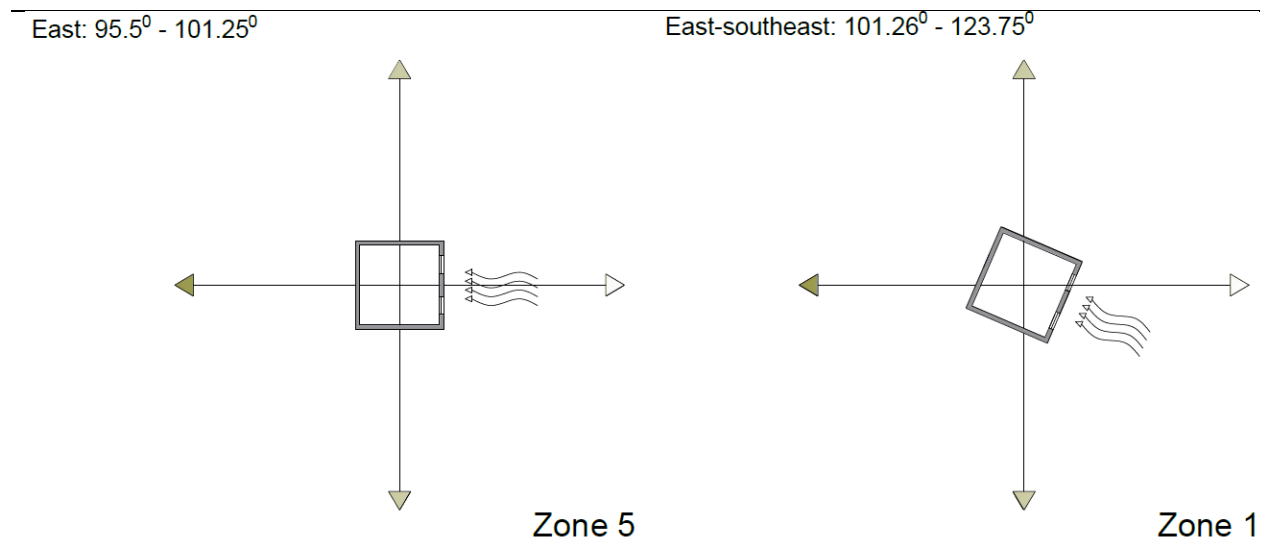
The window size in opposite direction for cross ventilation is calculated by using the required airflow rate (m^3/s), coefficient of effectiveness (which is related to the airflow angle), and outdoor wind speed (m/s).

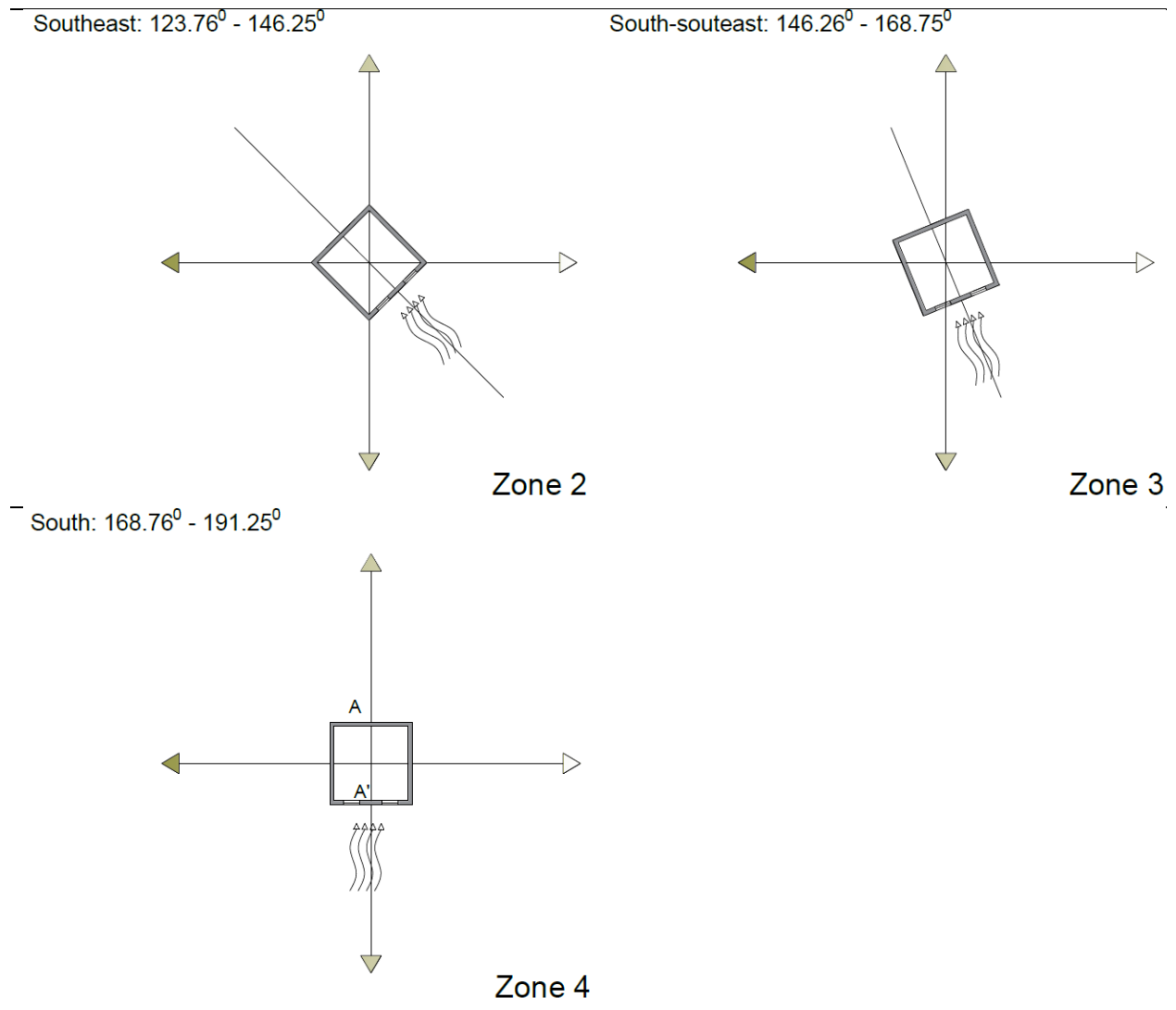
In this study, the wind speed provided is at the height of 10m and 50m. To calculate wind speed at different height mentioned wind speed at reference height of 10m and the correction factors given in table 4.

4.2.2 Window size and orientation for single-sided ventilation

From the regionalized zone, five are selected depending on the influence on natural ventilation. The orientation of window placed at an angle of oblique specifically in the angle of 20 to 70 degrees with relation to wind flow direction. The two openings are placed apart as possible (Table 10).

Table 9: Opening orientation of single-side ventilation with relation to Wind Direction





From the regionalized map, depending on wind direction at 10m (Figure 40 and 41) the regions of Ethiopia is categorized in five zone. For each zone, appropriate study is performed to estimate the optimum window size. For cross-ventilation scenario for regions in the same zone, the output user-friendly method of window sizing can be applied as shown in Table 11. In case of cross-ventilation, Equation 2 is provided for regions in accordance with Table 11 to get the optimum window size. The coefficient of effectiveness “K” depends upon the direction of the wind relative to the opening. The value of “K” is illustrated with respect to the five zones. For each classified zone, 16 window orientation scenarios are discussed and labeled the value of “k”.

Table 10: The value of “K” (coefficient of effectiveness) for each zone with respect to the selected cardinal direction of window orientation in case of cross-ventilation

	N	NNE	NE	ENE	E	ESE	SE	SSE	S	SSW	SW	WSW	W	WNW	NW	NNW
Zone 1				0.3		0.6		0.3				0.3		0.6		0.3
Zone 2	0.3				0.3		0.6		0.3				0.3		0.6	
Zone 3		0.3				0.3		0.6		0.3				0.3		0.6
Zone 4	0.9		0.3				0.3		0.6		0.3				0.3	
Zone 5			0.3		0.6		0.3				0.3		0.6		0.3	

CHAPTER FIVE

DISCUSSION

5.1 Regionalizing

The World Bank wind-mapping project for Ethiopia produced a wind resource mapping by using annual mean wind climate data of 10 years of simulation at the height of 100m, covering the period of August 2004 to August 2013. The wind modelling is presented in the form of simulated and generalized wind maps (Badger, 2016).

On this study, the Ethiopian wind regions is divided based on the span of wind vectors using the hourly wind speed and wind direction data extracted from the wind resource. 30 years of data from the period of 1989 to 2019 at the height of 10m and 50m. It is anticipated that the method used in this study provides a precise wind regionalization. The regionalized map classified into three zones depending on the wind speed at the height of 10m and 50m shows a little difference on the output. When the height from the ground is higher, the wind speed also increase, so the wind speed is directly related to the height. On the wind map at the height of 10m, the maximum average wind speed is 5.4m/s but at the height of 50m, it increase to 7.9m/s. The overall wind direction is almost the same at different height. In both scenarios (10m and 50m), the wind flow between the cardinal direction of East and South. For the purpose of calculating the air speed in different height the wind speed at 10m is used. Wind speed and wind direction of each urban centers in the same wind region are similar.

5.2 Size and orientation of window

The urban patterns massively affect the performance of natural ventilation. The patterns should be designed to maximize cooling breezes. For example, streets oriented to the prevailing wind maximize wind movement in urban environments and increase the access of buildings to cross ventilation. According to (Aste, 2015), Building in which cross ventilation is important should be separated by a distance of seven times the building height. Nevertheless, in dense urban area this rule cannot be applied, so this problem can be overcome by providing optimum opening to the buildings or by active method.

The wind flow around façades with obstacles is very complex and strongly depends upon the façade geometry. On this paper, only the flat façades are addressed here because the findings can be generalized to apply to all buildings of this type. Other types of façades cause complex pressure patterns and must be studied individually. This study consider designing optimum opening on opposite wall with equal size at different orientations. To design openings with different inlet and outlet opening, at different orientation the graph of figure 17 and 18 provide the air flow rate with relation to ratio of opening.

Opening a window is a common and simple way of using natural ventilation to provide fresh air and cool the internal spaces of a building, but the airflow that occurs in this process is rather complicated due to the involvement of several parameters. The level of airspeed, wind direction, the temperature difference between inside and outside, pressure variations, and turbulence characteristics determine the amount of air coming through the openings. From an architectural point of view, the amount of airflow also depends on the size, orientation, location, fracture of opening, and type of window. Single-sided natural ventilation can become more complex compared to cross-flows by reason of involving both wind and thermal effects at the same time. In general, for Ethiopia cross-flow by a window combination of the east and south windows is the most effective case. In case of single-side ventilation southeast facing windows is the most effective orientation for Ethiopia in general while the rest orientation is less effective. Table 10 outlines the most and least effective window orientation, in terms of providing a maximum natural ventilation.

Table 11: The most and least effective window orientations for providing a maximum natural ventilation.

Ventilation strategy	Zone	Best orientation	Worst orientation
Cross-ventilation	Zone 1	East, Southeast	North, Southwest
	Zone 2	East, Southeast	North, Southwest
	Zone 3	North, South	West
	Zone 4	North, South	West
	Zone 5	East, Southeast	North, Southwest
Single-side ventilation	Zone 1	Southeast	Excluding Southeast
	Zone 2	Southeast	Excluding Southeast
	Zone 3	South	Excluding South
	Zone 4	south	Excluding South
	Zone 5	East	Excluding East

In case of cross ventilation, the size of the window is calculated dependent on the coefficient of effectiveness “K” which mean on the orientation of the windows with respect to the wind. When the wind flow in perpendicular to the window the “K” value is 0.6 and the effectiveness of natural ventilation is to the maximum. When the wind flow at an angle of 45 degree with respect to the window the value of “K” is 0.3 which is slightly lower than perpendicular wind flow. Then the area of the window “A” is calculated by dividing the required air flow rate “V” to the result gain by multiplying coefficient of effectiveness “K” and outdoor wind speed “v” (Equation 2).

The average interior air velocity is a function of the exterior free wind velocity, the angle at which the wind strikes the inlet, and the location and size of the opening. However, for single-side ventilation this all are not true. For single-side ventilation, when a single

window is placed on one surface its natural ventilation effectiveness is very low when it compared with multiple windows placed on a single surface. Overall, the results of unshaded windows of this study indicate that single-sided ventilation through a small window size (i.e., 10% WFR) with half to fully opened area can be more effective than larger window sizes of the same ventilation strategy (HK Abdullah, 2020). When the room has only one opening in one wall have average velocities of 13% - 17% of the outside air velocity depending on the wind direction. But for two openings placed in the same wall average velocities are higher, about 22% of the outside velocity, because one opening acts as an inlet and the other as outlet (DeKay M. 2013).

CHAPTER SIX

CONCLUSION AND RECOMMENDATION

6.1 Conclusion

Based on this results of the research, it was verified that depending on the geographical location of the different regions of Ethiopia there is different wind speed and direction recorded. Therefore, the effectiveness of natural ventilation is associated with the size and orientation of windows with respect to the wind zone where the urban centers are located.

Cross-ventilation scenarios are more efficient in terms of allowing a greater amount of airflow to pass through openings. In general, for Ethiopia cross-flow by a window combination of the east and south windows is the most effective case. Conversely, the west-oriented windows offer the least effective cross-ventilation scenario. The result of the study indicates that, in the case of cross ventilation the east and south east facing windows provide more natural ventilation for a room inside zone 1 and zone 2 and zone 5, while the north and south west facing windows represent the less effective orientation. For zone 3 and zone 4, the natural ventilation is higher when the window is facing south and north while the natural ventilation is lesser for east and west facing windows.

In case of single-side ventilation southeast facing windows is the most effective orientation for Ethiopia in general while the rest orientation is less effective. In zone 1 and zone 2, southeast facing is the only effective orientation. Only south facing windows are effective orientation for zone 3 and zone 4. For zone 5 east facing is the effective orientation. In single side ventilation window size has a little impact on ventilation effectiveness. A user friendly application of the study is annexed at the end with an example.

6.2 Recommendation

- It is recommended that building designers to design optimal window size and orientation to increase the effectiveness of natural ventilation, this will lead to improve indoor air quality, occupants comfort and consequently the reduction of the use of electric energy needed for ventilation.
- The study can guide architects towards to the designing of optimum window size and orientation for the different regions of Ethiopia. It is highly recommended to evaluate the actual climate and environmental context of the regions of Ethiopia to set building design codes and regulation.
- The study came with the findings to improve existing building guidelines and regulations in local context way.
- Further study is also needed to verify this generalized window size baseline data for each urban centers in detail.

Appendix

30 Years Average Wind Speed and Direction (Source: <https://power.larc.nasa.gov/data-access-viewer/>)

City	LAT	LON	WS50M_RANGE	WD50M	WS10M_RANGE	WD10M
Addis Ababa	9.02501	38.74691	3.04	122.6	2.65	124.4
Dire Dawa	9.59311	41.86611	6.41	121.1	4.81	115.7
Mekele	13.49671	39.47531	3.50	148.0	3.30	145.5
Nazret	8.55001	39.26671	4.04	113.7	3.73	113.6
Bahir Dar	11.59361	37.39081	4.43	196.7	3.26	198.1
Gondar	12.60001	37.46671	4.72	191.1	3.76	201.7
Dese	11.13331	39.63331	3.69	123.1	3.74	110.9
Hawassa	7.06201	38.47631	3.36	134.5	2.61	135.0
Jimma	7.67341	36.83441	2.13	158.1	1.25	158.3
Bishoftu	8.75221	38.97851	3.54	123.9	3.25	124.7
Kombolcha	11.08151	39.74341	3.69	123.1	3.74	110.9
Harar	9.31391	42.11811	4.63	134.1	3.83	135.8
Sodo	6.86001	37.76161	2.98	143.9	2.33	146.5
Shashemene	7.20001	38.60001	3.64	132.7	2.74	134.4
Hosaina	7.54981	37.85371	2.93	136.8	2.61	138.2
Arba Minch	6.03331	37.55001	2.94	141.7	2.38	142.9
Adigrat	14.27701	39.46201	3.50	168.6	3.34	164.4
Debre Markos	10.35001	37.73331	2.74	162.3	2.29	162.8
Debre Birhan	9.67951	39.53261	3.44	95.5	3.36	96.7
Jijiga	9.35001	42.80001	4.95	134.9	4.04	135.7
Inda Silase	14.10311	38.28291	5.34	191.9	4.41	196.0
Ziway	7.93331	38.71671	3.45	120.8	2.72	199.9
Dilla	6.41671	38.31671	3.24	138.3	2.36	141.3
Ambo	8.98331	37.85001	3.43	144.8	2.85	146.7
Gambela	8.25001	34.58331	4.07	137.4	2.84	150.6
Axum	14.12111	38.72341	4.55	183.2	3.84	185.4
Waliso	8.53421	37.96511	3.43	144.8	2.85	146.7

Yirga Alem	6.75001	38.41671	3.45	142.7	2.47	145.3
Mojo	8.58681	39.12111	4.04	113.7	3.73	113.6
Goba	7.01671	39.98331	3.24	122.0	3.06	119.3
Shakiso	5.76491	38.91011	2.49	123.4	2.20	123.9
Felege Neway	6.30001	36.88331	2.41	143.0	2.04	147.2
Areka	7.06671	37.70001	3.03	138.3	2.51	139.9
Boditi	6.96671	37.86671	2.98	143.9	2.33	146.5
Debre Tabor	11.85001	38.01671	2.82	133.6	2.37	131.1
Jinka	5.65001	36.65001	3.35	133.4	2.90	137.7
Gimbi	9.17031	35.83491	3.67	195.9	2.56	186.9
Korem	9.08571	40.86711	5.44	103.8	3.94	101.6
Asosa	10.06671	34.53331	4.03	161.3	2.98	161.3
Butajira	8.11671	38.36671	3.34	128.5	3.10	129.0
Metu	8.30001	35.58331	3.07	165.0	2.14	166.8
Agaro	7.85001	36.65001	2.13	158.1	1.25	158.3
Kibre Mengist	5.88331	38.98331	2.49	123.4	2.20	123.9
Maychew	12.78751	39.54221	3.74	149.0	3.72	141.0
Werota	11.91671	37.70001	3.65	172.4	2.85	171.2
Dembi Dolo	8.53331	34.80001	3.96	144.3	2.93	153.0
Dubti	11.73291	41.08201	5.47	149.8	4.29	151.8
Fiche	9.80001	38.73331	2.84	132.5	2.35	133.7
Kolito	7.31671	38.08331	3.36	134.5	2.61	135.0
Mendi	9.80001	35.10001	3.71	189.8	2.69	182.4
Debark	13.15611	37.89811	3.68	183.6	3.33	189.7
Teppi	7.20001	35.45001	2.94	129.0	1.77	137.3
Kemise	10.71671	39.87001	3.79	102.1	3.76	97.7
Asasa	7.10001	39.20001	2.83	124.8	2.63	124.4
Holeta	9.06671	38.50001	3.04	122.6	2.65	124.4
Finote Selam	10.70001	37.26671	3.54	155.6	2.59	163.5
Metahara	8.90001	39.91671	4.32	108.2	3.58	107.1
Dodola	6.98331	39.18331	2.35	128.6	2.17	130.1
Addiet Canna	11.26671	37.48331	3.75	178.3	2.88	180.3

Addis Zemen	12.11671	37.78331	3.76	152.3	2.95	155.2
Hagere						
Maryam	5.63421	38.23601	2.92	127.6	2.67	128.5
Bure	10.70001	37.06671	3.54	155.6	2.59	163.5
Robit	12.01671	39.63331	3.67	142.5	3.62	132.0
Asaita	11.56841	41.43871	5.47	149.8	4.29	151.8
Bedele	8.45601	36.35301	2.45	176.2	1.33	175.1
Nejo	9.50001	35.50001	3.76	216.0	2.60	206.3
Sebeta	8.91671	38.61671	3.54	123.9	3.25	124.7
Bati	11.19151	40.01681	4.22	138.7	3.50	131.7
Bonga	7.28331	36.23331	2.12	148.6	1.13	150.8
Bako	5.78331	36.56671	3.35	133.4	2.90	137.7
Yabelo	4.88331	38.08331	3.45	122.0	3.81	121.8
Bedesa	8.90001	40.78331	3.98	110.9	2.89	112.7
Wenji	8.45001	39.28331	3.91	119.7	3.55	118.5
Ginir	7.13951	40.71081	4.13	146.5	3.47	142.0
Gebre						
Guracha	9.80001	38.40001	2.46	149.9	2.14	150.6
Bichena	10.45001	38.20001	2.53	147.1	2.11	145.8
Gelemso	8.81671	40.51671	3.98	110.9	2.89	112.7
Shambu	9.56671	37.10001	3.12	195.7	2.49	193.4
Abomsa	9.98331	39.98331	3.44	95.5	3.36	96.7
Mizan Teferi	6.99871	35.58881	2.31	140.0	1.28	139.3
Wendo	6.60001	38.41671	3.45	142.7	2.47	145.3
Huruta	8.15001	39.35001	3.91	119.7	3.55	118.5
Hirna	9.21671	41.10001	4.64	113.6	3.68	112.4
Dejen	10.16671	38.13331	2.53	147.1	2.11	145.8
Dabat	12.98421	37.76501	3.47	152.0	2.93	155.8
Awash	8.98331	40.16671	4.14	104.4	2.99	103.0
Leku	6.87311	38.44421	3.45	142.7	2.47	145.3
Gewane	10.16661	40.64691	6.03	107.4	4.23	107.7
Lalibela	12.03221	39.04761	3.08	126.5	3.02	124.1

Gidole	5.65001	37.36671	3.17	131.4	2.96	133.4
Debre werk	10.66671	38.16671	2.57	143.1	2.25	140.2
Tulu Bolo	8.66671	38.21671	3.28	134.4	2.92	135.6
Sirre	8.31671	39.48331	3.91	119.7	3.55	118.5
Addis Alem	9.03331	38.40001	2.90	140.2	2.54	142.0
Kofele	7.06671	38.78331	3.64	132.7	2.74	134.4
Debre Sina	9.84751	39.76031	3.44	95.5	3.36	96.7
Gore	8.15001	35.53331	3.07	165.0	2.14	166.8
Deder	9.19191	41.26461	4.64	113.6	3.68	112.4
Were Ilu	10.35231	39.26151	2.89	109.8	2.75	111.5
Gedo	3.29101	42.14041	3.66	142.6	3.61	142.1
Sendafa	9.08531	39.01281	3.34	108.8	3.48	109.1
Mega	4.03291	38.19091	3.38	120.6	4.07	121.1
Hagere Selam	13.39011	39.10211	3.50	148.0	3.30	145.5
Konso	5.20261	37.26191	3.93	123.7	3.88	125.7
Lobuni	4.49601	36.06001	5.98	126.4	5.88	126.9
Turmi	4.57501	36.29161	5.50	130.5	5.26	131.7
Semera	11.47301	41.00331	6.19	138.9	4.88	138.9

Example for user-friendly application of the study. The example shows the step-by-step procedure to be used for designing optimum window size for natural ventilation in building.

Example:

Determine optimum window size and appropriate orientation for natural ventilation of a room located at the height of 21m. The required airflow rate is 8m³/s and the building is located in Dire Dawa, Arba Minch, Bahir Dar, Jimma and West wolega respectively. The windows are assumed in opposite wall with equal size.

Solution: Dire Dawa

Step 1, calculating the wind speed at the height of the opening. By using equation 4 at (page 44)

$$V_z = (KZ^\alpha) * (V_{10})$$

- Since Dire Dawa is categorized in urban area the correction factor are $\alpha=0.25$ and $k=0.35$ from table 6. From the regionalized map (figure 52) the mean wind speed of Dire Dawa at 10m height is 4.81m/s

$$V_{21} = (0.35 * 21^{0.25}) * (4.81 \text{m/s})$$

$$V_{21} = 7.9 \text{m/s}$$

Therefore, the average wind speed at the height of 21m in Dire Dawa is 7.9m/s.

Step 2, Determining the orientation and size of the window. From the regionalized map (figure 42) Dire Dawa is located in Zone 1, therefore East-southeast facing window are the best orientation. Since the window is facing East-southeast it is perpendicular to the wind flow. From the table 10 coefficient of effectiveness (K) is 0.6

From the equation 3 (page 32).

$$A = V/Kv$$

$$A = 8 \text{m}^3/\text{s} / 0.6 * 7.9 \text{m/s} = 1.69 \text{m}^2$$

The optimum opening area for a room located in Dire Dawa at the height of 21m to get 8m³ air flow is 1.69m²

Solution: Arba Minch

Step 1, calculating the wind speed at the height of the opening. By using equation 4 at (page 44)

$$V_z = (KZ^\alpha)*(V_{10})$$

- Since Arba Minch is categorized in urban area the correction factor are $\alpha=0.25$ and $k=0.35$ from table 6. From the regionalized map (figure 52) the mean wind speed of Arba Minch at 10m height is 2.38m/s

$$V_{21} = (0.35*21^{0.25})*(2.38\text{m/s})$$

$$V_{21} = \mathbf{3.97\text{m/s}}$$

Therefore, the average wind speed at the height of 21m in Arba Minch is 3.97m/s.

Step 2, Determining the orientation and size of the window. From the regionalized map (figure 42) Arba Minch is located in Zone 2, therefore Southeast facing window are the best orientation. Since the window is facing Southeast it is perpendicular to the wind flow. From the table 10 coefficient of effectiveness (K) is 0.6

From the equation 3 (page 32).

$$A = V/Kv$$

$$A = 8\text{m}^3/\text{s} / 0.6 * 3.97\text{m/s} = \mathbf{3.3\text{m}^2}$$

The optimum opening area for a room located in Arba Minch at the height of 21m to get 8m^3 air flow is **3.3m²**

Solution: Bahir Dar

Step 1, calculating the wind speed at the height of the opening. By using equation 4 at (page 44)

$$V_z = (KZ^\alpha) * (V_{10})$$

- Since Bahir Dar is categorized in urban area the correction factor are $\alpha=0.25$ and $k=0.35$ from table 6. From the regionalized map (figure 52) the mean wind speed of Bahir Dar at 10m height is 3.26m/s

$$V_{21} = (0.35 * 21^{0.25}) * (3.26\text{m/s})$$

$$V_{21} = 5.37\text{m/s}$$

Therefore, the average wind speed at the height of 21m in Bahir Dar is 5.37m/s.

Step 2, Determining the orientation and size of the window. From the regionalized map (figure 42) Bahir Dar is located in Zone 4, therefore south facing window are the best orientation. Since the window is facing south, it is perpendicular to the wind flow. From the table 10 coefficient of effectiveness (K) is 0.6

From the equation 3 (page 32).

$$A = V/Kv$$

$$A = 8\text{m}^3/\text{s} / 0.6 * 5.37\text{m/s} = 2.48\text{m}^2$$

The optimum opening area for a room located in Bahir Dar at the height of 21m to get 8m^3 air flow is 2.48m²

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