Improving the quality of urban indoors' life

Bachelor thesis Stefan Rozeboom

Research thesis on improving the quality of urban indoors' life. Through experimental research the effects that the use of tropical green roofs and tropical windpipes can have on the indoor climate when installed in a building are determined.

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Colophon

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Preface

Abstract

This research on two bioclimatic design strategies is part of a long-term project in making a bioclimatic design guideline for tropical urban context. Expected is that the total urban is increased to 5 billion people in 2025. This rapid urbanization also occurs in tropical cities. The majority of these people will live in poorly designed buildings where they suffer from high indoor temperatures during the summer. Two main causes are found why the indoor temperatures get this high; at first, the exposure of buildings to the sun all day because there is little shadow in the city; secondly houses are built close to each other, have small and poorly located windows, and are surrounded by high fences so proper natural ventilation gets almost impossible. For each of these causes a design strategies is selected that possible can help to reduce the problem. Both are ancient building techniques that have regained the attention of the construction sector in the past decades.

The first bioclimatic design strategy is the use of green roofs. Research is already done to the best design for the use on inclined roofs in the tropics and to the performance. However, that was done in the colder rain season. This research is a follow up and determined the performance in the hot season. Found is that the heat gain through a green roof is much lower as through the normal used corrugated metal sheet roofs. This results in a lower indoor temperature when using a green roof.

The second strategy researched is the use of wind towers. Wind towers are used in the Middle East to ventilate buildings. In this research the idea of wind towers is transformed in to a design that is suitable for use in a tropical urban context. Instead of a massive tower there is chosen to use lightweight materials, mainly PVC. This new system is given the name tropical wind towers. With a six-inch diameter pipe it is possible to properly ventilate a one-story building with a floor area of 19m^2.

The green roofs have an isolating characteristic, which results in a lower indoor temperature. It also makes that the building cools down slower in the afternoon when the sun radiates less on the roof. Proper ventilating of the building by the use of a windpipe can make the building cool down faster, mainly because the windpipe functions at his maximum at the end of the afternoon. So both systems are a complement to each other.

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1 Introduction

This research is part of a long-term project in making a bioclimatic design guideline for tropical urban context. The goal of this project is to become public and convince the city council of San Pedro Sula, Cortes, Honduras to use it. The need for a bioclimatic design guideline is not something that only applies to the urban area of San Pedro Sula. It is also relevant for the rest of the world, and especially for cities in an area with a tropical climate. The relevance will be illustrated in the first paragraph of this chapter.

1.1 Problem definition

Due to the very rapid Urbanization it is expected that the total urban population will increase from 3 billion people at the end of the last century to 5 billion by 2025. (UNFPA, 1998) The World Bank estimates that almost 60% of this 5 billion people will live below the poverty line and most will have no access to electricity. The majority of these people will live in poorly designed buildings where they suffer from high indoor temperatures during the summer. (Santamouris, Pavlou, Synnefa, Niachou, & Kolokotsa, 2007)

The increase in urban temperatures caused by the heat island effect mainly affects low-income people. During the summer period high ambient temperatures and heat waves cause dramatic problems to vulnerable people living in overheated households. (Santamouris, Pavlou, Synnefa, Niachou, & Kolokotsa, 2007) “Concerning the use of air conditioning, it is found that although there is a very high increase in the installed a/c per household as a function of income, the density of installed air conditioner per square meter is much higher for the lower income people than for all other groups. Although middle and high-income people use more air conditioning. The relative cost of comfort during the summer period is much higher for the lower income people as they live in buildings with limited thermal protection and also because low-income housing is located in areas where the heat island has maximum intensity. In parallel, it is found that the use of air conditioning significantly increases the annual electricity cost especially in the low-income groups. While as the mean value, the use of air conditioning increases the annual expense by about 100 Euros/household, the increase is much higher for the low-income groups, where the relative increase of the cost because of the use of air conditioning is close to 195 Euros/household.” (Santamouris, Pavlou, Synnefa, Niachou, & Kolokotsa, 2007)

According to M. Santamouris et al.(2007) next to high indoor temperatures, lack of proper ventilation is an important source of health problems during the summer. Klinenberg in 2002 investigated a heat wave that hit Chicago, USA in July 1995. This heat wave killed between 485 and 740 citizens. From which a large proportion of the victims lived in single room occupancy. Many lived in rooms with sealed windows they could not open and only about the half of the residents had fans.

This problem of inappropriate housing also exists in Latin America, where 25% of the urban households are living below locally defined poverty lines. (United Nations Environmental Program, 2002)

The above written shows that there is a real problem with the indoor climate of some urban buildings and that this problem will expend in the future. San Pedro Sula, a city located in Honduras, Latin America also has these problems. The heat problem in San Pedro Sula, and in cities in hot climates in general, can be split in to two main problems; at first, the exposure of buildings to the sun all day because there is little shadow in the city that results in high indoor temperatures; secondly houses are built close to each other, have small and poorly located windows, and are surrounded by high fences so proper natural ventilation gets almost impossible. These problems ask for low energy consuming systems that reduce the indoor temperature and provide proper ventilation. Green roofs; placing plants on top of a roof is a method is an ancient building method that made the last decades a reappearance in the building sector. Green roofs are used to decrease the indoor temperature because can reduce the heat gain through the roof. Large wind towers are used in the Middle East for many years to ventilate buildings and to reduce the indoor temperatures. Because of the height of the towers, surrounding buildings do not influence the airflow.

1.2 Research goal

The long-term project in the developing of a bioclimatic urban design guideline for a tropical climate started with the publication of a book by Angela Stassano on architectural styles used in tropical cities between 1900 and 1950 and how these styles helped to get a proper indoor climate. This is followed up by several co-researches with local and foreign students; the first research was on the development of a green roof system to be used on inclined roofs in the tropics and the influence on the indoor temperature; followed by a research on the influence of green roofs on the rainwater runoff; the third was on the opinion of local people on the appearance and comfort of bioclimatic design; finally research is done by a legal student on how this data can be implemented in to a guideline that in the future can be adopted by the city council of San Pedro Sula.

The goal of the research is to make a contribution to this research by evaluating two bioclimatic strategies. The two strategies that will be evaluated are: tropical green roofs and tropical windpipes. As said above the use of green roofs is already evaluated, however this was done during the rain season, it will be re-evaluated in the hot season. For both strategies a different research goal is made, these are presented below:

Research goal tropical green roof: To (re-) validate, the benefits of installing green roofs on metal sheets in the hot season in a tropical urban context.

Research goal tropical windpipe: To validate the feasibility of using wind pipes in an urban tropical environment, for a possible additional strategy for improving the quality of urban indoors' life.

For the design of the tropical windpipe system extra goals are made. The system needs to be designed, in special, to use in the houses of the low and middle-income class, this because in general they have the worst indoors conditions. Low costs should be required to build and to maintain the system and it should be possible to after install it in a building.

1.3 Research questions

To reach the goals that are mentioned in the previous paragraph, two main research questions are formulated. These research questions are divided in smaller parts so they can be answered. One research question is made for the tropical green roofs and one for the tropical windpipes.

1.3.1 Research question green roof

The research question: How does a tropical green roof behave in the hot season in comparison to the rain season?

The questions that need to be answered before this are:

- What is the indoor temperature behaviour of a green roof on scale models during the rain season?
- How does the indoor temperature of a green roof scale model behave compared to a non-green metal roof on scale model during the hot season?
- What are the expected benefits of installing green roofs on metal sheets in the tropical urban context?

1.3.2 Research question wind tower

The research question: Can a tropical windpipe improve the indoor living comfort in an urban tropical climate?

The questions that need to be answered before this are:

- How is the effectiveness of a tropical wind tower influenced in theory?
- What is the ideal design of a tropical wind tower for an urban tropical environment in Honduras?
- How does the made design perform in practice?

1.4 Reading guide

The following chapters all have one paragraph were the green roofs are discussed and one for the windpipes. In the next chapter, chapter two, the theorie of both strategies is discussed. In the third chapter, the research set up and the ideal design for the windpipes is discussed. In the fourth chapter the results of the research are given and in the last these are discussed and concluded on.

2 Theoretical background

The first step to answer the research questions is the theoretical background, the literature that can help answering the questions is written below. At first the theory of green roofs will be discussed followed by information about wind towers. What the ideal indoor climate is for this environment is presented in the third paragraph.

2.1 Green Roofs

Green roofs are vegetation layers placed on top of roofs of buildings. So 'green' refers to the environmentalism and not necessarily to the colour of the roof. There are two main types of green roofs; the intensive green roof and the extensive green roof. The main difference between these two types is the thickness of the used soil layer. Intensive green roofs have a thicker soil layer; their soil layer is at least 15 cm (6 inch). They are also called roof gardens because all sorts of plants can grow in the soil layer and they are fabricated on top of a strong roof construction (O'Keefe, Babaian, & Louis, 2008).

Extensive green roofs have a lower weight than intensive green roofs because of the use of a thinner soil layer; 5-15 cm (2-6 inch). The use of special soil mixes can lower the weight even more, the weight of these roofs is between 50 and 150 kg/,m^3. Because of this low weight the roof constructions do not have be altered (much). These roofs are not used as gardens and often grasses or other plants that require low maintenance are used (O'Keefe, Babaian, & Louis, 2008).

The basis for green roofs used in Honduras is a metal frame that is placed on top of the inclined roof, in which the following layers are placed; for insulation a sheet of 3/4 inch Styrofoam, black industrial plastic that acts as a waterproofing membrane, a root barrier in the form of geotextile, soil and grass. This metal frame has the same size as the top of the house and not necessarily of the roof. Normally the roof is slightly bigger as the house (Meijer, 2009). The layout of the used green roofs is shown in Figure 1.

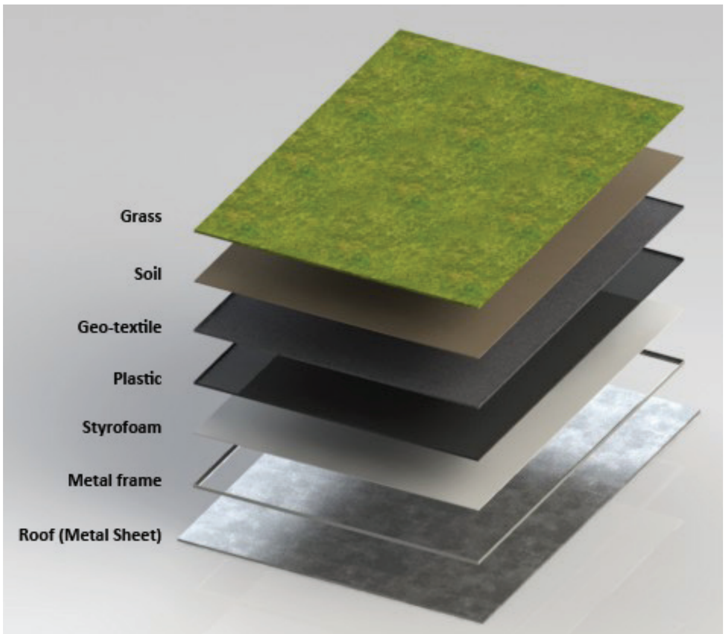

Figure 1 Lay out of the tropical green roof.

In tropical countries green roofs can reduce the indoor temperature of a building. The energy reduction of a green roof is measured at 1396 kJ/m². The R-value is determined at 4.88 m³K/W. These values are gathered by tests in the rainy season in San Pedro Sula, Honduras. The data was gathered using two scale models; one model was fitted with a green roof on a metal sheet and the other only with a metal sheet as the roof. The green roof model had an average difference of 4°C between the inside and the ambient air temperature during the hours that the sun radiated on the roof with a maximum of 7°C. With the metal sheet model the average difference was 12.5°C and the maximum 15°C (Meijer, 2009).

2.2 Wind Towers

To better understand why wind towers are a possible solution for the indoor ventilation in an urban tropical climate a description is given about the origin, the working and the different types of wind towers. Wind Towers are used for centuries in places with a high urban density in the Middle East, where surrounding buildings obstruct the free stream airflow, to ventilate and cool buildings. The shape, height and internal structures of conventional wind towers were most of the time not based on the air delivery and cooling capacity of the building. They were an indication of wealth and social position of the house owners. Outside this region wind towers are a scarce phenomenon, other common names for wind towers are wind catchers or their Persian name Baud-Geers (Montazeari & Azizian, 2008) , (Bahdori, 1994).

The basic workings of a wind tower rests on capturing wind from an external air stream and lead it in the building to cool the occupant. This cooling works directly by increasing the convective and evaporative heat transfer from body surface. It works indirectly by removing heat stored in the building structure. The wind creates a pressure difference when it flows over the tower. Air enters the building at the windward side, creating a positive wind pressure. At the leeward side the wind creates a negative pressure by flowing past the building. Air leaves the building through openings at the leeward side (Montazeari & Azizian, 2008), (Bahdori, 1994).

The different wind tower models can be categorized in three groups on behalf of their basic functioning, they can function as; wind catcher; chimney; or fulfil both functions at once. The first group of wind towers, the wind catchers, have an opening at the windward side of the tower. This opening of the tower is used to lead air in the building. Air can flow out the building through windows or openings in the building. The system functions because the wind creates a positive pressure difference at the opening of the tower and a negative pressure difference is formed at the leeward side of the building. To improve the functioning of these towers in the Middle East, the towers can be fitted with evaporating cooling pads in the opening. These pads cool the incoming air and add extra moisture to it; this results in a denser and heavier air that flows down faster. The height of used towers vary between two and twenty meters above the roof level, taller towers admit winds at higher speeds that also contain less dust. (Bahdori, 1994) An opening can catch wind coming from a maximum angle of 60°, when the angle exceeds 30° the efficiency drops. The efficiency is maximized when the angle is 0° and drops to 35% when the angle is 60° (Montazeari & Azizian, 2008).

The second group of wind towers, the wind chimneys, have an opening at the leeward side or the top of the tower. Hot excess air can leave the building through this opening. Windows or other openings are used to lead fresh air in the building. The air flows because the wind creates a negative pressure difference at the tower opening and a positive pressure difference at the windward side of the building. The wind creates this negative pressure when it is flowing from an angle between -90° en +90° (Montazeri, Montazeri, Azizian, & Mostafavi, 2010). Another effect that stimulates the airflow is the buoyancy effect, hot air is less dense then cooler air, which makes that the hot air, rises up.

The third group of wind towers are the multi opening wind towers. These towers combine the function of the towers of group one and two. The towers have at least two openings, one at the windward and one on the leeward side. Some towers have up to eight sides, with an opening at every side. The wind creates a pressure difference between the windward and the leeward side. Air flows in to the tower at the windward side, and at the same time the excess air of the building is pulled out via the opening at the leeward side. This type of wind tower is commonly used at places where the wind speeds are lower and where the wind changes direction during the day or season. (Bahdori, 1994) The two sided wind tower has a change of short-circuiting when the wind is flowing from an angle between 60° en 90°. When the tower short circuits the air does enter the tower, but it is sucked out via the other half before it can enter the building (Montazeri, Montazeri, Azizian, & Mostafavi, 2010).

2.3 Indoor climate

The human body must maintain an internal body temperature of 36,5°C to 37°C for humans to feel comfortable. To maintain this temperature there is a constant heat exchange between the body and its environment. According to Koch-Nielsen (2002) there are four ways in which this exchange takes place: conduction, convection long-wave radiation and evaporation. Conduction is heat transfer with materials directly in contact with the skin. Confection is heat transfer between the body and the surrounding air. This process mainly depends on the difference in temperature between the skin and the surrounding air and on the speed of the air. Long-wave radiation takes place inside a building between the human body and the surrounding surfaces. This depends mainly on the temperature difference between the skin of the human body and the surrounding surfaces. Evaporation becomes the primary mechanism when the body cannot lose enough heat trough convection or radiation. When the temperature of the surrounding air and surfaces is above 25°C evaporation takes place. The clothing worn, the temperature, the humidity level and the amount of air movement influence the effect of the evaporation. The body cannot cool through evaporation when the surrounding air temperature exceeds the temperature of the skin (Koch-Nielsen, 2002).

The surrounding temperature, the humidity level, the amount of radiation and the air movement influence the rate of heat loss and gain from the body. Together these four factors make the thermal environment. Some key points about a comfortable thermal environment are sum-up: When the surrounding temperature exceeds 30°C excessive air movement and sweating is required to maintain comfort; when the relative humidity level is above 90% the air feels clammy and damp; the main source of discomfort in hot climates is the heat gain due to radiation from the surrounding surfaces, discomfort will occur when the surface temperatures are above the comfort range; in a hot humid climate indoor air speeds up to 2.0 m/s are accepted, an air speed of 1.0 m/s is normally considered as the maximum limit for night comfort (Koch-Nielsen, 2002).

The American Society of Heating, Refrigerating and Air-Conditioning Engineers (ASHRAE) has developed standards for the indoor climate of mechanical ventilated buildings. They also develop the Adapted Comfort Standards (ACS) specified for thermal comfort in naturally ventilated buildings. The required indoor temperatures according to the adaptive comfort model are shown in figure 2. The figure shows only the acceptable temperature of indoor air when the outdoor temperature is within the range of 0-40°C and does not recommend the ventilation rate (Brager & Dear, 2000). Koch-Nielsen (2002) does recommend a ventilation rate; a ventilation rate of 2 m/s or a refresh rate of ten times per hour should keep the structure of the building cool. Removing heat from the structure is a proper way to indirectly cool the occupants (Montazeari & Azizian, 2008).

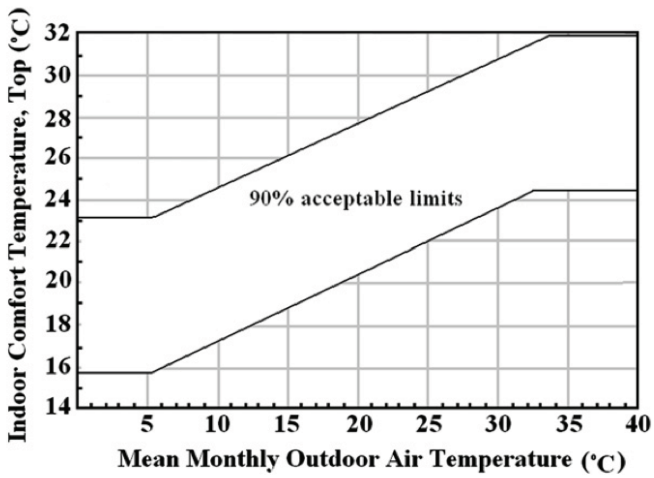

Figure 2 Adaptive standard for naturally ventilated buildings **(Maerefat & Haghighi, 2010)**.

3 Research design

This chapter describes the research methods used to answer both research questions. At first the study area will be described, the second paragraph describes the tropical green roof research and the research about the tropical windpipes is described in the third paragraph.

3.1 Study area

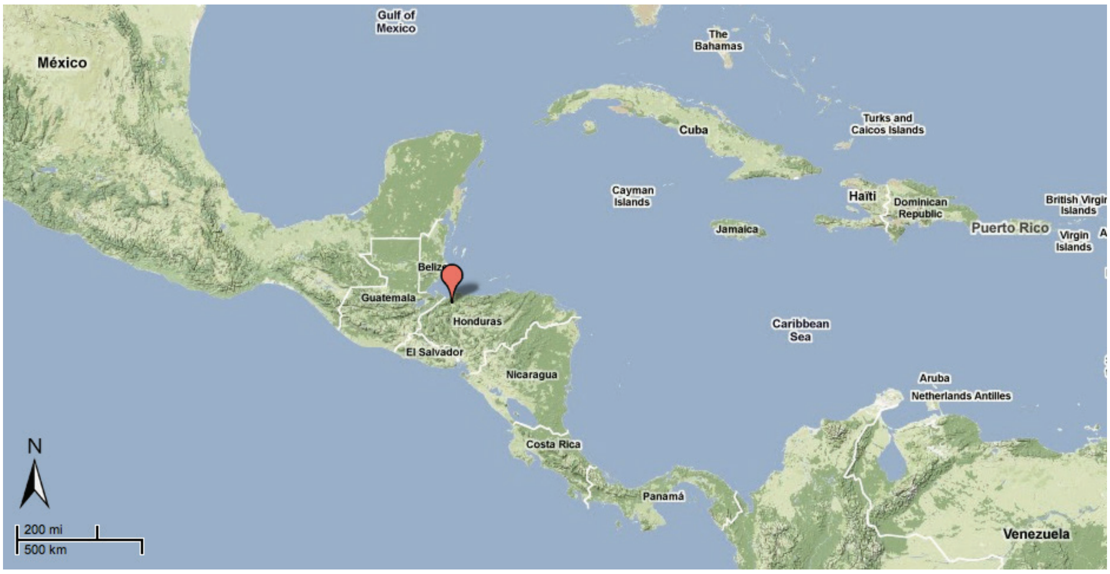

Figure 3 Map of Central America (Source maps.google.com).

The research took place in the city San Pedro Sula, the second largest city in Honduras. San Pedro Sula is marked in Figure 3. Currently there are living around one million people in this city and it is known as the industrial capital of Honduras. (Wikipedia inc., 2011) San Pedro Sula has almost no multi-storey apartment buildings. The mass of the people lives in close-to each other build houses. High closed fences often surround these homes. Most of these houses only have a ground floor and have low ceilings. Examples are illustrated in Figure 4.

Figure 4 Illustration of houses in San Pedro Sula.

San Pedro Sula features a tropical savannah climate. Köppen classifies this as Aw. An Aw climate has monthly mean temperature above 18ºC in every month, and a moderate high rainfall. Table 1 gives an overview of the average temperatures and the average precipitation in San Pedro Sula. Remarkable is that the difference between the average high and low temperature is really small.

Table 1: Climate data San Pedro Sula (wikipedia,.2011).

Climate data for San Pedro Sula, Honduras (1991 – 2009)													
Mont	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Year
Average high °C	28	29	31	32	33	33	33	32	32	30	29	28	31
Average low °C	20	21	22	23	24	24	23	23	23	23	22	21	22
Precipitation	70	50	30	30	60	160	120	100	160	160	130	110	1,210

Table 2 gives an overview of the average wind speeds during a day. These wind speeds are measured at the weather station of the airport of San Pedro Sula. In the morning and during the night there are no noticeable wind speeds. Something that should be taken in account is that the wind direction during the day is opposite to the wind direction during the evening.

Table 2 Average wind speeds San Pedro Sula (Mendez,2010)

Average wind speeds during a day in San Pedro Sula, Honduras (2009)												
Day	6hr	7hr	8hr	9hr	10hr	11hr	12hr	13hr	14hr	15hr	16hr	17hr
Speed(m/s) (direction)	Low							2,7 (S)	2,7 (S)	2,7 (S)	2,7 (SW)	4,5 (N)
Night	18hr	19hr	20hr	21hr	22hr	23hr	24hr	1hr	2hr	3hr	4hr	5hr
Speed(m/s) (direction)	4,5 (N)	6,3 (N)	6,3 (N)	7,2 (N)	7,2 (N)	7,2 (N)	8 (N)	2,7 (N)	Low			

All the measurements for the green roof are executed around in the district where the office and the facilities of Techos Verdes are located, “Colonia El Barrial”, a gated residential community. The measurements for the green roofs were done in a green space between houses, the inside measurements for the windpipes are done in one of the offices of Techos Verdes.

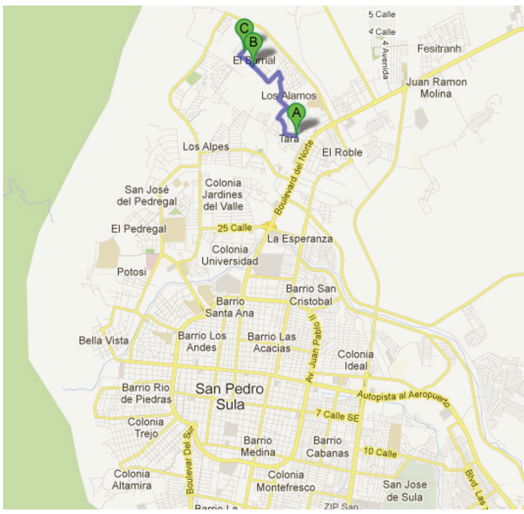

Figure 5 Map of San Pedro Sula with measurement locations.

The location for the outside measurements was a large garden in the residential district "Colonia Tara". This garden is surrounded by a two-meter high fence and located opposite of a T-junction with no high building surrounding it. Both districts are located in the north part of San Pedro Sula as can be seen in Figure 5; 'a' is the location of the outside windpipe measurements; 'b', the office of Techos Verdes; and 'c' the location of the green roof measurements.

3.2 Tropical green roof

The tropical green roof research is a follow up of a research that Jitta Meijer and Angela Stassano did two years prior to this research, in the rainy season. The goal of this research is to compare the results of this previous research with the results of this research in the hot season. That is why the research method is copied in the most exact way as possible. The only thing that has changed between the two researches is the weather condition.

The two exact same boxes as in the previous research were used. These were two identical plywood boxes; the size of a box is shown in Figure 6. The walls and the floor the boxes were insulated with a ¾ inch thick layer of Styrofoam, this layer reduces the in and out going heat flow through these sides of the boxes. Both boxes were attacked by time and the weather a bit so they needed to be refurbished. They were with a new corrugated aluzinc sheet. The sheet is made of 60% aluminium and 40% zinc. As the old one, the new sheet is slightly bigger as the top of the box (one inch one every edge). For the green roof model, a new green roof needed to be made to place on top of the corrugated iron roof. For this a new frame was constructed and mounted it on top of the roof. The frame was filled with the following layers, 3/4 inch Styrofoam, black industrial plastic, geotextile, soil and grass. This metal frame has the same size as the top of the box, so it is smaller as the metal sheet.

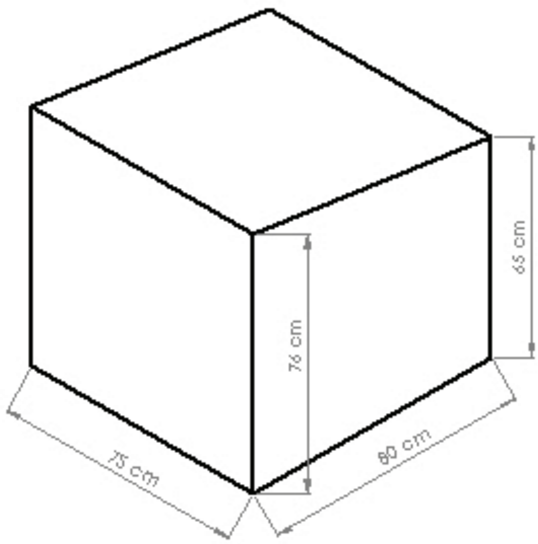

Figure 6. Dimension of the model.

3.2.1 Research setup

The effectiveness of the tropical green roof is determined by a comparison between the models. The models are both fitted with two type-K thermocouples one of the thermocouples is attached at the middle the roof of the box at the underside of the metal sheet; the other thermocouple is placed inside the box. These thermocouples are placed in the middle of the box about 15cm below the roof. A fifth thermocouple was placed in a shaded place on the grass; this thermocouple measures the outside temperature and acts as a reference point. The five thermocouples were connected via a National Instruments data logger to a notebook computer. With this set-up a measurement was taken every second, these measurements where averaged every half hour.

3.3 Tropical windpipe

The design process of the tropical windpipes was an iterative design process. It had three iterative stages: predicting, designing and testing. After the literature research it was possible to predict a bit how a pipe would behave, which factors should be taken in to account when designing a windpipe. The model is designed so low skilled workers can make it with common materials in a short period of time and with a low budget. The use of common materials limits the design of the pipes. All the materials used where never designed to be part of a windpipe. Because of this it was uncertain how the materials would behave for this purpose.

The windpipes are designed mainly for the lower income class of Honduras. Often these people live in closely the each other built houses with almost no outside space. Often the walls of these houses are low; they only have a ground floor; and high closed fences surround these houses, which makes proper ventilation almost impossible. The following basic rules are made for the design of the tropical windpipes:

- Low construction and maintenance costs;
- Easy to install and construct;
- Largely made out of standard materials;
- Possibility to after install in to a house;
- Earthquake friendly.

The tropical windpipes are based on the theory of Middle Eastern wind towers; also ventilation systems used in large old ships are used as inspired. The ship ventilation system consists of a set two vertical pipes with an opening above deck and one below. Of the above deck openings face the leeward and the other in the windward side. The windward facing opening induces air into the ship and the other abstracts the air. This was inspiring because it is a simple and lightweight construction.

3.3.1 Ideal design of the tropical windpipe system

From the theory, the requirements made and available materials we designed two ideal windpipe-systems for the use in the urban area of San Pedro Sula, Honduras. This paragraph presents the two designs. The first design is more technical and has a rotating mechanism so wind is cached at all times, the second design is more basic because it has fixed pipes and that is why it only works when the wind flows in one of the two predefined directions. Names of parts of the system are use throughout this chapter and the names of the parts are presented in Figure 7. The complete design process is presented in appendix A1.4.

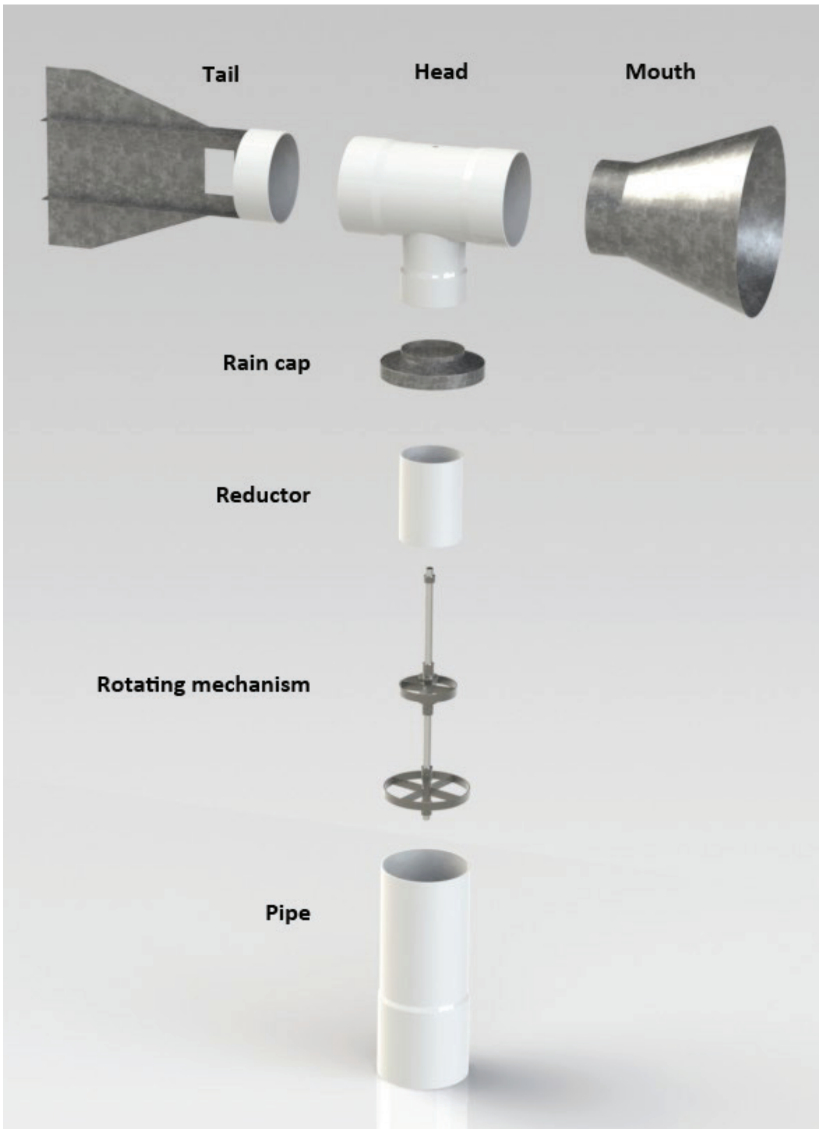

Figure 7 Parts of the (rotating) wind pipe in a exploded view.

3.3.1.1 System 1: Rotating windpipe

This system has one long pipe, on top of this pipe a head with a mouth is placed. This head is connected to the pipe via a rotating mechanism that allows the mouth to 'catch' wind coming from every direction. The air enters the house via an opening at the bottom of the pipe. Through a gap/window located (high) at an opposite wall the air can flow out of the building. This is visualized in Figure 8. The rotating mechanism in the pipe makes the system a bit more complex as a pipe with a fixed head. But the mechanism is simple and consists of little parts. Because of this mechanism the working of the system is not influenced by the direction of the wind. This system has only a head directed in the wind; it is also possible to design a head that always turns with it. This head can function as an air outlet, because the wind flowing round the head creates a lower pressure as present inside the house. Assumed is that the performance of a gap or window in an opposite will be a bit lower but still good enough so a second pipe can better be used as an extra wind catcher.

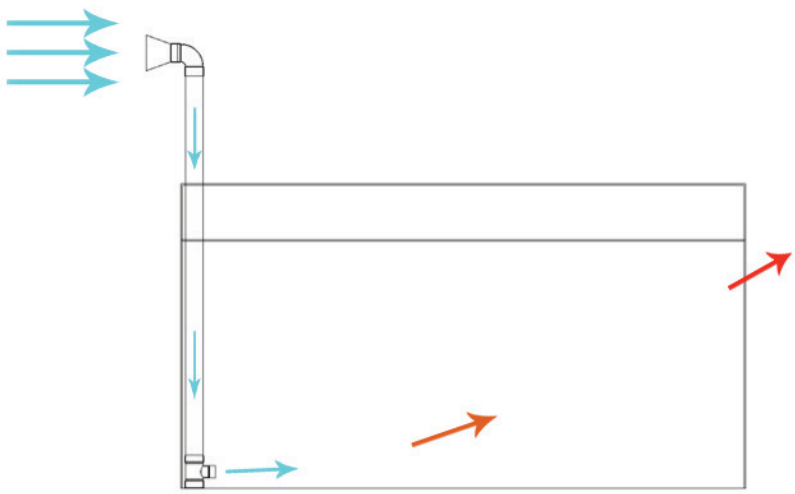

Figure 8 Schematic view windward facing wind pipe.

3.3.1.2 System 2: Static windpipes

Two pipes with fixed heads and mouths form this system; one of the mouths is fixed at the north direction and the other one at the south. This system is almost completely built op from standard available parts, the mouth is the only part that is (hand) made from sheet metal. This system is only able to catch wind directed in two predetermined directions, but according to the collected wind data the wind in San Pedro Sula is almost always directed in the north or south. When the wind is divided in four directions (north; east; south; and west) it is directed in 85 per cent of the time in these directions. In the morning the wind is more directed at the south and in the afternoon and night at the north. When one pipe is directed in the wind the air will flow in to the building via this pipe. At that moment the wind flows around the other head, this will create a pressure difference between the top of the pipe and the building, so the wind will flow out via this pipe. This is presented schematically in Figure 9. Expected is that in the morning one-pipe act as a wind catcher, the other one as chimney and that the roles change in the afternoon.

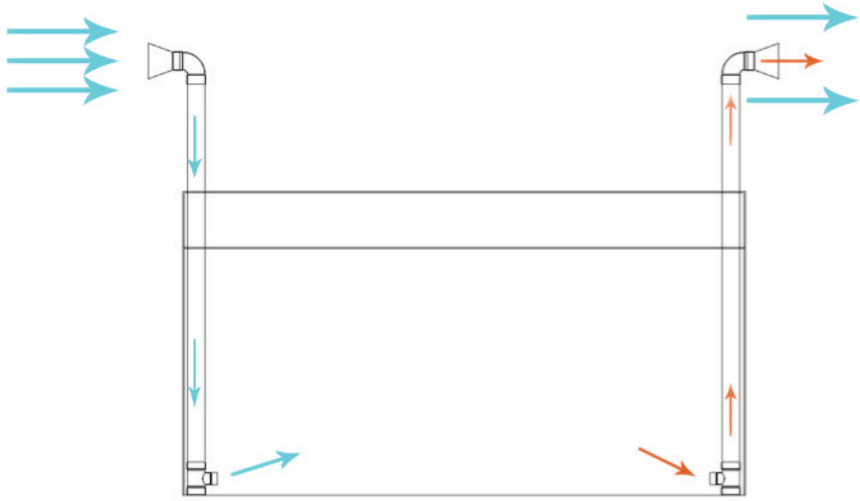

Figure 9. Schematic view combined system.

3.3.1.3 Technical information

Both systems are mainly constructed out of plastic polyvinyl chloride (PVC) parts, the PVC parts are designed to be used as (waste) water pipes. This material is selected for the pipes because it is relatively cheap; light weight; easy to process and there are a lot of standard parts, curves and such, available. A six-inch diameter pipe is chosen because the value/diameter ratio of this pipe is the most favourable. For example the price of one eight-inch pipe is equal to the price of two six-inch pipes. The six-inch pipe is used a lot in construction, and is widely available, which explains the favourable price. A typical one-story home in Honduras has a height of two and a half meters; depending on the surroundings the length of the pipe should be determined. The pipe is designed to be at least four and a half meters, so it sticks two meters out above the house. The head of the fixed pipes is a 90 degrees curve (Figure 10 left), for the rotating model two heads are made, one also of a 90 degrees curve (Figure 10 middle) and the other from a T-connection part (Figure 10 right). The benefit of the curved part is that is a has shape for a smooth air flow, but the drawback is that it is in nature out of balance which makes it harder to rotate. The T-part is a perfect balanced part however it is not shaped for a smooth airflow. To the head a cone shaped mouth is connected to increase the amount of air that can be caught, the angle of the cone is twenty degrees and it has a length of 25.4cm (10 inch). The best angle is chosen through performance tests of several models.

Figure 10 Windpipe heads: Fixed; rotating curve shaped; rotating t-shaped.

Figure 11. Rotating mechanism.

The designed rotating mechanism (Figure 11) for the rotating head is a simple system which craftsmen like a welder can make. It consists of two rings; a treated rod, used as axle; and some bolts and washers. The lower disc has a diameter of six-inch and fits precisely in the pipe, to this disc the axle is fitted. The upper disc has a diameter of 4 inch an rotates around the axle, to this disc a four-inch pipe is fitted that is slid in the pipe a bit and is connected to the head. The discs are made from a steal strip that is formed to a circle in a mould.

3.3.2 Research setup

This paragraph describes how the two described models were tested in practice. As said, indoor tests were already done with several parts of the models to select the best parts for the final assembly. Deliberately there is chosen for indoor test with a fan because the wind conditions outside change every second, with the fan it was possible to create similar conditions for every test. The goal of these indoor tests was to compare the different parts so the optimum configuration can be selected. These optimum configurations were tested outside to see how these performed in natural conditions.

3.3.2.1 Indoor testing

A room ventilator generated the airflow for the indoor test. The different heads and mouths tested were placed on top of a 1.5-meter high pipe that was placed 1.5 meter away from the fan. The fan was placed so that the midpoint of the fan was aligned with the midpoint of the mouth. Three different air speeds were made with the fan, to measure performances at different air speeds. The pipe was mounted on a t-part, with one closed opening, that simulates the in room opening. Two measurement points were used; the first was between the head of the pipe and the fan; and the second was at the outlet of the pipe, the room opening. A TIF VA 500 HVAC measuring device was used to measure the air speeds and the mass flows. Figure 12 shows how the measuring device was used in practice.

Figure 12 TIV VA500 in use during outdoor testing.

3.3.2.2 Outdoor testing

The two models that were designed needed to be tested outside, to see how they behave in nature. Resources where not available to do a full-scale test, like fitting the pipes to a house or construct a room but it was possible to construct full size windpipes.

Airflow measurements were taken with four parts of the system to test the design; a fixed windward facing pipe; a rotating windward facing pipe; a fixed leeward facing pipe; and with a connected fixed leeward and windward facing pipes. Tests were done with the pipes for several days, six in total. During a day one or two pipes were tested at a time this because of the limited amount of measurement point since only one HVAC measuring device was available. The speed of the wind was compared to the flow through a pipe to determine the ratio between wind speed and output air speed. Also comparisons were made of the speeds through different pipes at the same moment at the same time to determine which pipe performed better under that condition.

For the measurements three meter high pipes were fixed to a two meter high closed fence, this gave a condition that the speed of the air coming out of the pipe was not influenced by the outside air, as it also will not when the air is let in to a house. The fence was located next to a T-junction, and there were no high buildings surrounding it, so for an urban area it was a pretty open location. Measurements where taken above the fence to determine the wind speed, and at the outlet of the pipe to measure the flow through the pipe. For the measurements with the connected leeward and windward-facing pipes sheet metal box of 30.5 x 30.5 x 45.7 cm (12x12x18 inch) was constructed in which the pipes were connected and the measurement device was installed. The goal for this test was to see if this gives a more stable flow as the loose pipes. This setup is visualized in Figure 13.

Figure 13 Model of combined pipe system with measurement box.

4 Results

It took several weeks per research to collect all the needed data. This chapter presents the data and the analysis of this data per research. At first the results of the green roof research will be presented followed by the results of the windpipe.

4.1 Tropical Green roof

During seven days data is collected which can be used for the analysis, because of the equipment that was used, the measurements were stopped when it really started raining. The collected data is presented in the first paragraph, in the second it is analysed and in the third it is compared to the result gathered in the previous research..

4.1.1 Average temperatures

For several days the average temperatures of the models were measured, all measurements were conducted between at least 8:00 in the morning and 5:30 in the afternoon. Measurements where taken every second and these are averaged over every half an hour. The temperatures of the 30th of June are presented in Figure 14. There is a big difference between the temperatures of the metal sheet of box N and the sheet of box G, the maximum difference is over 17°C. That is a lot for a roof that is placed just above an occupant's head. The temperature of the metal sheet of box N fluctuates much more as the sheet of box G the sheet heats up and cools down faster. Also the temperature inside Box N is much higher as in box G. The temperature inside box G is at his maximum just under six degrees higher as the outside temperature while the inside of box N gets over thirteen degrees hotter. The temperature in box G does not heat up as fast as the inside temperature of box N, also the cooling down process is slower. This indicates that box G is more insulated as box N.

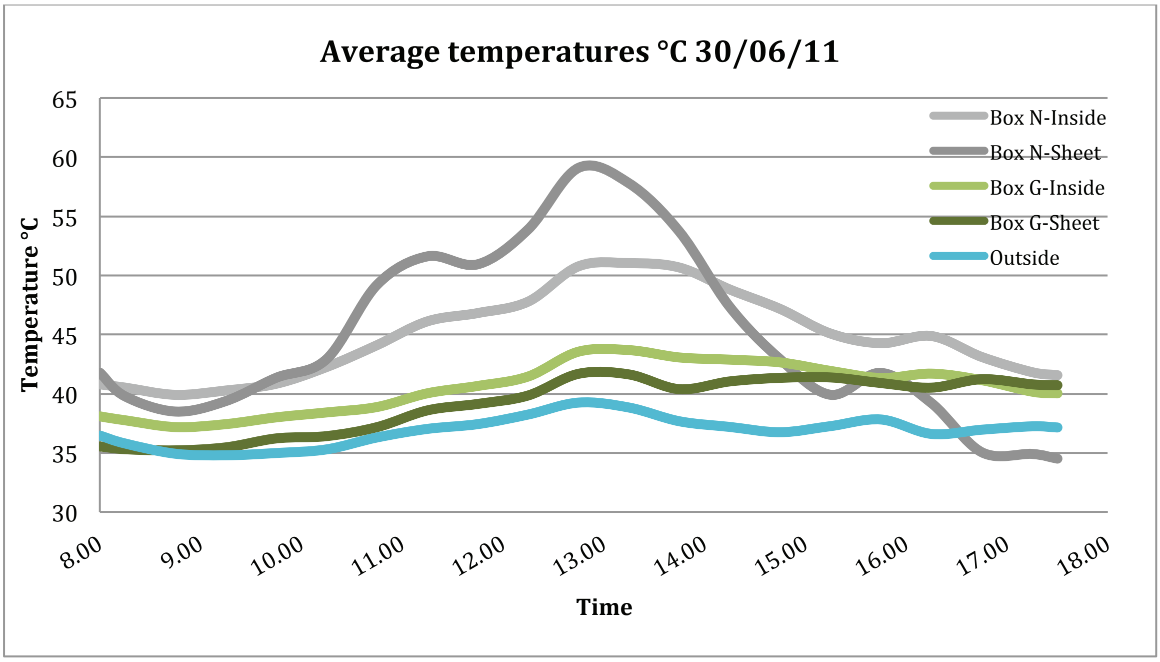

Figure 14 Average temperatures of 30 June 2011.

4.1.2 Analysis TGR

The performance of the green roof will be measured to the energy performance; what is difference in energy gain inside the boxes. The law of energy conservation is important to calculate the energy performance. This law states that in an isolated area the total amount of energy stays constant over time, it can change form but it cannot be created or destroyed.

$Law\ of\ energy\ conservation\colon \Delta E = E_{in} - E_{out}$

Inside the boxes the energy changes by the change of temperature inside the box. The flow of heat in or out the box can occur through: convection; conduction; and radiation. Convection is heat transfer caused by the mass motion of air; when air is heated it get's less dense and rises, cooler and denser air flows down, this effect can cause a temperature loss. Assumed is that this method, which mainly occurs in the cavity of a wall or above the false ceiling, does not occur in this model. The second method, conduction, is the transfer of energy between a hotter and cooler material in contact with each other. Radiation, the last method, is the absorption of energy radiated through air by surfaces.

To determine the difference in in the incoming energy, the daily heat gain, between the models, the outgoing energy and the difference in energy are calculated. These two are dependent on the difference between the indoor temperature of the model and the outdoor temperature and dependent on the isolation value of the model. Figure 15 presents the temperature differences between the indoor and ambient air temperature of three days. The blue lines present the 'normal' boxes and the green lines the green roof boxes.

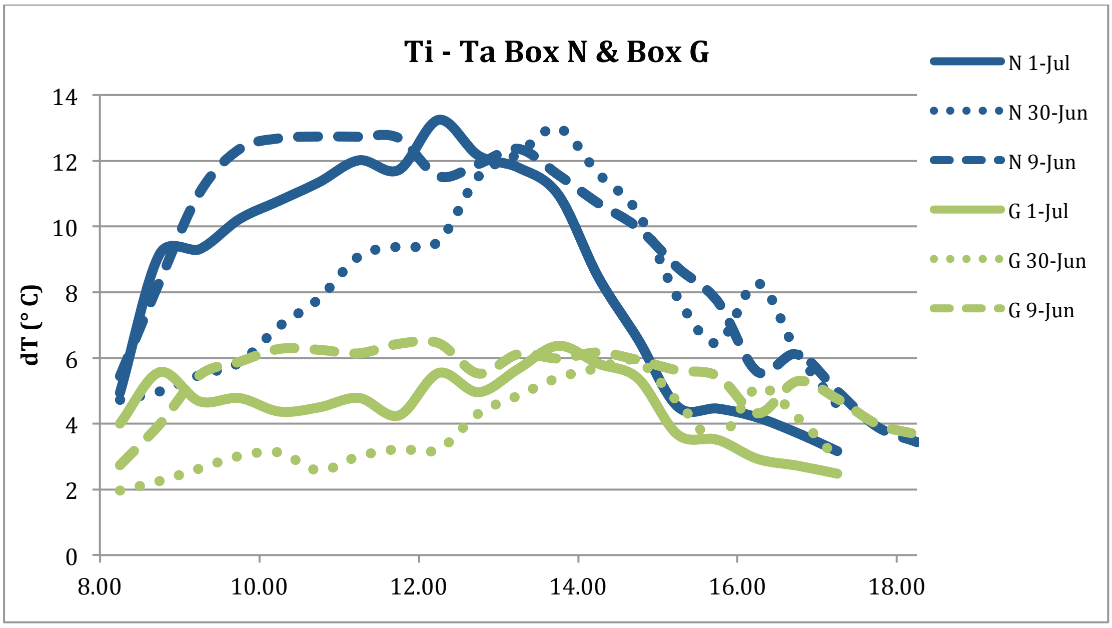

Figure 15 Temperature differences between inside and ambient air.

Table 3 gives the averages of these lines. When they are deducted from each other it can be seen that the differences between the days are small. The average difference between the green and normal roof are all around 4 degrees Celsius.

Table 3 Average difference between inside and ambient air.

	N (Ti-Ta)	G (Ti-Ta)	dT (N-G)
N 1-Jul	8.57	4.53	4.04
N 30-Jun	8.21	3.77	4.44
N 9-Jun	9.96	5.52	4.44

The temperatures of the 30th of June are used in the calculations for the energy gain difference between the models. The temperature of the outside air is the same or lower as the inside temperature. So there is a difference in material temperatures, this difference creates energy conduction. At first the energy out flow is calculated, this E_{out} is calculated on the basis of the characteristics of the models and the difference between the inside and the ambient temperature. E_{out} is calculated with the following formula:

$$E_{out} = (U_{walls} \times A_{walls} + U_{roof} \times A_{roof}) \times (T_i - T_a).$$

Table 4 and 5 present the input variables for this formula. The R-value of the green roof presented in table 4 is deducted form the preceding research by Jitta Meijer.

Table 4 R-value's of used materials.

Material	R value (m³ K/W)
Plywood ⅜"	0.47

Styrofoam ¾"	3.75
Metal sheet	Neglected
Green Roof	4,88

With the R-values for the used materials presented in table 4, the R-values for the walls and the roof of the models are calculated. The U value is calculate with the following formula: $U = \frac{1}{R}$. The area is deducted from the size of the model that is already presented in the previous chapter.

Table 5 Inslulating charactaristics boxes

	R-value (m^2K/W)	U (W/m^2K)	A (m^2)
Box N			
Walls	4.22 (3.75 + 0.47)	0.24	2.12
Roof	0.47 (0.47 + 0)	2.13	0.64
Box G			
Walls	4.22 (3.75 + 0.47)	0.24	2.12
Roof	4.88	0.21	0.64

The values presented in table 5 are used to calculate the total heat loss of the models;

$E_{out,box\ N} = (0.24\times2.12 + 2.13\times0.64)\times(T_i - T_a) = 1.86\ W/\Delta\mathrm{T}$

$E_{out,box\ G} = (0.24\times2.12 + 4.88\times0.64)\times(T_i - T_a) = 0.63\ W/\Delta\mathrm{T}$

The heat loss in the calculation takes place 12 hours a day because assumed is that the temperature difference is zero degrees when the sun does not radiates on the roof. Tehe heat loss calculated is for a roof of 0.64 m^2, the heat loss is divided by the area of the roof to get the heat loss per square meter.

Table 6 Eenergy out.

	E_{out} (W/dT)	(T_i-T_a)	E_{out} (W)	E_{out}(Kj)	E_{out} (Kj/m^3)
Box N	1.86	8.21	15.30	660.9	1032.7
Box G	0.63	3.77	2.39	103.1	161.1

The change of energy caused by the heat change inside the box is equal to: $\Delta E = V\times Q\times\Delta T$; Q is the specific heat of air 1,29 kJ/m^3; V the volume of the box; and ΔT the temperature difference between the inside and the ambient air in degrees Kelvin.

$\Delta E_{box\ N} = 0.393\times1.29\times8.21 = 4.16$

$\Delta E_{box\ G} = 0.393\times1.29\times3.77 = 1.91$

With these numbers and the basic formula of the law of energy conservation, $\Delta E = E_{in} - E_{out}$, the daily heat gain through the roofs is calculated. This is presented in table

7. The daily heat gain of a tropical green roof in the hot dry season of San Pedro Sula, Hondurs is 869,3 kJ/m^2 less compared to a poorly insulated, common used, roof

Table 7 Energy flows.

	E_{out}	ΔE	E_{in}
Box N	1032.7	4.16	1028.5
Box G	161.1	1.91	159.2

4.1.3 Comparison with results previous research

When the results of this research are compared to the results of the previous research done by Jitta Meijer we can see that the reduction in the daily heat gain in this research is lower, it is 869,3 kJ/m^2 compared to 1395,5 kJ/m^2 measured in the rainy season. Looking at the temperatures measured with the same equipment and the same models placed at the same location it can be seen that the outside temperature in this research was about 8-10 degrees hotter. In both researches the temperature of the green roof is a few degrees hotter as the outside temperature and lower as the inside, which is in both researches 5 to 7 degrees hotter as the ambient air temperature. The inside temperature of box N did not rise equally to the outside temperature. It is around 12 degrees hotter as the ambient air compared to the 15 measured in Jitta her research. The metal sheet has around the same temperature in both researches during the hot hours of the day it is between 50 and 60 degrees, depending on the amount of clouds. This can clarify the smaller temperature difference between the air inside box G and box N compared to the previous research; the outside temperature has increased but not the temperature of the metal sheet of box N. So the energy transfer by radiation stayed the same while the conduction changed.

4.2 Tropical Windpipe

Four configurations of the windpipes were tested outside, the performance of each configuration is discussed in this chapter. The performance is referenced to the air output and is analysed to the expected effect on the inside air of a building. For this expectation wind data is collected at the airport of San Pedro Sula. The digitalized wind data is of eighteen days in July 2011. According to Jusi Juarez & Evelio Montoya, employees at this weather centre the wind speeds and directions do not change much over time. So this collected data should be representative for the whole year. The wind speeds are averaged to make a standard day that can be used for forecasting. The times a specific wind direction is measured in these eighteen days was counted, with this a percentage of the time a wind flows in the specific direction can be given. The average day is presented in Figure 16 and the percentage of wind directions in Figure 17. The data collected at the airport implies that wind speeds are pretty stable, but during the measurements there was noticed that the wind speeds and the directions change a lot, especially with lower wind speeds. After the results of the configurations are presented in the following three sub-paragraphs, the fourth analysis the expected consequence for the indoor climate.

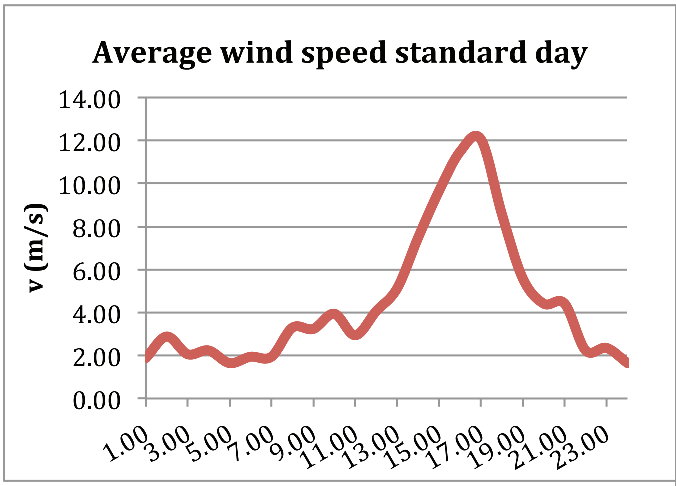

Figure 16 Average wind speed standard day.

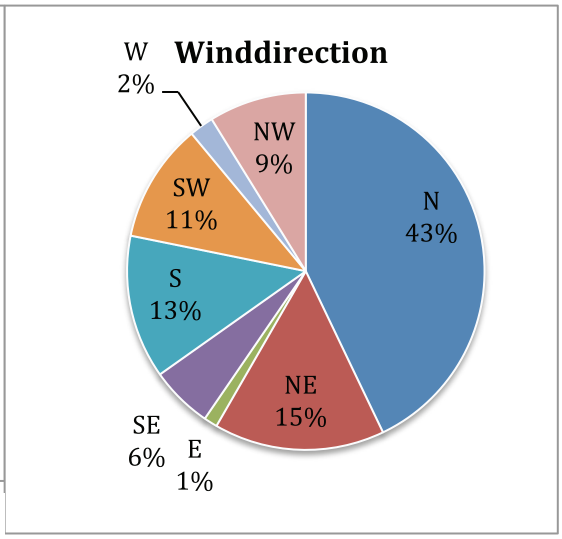

Figure 17 Degree of occurance of a winddirection.

4.2.1 Windward facing pipes

Two windward facing configurations are tested, one with a fixed and one with a rotating head. The indoor test gave the expectation that the flow through the fixed head would be better, but the question was what would be the influence of the changing angle of the wind. The set-up of these pipes can be seen in Figure 18. What is seen is that the both of the pipes don't pick up any wind in the morning, around 13:00 the first signs of airflow through the fixed pipe. This pipe requires less input to get an output as the rotating configuration. The air through the rotating model starts flowing when the fixed model has already an output speed of three meters per second. When the wind speed increases the speeds of the air in the rotating model stays the around half of the speed in the fixed model. The speed of the air through the fixed pipe is almost the same as the speed of the wind. The output speeds that are measured with a referenced wind speed are presented in Figure 19. The maximum output speeds measured for the fixed and rotating pipe are respectively 17.4 and 8.2 meters per second when the wind speed at the airport was 14 meters per second.

Figure 18 Set-up windward facing pipes.

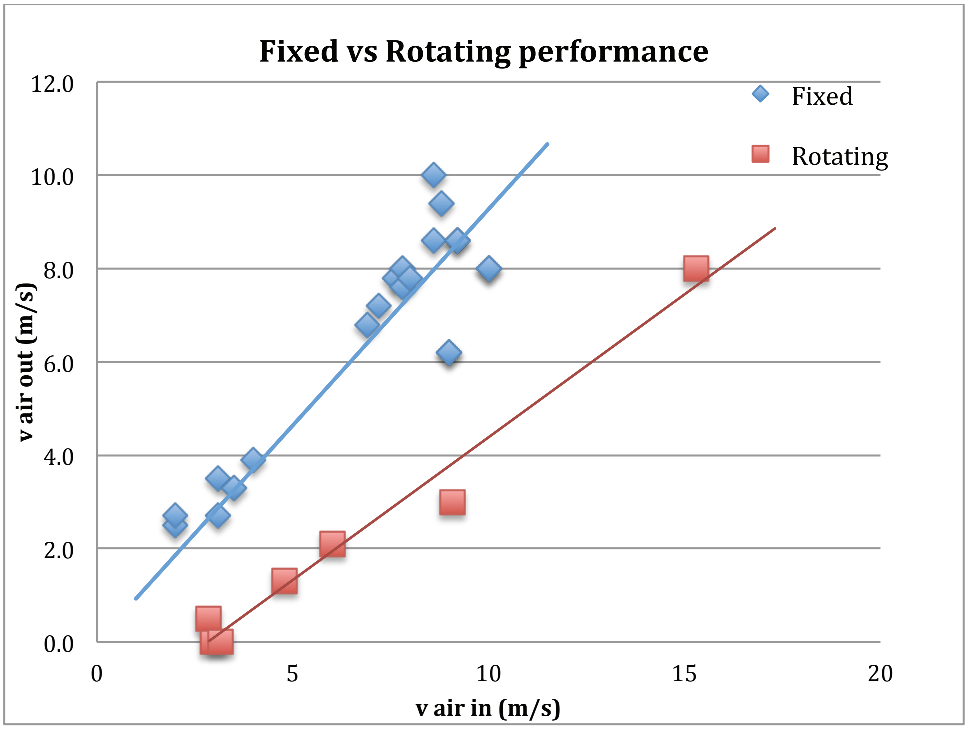

Figure 19 Measured speeds fixed and rotating pipes.

4.2.2 Leeward facing pipe

Leeward facing pipes can be used to abstract air from a room; the wind flowing around the head of the pipe creates suction at the bottom opening of the pipe. A test setup with a leeward and a windward facing pipe is presented in Figure 20 The measured speeds of air passing through this pipe were much lower as the speeds through a windward facing pipe. The speeds were around a quarter to a third of the speed of the wind. The airflow through a leeward facing pipe is according to the theory less influenced by the direction of the wind, the range under which it still works is larger (-90° till 90°). So the model should be more stable during changing wind directions. During the testing it showed that the pipe needed a sufficient wind speed to get airflow through the pipe. Most of the measured speeds through the pipe were around two meters per second with a corresponding wind speed of eight meters per second. Figure 21 presents the measured speeds with their corresponding wind speeds. The maximum measured speed was 3.5 meters per second, with measured wind

Figure 20 Set up with leeward and windward facing pipe.

speed on site and at the airport of respectively 9.6 and 10 meters per second. Observed is during the test that the flow through the pipe was not that fast and it was not consistent. In the morning there was almost no airflow, the flow started in the afternoon but it was not continuous, only in the late afternoon there was a bit of a stable slow airflow.

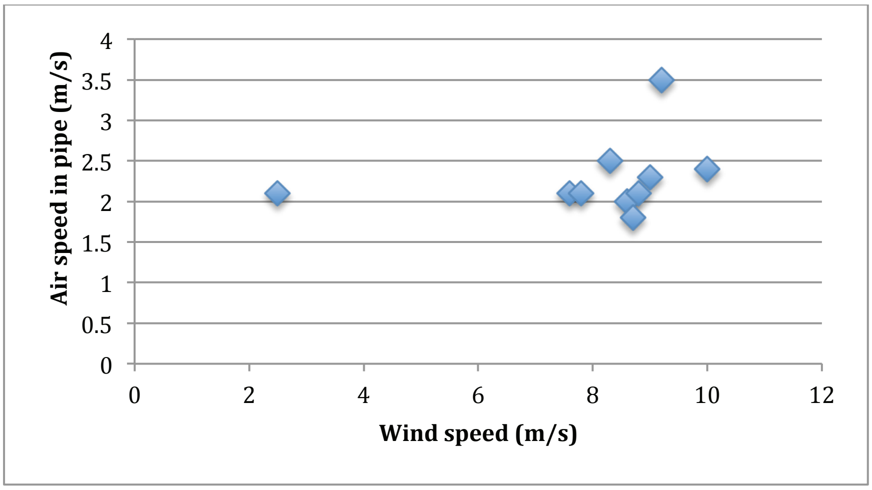

Figure 21 Measured airspeeds leeward facing pipe.

4.2.3 Combined system

The combined system consists of one windward and a leeward facing pipe that are connected in metal box. The measurements were taken inside this box. The system is presented in Figure 22. The goal of this test was to determine if this system was more consistent as loose pipes. One mouth of the system faced to the south and the other faced north. The expectation was that around noon the south facing should push air in and the other should abstract the air. In the after noon the direction of airflow was expected to change. But testing this model we saw that the system did almost nothing in the morning and it started functioning in the late afternoon, as the other the loose pipes also do. The system was not significantly more consistent as the loose pipes. The system started working just after 15:00, when the wind was directed north, the measured wind speeds at the airport increased to 10 m/s. It took till 17:00 when the wind speed at the

Figure 22 Test set up combined system.

airport was 14 m/s, before we could measure a constant airstream through the box of 4.5 m/s. The maximum measured speed was 6.1 m/s. These speeds where measured in a box with a larger cross-section as the one of the pipe, so these speeds cannot be compared directly with the other measured speeds. In the analysis the speeds are converted in to mass flows so all can be compared. Figure 23 presents the measured speeds through the box and the measured wind speeds at the airport at the same time on the 19th of June 2011. Because we built the measurement the device inside the box we were not able to measure the local wind speeds at the same time. That is why the airport measurements are used.

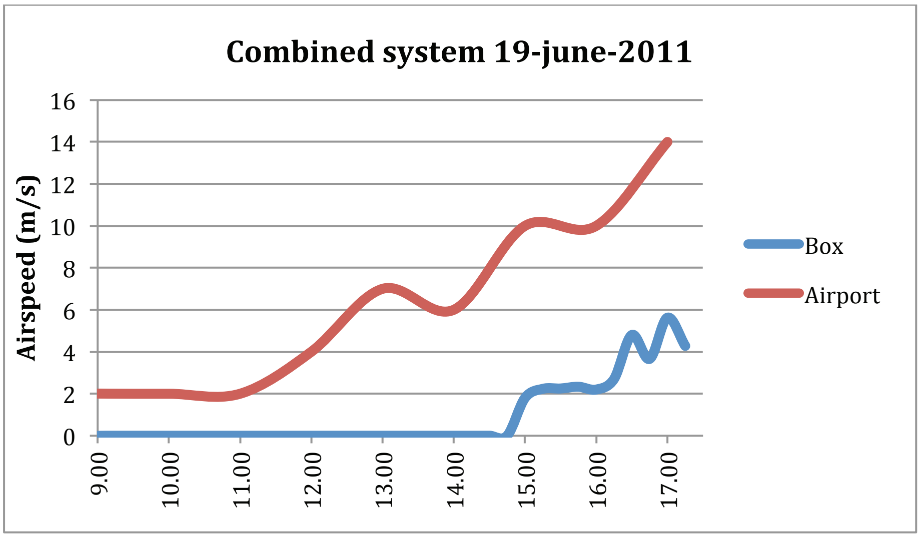

Figure 17 Measured vs. airport wind speed combined system.

4.2.4 Analysis

Not all measurements are taken in a sectional plane with the same area; the measurements for the combined system are taken inside a larger box. The continuance law describes that when the area increase the velocity of the air decreases, the mass flow of the air is constant. In this analysis we convert the measured air speeds to mass flows, so the performances can be compared. With the measurements and the airport wind data a prediction is made of the performance of the models for an average day. From this performance the size of the room that can be properly ventilated by this system is deducted.

The sectional plane of the box is 30.48 x 30.48 cm (12x12 inch) and the pipe has a diameter of 15.24 cm (6 inch). The reference input airspeed is chosen as 10 m/s and assumed is that the density of the air is 1 Kg/m^3 at all times. The results of this comparison are given in table 8. The results of fixed windward facing model and the combined pipes are close together; the other two perform much lower.

Table 8 comparison windpipe models.

Model		$A_{measurepoint}$ (m²)	$v_{measurepoint}$ (m/s)	dM (Kg/s)	v_{pipe} (m/s)
Windward	Fixed	1.82E-02	9.60	1.75E-01	9.60
	Rotating	1.82E-02	4.24	7.74E-02	4.24
Leeward		1.82E-02	3.50	6.38E-02	3.50
Combined		7.30E-02	2.30	1.68E-01	9.20

A linear comparison is made between the measured wind speeds and the measured output speeds of the models. These formulas are used to predict how the models perform at the earlier determined averaged day (presented in appendix A1.2). The predicted speeds are converted to mass flows. Only the flows are calculated of the hours between 13:00 and 21:00 this because during the measurements we noted that there is no flow through the models in the morning, the same is expected during the night when the wind speeds are low. The mass flows are presented in Figure 24.

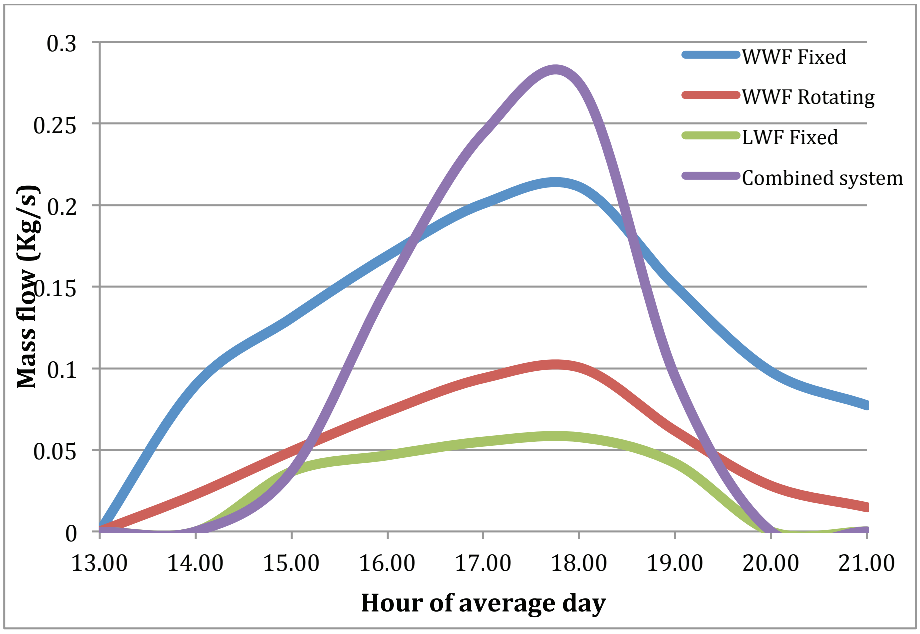

Figure 18 Measured mass flows.

The figure shows that the combined system has the highest peak in the mass flow, overall the area the windward facing fixed model is the largest. The mass flows per hour are given in the left part of table 9. Literature taught us that to effectively prevent the heating of a building, the heating of the construction the construction should be avoided. To do this the air inside the building should be replaced 10 times an hour. With this information and the assumption that the height of a storey is 2.5 meters the size of the building that the systems can effectively cool can be determined. The right side of table 9 presents the area where the air can be refreshed ten times an hour. The average area is the largest for fixed windward pipe; in average it can ventilate a building of 19.27 m^2, the size of a normal room. Around noon and in the evening enough air comes out the pipe to ventilate a room of at least 11.13 m^2. The combined system, with two pipes, performs better around 17:00 as the single pipe but overall it underperforms.

Table 9 Mass flows per hour and size of proper ventilated room.

	M (Kg/h)				10 cycle per hour/m2			
	WW_{Fixed}	$WW_{Rotating}$	Leeward	Combined s	WW_{Fixed}	$WW_{Rotating}$	Leeward	Combined s
13:00	322.63	81.71	0.00	0.00	12.91	3.27	0.00	0.00
14:00	470.96	176.65	131.99	132.42	18.84	7.07	5.28	5.30
15:00	608.17	264.46	168.01	538.33	24.33	10.58	6.72	21.53
16:00	723.13	338.03	198.18	878.42	28.93	13.52	7.93	35.14
17:00	760.22	361.77	207.92	988.13	30.41	14.47	8.32	39.53
18:00	541.42	221.74	150.48	340.86	21.66	8.87	6.02	13.63
19:00	352.30	100.70	0.00	0.00	14.09	4.03	0.00	0.00
20:00	278.13	53.23	0.00	0.00	11.13	2.13	0.00	0.00
21:00	278.13	53.23	0.00	0.00	11.13	2.13	0.00	0.00
Sum	4335.10	1651.52	856.58	2878.17				
Avg	867.02	183.50	95.18	319.80	19.27	7.34	3.81	12.79

5 Conclusion and Discussion

5.1 Tropical green roofs

The green roofs behave roughly the same in the rainy season as in the hot season. The measured temperatures of as well as the roof as the inside are in both researches equally hotter as the measured ambient air temperature. In both situations the metal sheet beneath the green roof is 2 to 3 degrees Celsius higher as the ambient air and the inside temperature is 5 to 7 degrees higher. However the difference between the inside temperature of the box fitted with the normal roof and the ambient temperature is smaller in this research as in the rainy season. The indoor temperature did not raise proportional why the green roof performs relatively lower in this research.

The reduction in daily heat gain by the use of a green roof is measured at 869.3 kJ/m^2, 526 kJ/m^2 less as the 1395.5 kJ/m^2 measured in the rainy season. This daily heat gain is the result of the difference between the indoor and ambient air temperatures of the two boxes. As a result of a relative less increased indoor temperature of the box with the normal roof compared to the ambient air, the difference in the daily heat gain through the roof is lower. The daily heat gain of the green roof in this research is 159.2 kJ/m^2 while it was measured 176.1 kJ/m^2 in the previous research.

Tests are done with closed, non-ventilated, boxes so the results are valid for a fully air-conditioned situation. What noticeable effect for a well ventilated building is not determined jet. Besides, the green roof is only compared to with a ‘normal’ poorly insulated roof and not with other strategies to reduce the daily heat gain through a roof, like a larger layer of insulation or the use of two layers of corrugated metal sheets with an air layer in between. This could give a better impression of how good the results are of the green roof.

5.2 Tropical windpipes

Several model are tested to determine the performance of the on theory selected ideal systems. The first, the combined system with two pipes, one facing north and one facing south functioned less as expected. This because of the morning winds, mainly coming from the south, did not induce a significant airflow through the pipes. Also the combined system did not have a more stable airflow as a single windward facing pipe. The second as ideally selected system, the rotating windpipe was relative consistent during faster wind speeds (+ 8 m/s). However this system needed a wind speed of at least 3 m/s to function. Under faster wind speeds the out put speed was 50% of the wind speed. The pipe with the fixed head facing in the windward direction functioned relatively the best the speed of the flow through this pipe was close to the wind speed.

The problem of the pipe with the rotating head is that the rotating mechanism made the pipe to narrow; it decreased the area of the surface with 51%. When using mainly standard parts this research did not succeed to solve this problem. A special designed head needs to be developed to tackle this problem. But it is the question if the costs required to do this will weigh against the extra performance of the pipe. The fixed pipe stands out in simplicity, it has only four parts (room opening, pipe, head and mouth) of whom only one, the mouth, is specially made from a single piece of sheet metal all others are standard PVC parts. This pipe with a diameter of 15.24 cm (6 inch), has the capacity in average between 13:00 and 21:00 to refresh the air in a building with a floor area of 19 m^2 ten times per hour.

The data gathered for this research has its limitations because only one measuring device is used. So the speed of the wind and the air through the pipe could not be measured at the exact same time. It is not easy to measure the effects of this extra ventilation on the indoor climate, because when a model is scaled down the wind speed should be up scaled equally. So the effects on a building can only be measured in a full size model or with the use of a wind tunnel. What can be concluded from these tests is that this really simple system has a lot of potency to improve the ventilation in the poorly ventilated buildings, because this relative small pipe can already induce a lot of fresh air in a building.

5.3 Overall

The isolating characteristic of the green roof has a drawback that the building, at the end of the day, when the radiation of the sun on the roof decreases, cools down slower as a building with a poorly insulated roof. The proper ventilating of building by the use of a windpipe can reduce this negative effect of the green roof, mainly because the windpipe functions at his maximum at the end of the afternoon.

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Appendix 1. Windpipe

A1.1 Weather data

Via the airport of San Pedro Sula, Ramon Villeda Morales International Airport, data is collected of 17 days in July 2011. Misters Jusi Juarez and mister Evelio Montoya, two employees at the airport collected this data from a weather station at the airport. Normally this date is imported in to a database, and it is easy to access the data of a longer period. With the system being down for a longer period al the data was written down and archived. The data presented below was available at the time of visit; according to mister Juarez and mister Montoya the wind speeds and direction don't change much during the year. They where so kind to dictate this data so it could be entered in to a excel file.

The goal of this data is to present an overview of the wind speeds and directions that can be expected. In the next paragraphs calculations are made to present this.

Monday, July 04, 2011					Tuesday, July 05, 2011				
Time	Direction	v (m/s)	Tmax (°C)	Tmin (°C)	**Time**	Direction	v (m/s)	Tmax (°C)	Tmin (°C)
1:00	0	0	25	25	**1:00**	0	0	25	25
2:00	0	0	25	25	**2:00**	0	0	24	24
3:00	0	0	25	25	**3:00**	190	2	24	24
4:00	0	0	25	25	**4:00**	0	0	24	24
5:00	0	0	25	25	**5:00**	0	0	24	24
6:00	0	0	24.5	24.5	**6:00**	40	4	24.1	24.1
7:00	0	0	25	25	**7:00**	0	0	24	24
8:00	0	0	25	25	**8:00**	270	5	25	25
9:00	180	2	26.5	25.8	**9:00**	210	2	27.2	26.2
10:00	180	2	28	26	**10:00**	240	2	29	26
11:00	120	2	29	26	**11:00**	330	2	31	26
12:00	360	8	30.2	25.4	**12:00**	330	4	30.2	26.2
13:00	340	8	31	25	**13:00**	30	10	31	27
14:00	330	8	31	25	**14:00**	60	10	31	27
15:00	360	6	31.4	26	**15:00**	30	12	30.7	27
16:00	360	16	30	26	**16:00**	30	12	30	26
17:00	360	10	29	25	**17:00**	30	15	30	26
18:00	340	10	27.8	25.2	**18:00**	30	12	27.4	26.5
19:00	350	6	27	26	**19:00**	30	8	26	26
20:00	340	6	27	26	**20:00**	30	6	26	26
21:00	330	8	25.7	25.6	**21:00**	60	4	25.9	25.9
22:00	300	4	25	25	**22:00**	0	0	26	26
23:00	0	0	25	25	**23:00**	0	0	26	26
0:00	0	0	24.8	24.8	**0:00**	0	0	26	26

Wednesday, July 06, 2011				
Time	Direction	v (m/s)	Tmax (°C)	Tmin (°C)
1:00	190	4	26	26
2:00	0	0	25	25
3:00	0	0	25.1	25.1
4:00	0	0	25	25
5:00	170	6	25	25
6:00	170	6	24.9	24.9
7:00	180	4	26	25
8:00	180	4	28	26
9:00	180	4	28.5	25.8
10:00	60	4	31	6
11:00	180	3	31	26
12:00	30	3	31.2	26
13:00	30	6	32	26
14:00	360	6	33	27
15:00	360	10	32.4	26.7
16:00	20	10	32	27
17:00	30	16	31	26
18:00	360	10	29.9	26.3
19:00	330	6	29	26
20:00	330	6	28	27
21:00	330	6	27.7	26.8
22:00	0	0	28	27
23:00	150	8	25	25
0:00	180	4	24.7	24.7

Thursday, July 07, 2011				
Time	Direction	v (m/s)	Tmax (°C)	Tmin (°C)
1:00	160	6	25	24
2:00	150	4	25	25
3:00	190	6	24.5	24.5
4:00	190	6	24	24
5:00	180	6	24	24
6:00	190	4	23.7	23.7
7:00	220	4	25	24
8:00	180	8	26	25
9:00	180	6	27.9	25.1
10:00	270	4	30	26
11:00	360	3	31	26
12:00	90	4	31.9	26.9
13:00	30	5	33	26
14:00	40	8	32	26
15:00	60	8	31.2	27.3
16:00	20	12	31	27
17:00	350	10	31	27
18:00	330	10	30.5	26.7
19:00	360	8	28	27
20:00	330	4	27	26
21:00	360	4	27.2	26.6
22:00	360	4	27	26
23:00	360	4	27	26
0:00	0	0	26.5	26.1

Friday, July 08, 2011				
Time	Direction	v (m/s)	Tmax (°C)	Tmin (°C)
1:00	0	0	26	26
2:00	180	4	26	26
3:00	180	4	26.2	25.7
4:00	0	0	26	26
5:00	180	4	26	26
6:00	210	4	25.5	25.5
7:00	170	4	27	26
8:00	150	6	29	26
9:00	180	3	30	26.4
10:00	210	6	32	26
11:00	210	3	33	26
12:00	210	4	33.2	25.3
13:00	330	4	33	26
14:00	20	10	34	26
15:00	360	10	33.3	28.1
16:00	360	12	32	28
17:00	360	16	32	27
18:00	360	12	30.6	26.8
19:00	350	8	29	27
20:00	330	4	28	27
21:00	340	6	28.2	26.6
22:00	310	4	28	27
23:00	0	0	28	26
0:00	0	0	27.3	26.4

Saturday, July 09, 2011				
Time	Direction	v (m/s)	Tmax (°C)	Tmin (°C)
1:00	0	0	27	27
2:00	190	4	27	27
3:00	210	4	27	26.5
4:00	30	4	26	26
5:00	210	4	26	26
6:00	190	2	25.9	25.5
7:00	120	5	26	26
8:00	150	5	28	26
9:00	210	8	29	26.2
10:00	210	10	30	27
11:00	210	2	32	27
12:00	0	0	32.9	25.9
13:00	0	0	34	27
14:00	300	5	34	26
15:00	30	12	30.4	27.8
16:00	30	10	31	28
17:00	30	12	31	28
18:00	330	10	24.6	24.3
19:00	300	4	25	24
20:00	210	4	25	24
21:00	300	2	24.5	24.5
22:00	0	0	25	25
23:00	0	0	24	24
0:00	210	4	24.1	23.3

Sunday, July 10, 2011				
Time	Direction	v (m/s)	Tmax (°C)	Tmin (°C)
1:00	210	4	24	24
2:00	190	6	24	24
3:00	180	2	24	23.8
4:00	210	6	24	23
5:00	180	2	24	23
6:00	200	4	23.6	23.3
7:00	0	0	24	24
8:00	0	0	26	25
9:00	0	0	26.9	25.2
10:00	0	0	30	25
11:00	60	4	30	26
12:00	0	0	31.2	25.5
13:00	40	4	32	27
14:00	360	8	33	28
15:00	360	2	32.1	26.6
16:00	20	14	32	27
17:00	30	20	29	23
18:00	240	8	24.1	23.7
19:00	210	2	24	24
20:00	210	5	24	24
21:00	30	2	23.8	23.8
22:00	150	2	24	24
23:00	0	0	24	23
0:00	210	2	23.2	23.2

Monday, July 11, 2011				
Time	Direction	v (m/s)	Tmax (°C)	Tmin (°C)
1:00	180	2	23	23
2:00	180	10	23	23
3:00	220	5	24	23.7
4:00	180	8	24	23
5:00	0	0	24	23
6:00	150	5	23.4	23.4
7:00	0	0	24	24
8:00	210	2	26	25
9:00	0	0	27.1	24.5
10:00	60	6	28	26
11:00	360	4	29	26
12:00	360	6	29.6	27.2
13:00	350	10	30	26
14:00	350	6	30	26
15:00	350	8	30	26.3
16:00	320	6	25	25
17:00	320	2	25	25
18:00	320	2	25.9	25.7
19:00	0	0	26	26
20:00	0	0	26	26
21:00	0	0	25.5	25.5
22:00	0	0	25	25
23:00	0	0	25	25
0:00	0	0	25.2	25.2

Tuesday, July 12, 2011				
Time	Direction	v (m/s)	Tmax (°C)	Tmin (°C)
1:00	0	0	25	25
2:00	0	0	25	25
3:00	0	0	24.3	24.3
4:00	0	0	24	24
5:00	0	0	25	25
6:00	0	0	24.8	24.8
7:00	240	2	25	25
8:00	0	0	26	26
9:00	210	2	28.5	25.6
10:00	270	2	29	25
11:00	330	5	30	26
12:00	30	7	30.6	27.4
13:00	30	9	31	27
14:00	360	10	30	27
15:00	360	20	29.9	25.8
16:00	330	5	26	26
17:00	180	2	26	26
18:00	180	2	24.4	25.3
19:00	230	4	24	24
20:00	210	6	24	24
21:00	210	6	23.8	23.8
22:00	190	6	24	24
23:00	180	6	24	24
0:00	190	4	24.4	24.3

Wednesday, July 13, 2011				
Time	Direction	v (m/s)	Tmax (°C)	Tmin (°C)
1:00	150	6	25	24
2:00	180	4	24	24
3:00	210	4	23.9	23.9
4:00	180	4	24	24
5:00	0	0	24	24
6:00	190	2	23.4	23.4
7:00	210	2	24	24
8:00	150	2	26	25
9:00	210	2	28.1	25.7
10:00	200	5	29	25
11:00	150	2	31.1	25
12:00	180	5	31.1	24.1
13:00	330	2	32	24
14:00	30	8	32	27
15:00	30	10	30.6	25.5
16:00	30	12	30	27
17:00	30	10	30	26
18:00	360	10	29.3	25.2
19:00	350	4	28	25
20:00	320	4	27	26
21:00	300	2	27.2	26
22:00	180	2	27	26
23:00	180	2	27	26
0:00	210	4	25.8	25

Thursday, July 14, 2011				
Time	Direction	v (m/s)	Tmax (°C)	Tmin (°C)
1:00	150	6	25	24
2:00	0	0	25	25
3:00	180	4	24.7	24.5
4:00	170	4	24	24
5:00	120	4	24	24
6:00	0	0	23.8	23.5
7:00	0	0	25	24
8:00	210	4	27	25
9:00	220	4	27.5	24.8
10:00	180	6	30	24
11:00	0	0	31	26
12:00	360	4	30.7	26.2
13:00	0	0	31	25
14:00	40	6	31	25
15:00	360	6	31.7	24.6
16:00	40	12	31	25
17:00	40	12	30	25
18:00	30	10	29	25
19:00	330	5	28	26
20:00	300	8	27	26
21:00	300	5	26.6	25.6
22:00	0	0	26	26
23:00	0	0	26	26
0:00	0	0	25.8	25.5

Friday, July 15, 2011				
Time	Direction	v (m/s)	Tmax (°C)	Tmin (°C)
1:00	0	0	25	25
2:00	0	0	24	24
3:00	0	0	24	24
4:00	0	0	24	24
5:00	200	2	24	24
6:00	0	0	231	231
7:00	120	2	25	25
8:00	180	4	27	25
9:00	180	6	28.6	24.6
10:00	150	10	30	23
11:00	180	6	31	24
12:00	120	4	32	23
13:00	60	6	33	24
14:00	10	6	33	25
15:00	360	6	33.1	23.8
16:00	40	14	29	25
17:00	260	8	27	25
18:00	20	10	26.5	24.9
19:00	330	6	26	24
20:00	360	4	26	24
21:00	150	6	26.1	24.3
22:00	140	4	26	24
23:00	0	0	26	25
0:00	180	6	26	24.7

Saturday, July 16, 2011				
Time	Direction	v (m/s)	Tmax (°C)	Tmin (°C)
1:00	0	0	26	24
2:00	0	0	25	24
3:00	0	0	24.8	23.9
4:00	0	0	25	24
5:00	0	0	24	24
6:00	0	0	23.7	23.6
7:00	200	4	25	25
8:00	180	6	27	25
9:00	150	4	29	24.1
10:00	90	2	31	26
11:00	60	4	31	25
12:00	60	2	32.6	24.7
13:00	0	0	34	25
14:00	40	8	33	25
15:00	30	10	31	26.9
16:00	20	12	31	26
17:00	20	16	30	26
18:00	360	10	29.2	25.3
19:00	30	8	27	26
20:00	170	2	26	26
21:00	210	4	26.2	26.2
22:00	120	4	26	26
23:00	30	2	25	25
0:00	0	0	24.4	24.9

Sunday, July 17, 2011				
Time	Direction	v (m/s)	Tmax (°C)	Tmin (°C)
1:00	0	0	25	25
2:00	170	2	25	25
3:00	0	0	24.4	26.6
4:00	240	2	24	24
5:00	0	0	24	24
6:00	180	2	24	24
7:00	210	2	25	25
8:00	120	2	27	26
9:00	300	2	28.2	26.3
10:00	330	2	30	26
11:00	0	0	31	26
12:00	360	5	32.4	26.2
13:00	70	2	32	26
14:00	40	6	33	25
15:00	360	12	32.5	25.3
16:00	30	14	31	27
17:00	60	16	28	26
18:00	60	6	25.7	24.9
19:00	300	5	26	25
20:00	270	2	26	26
21:00	90	5	25.4	25.2
22:00	240	2	25	25
23:00	120	9	25	25
0:00	0	0	24.7	24.7

Monday, July 18, 2011				
Time	Direction	v (m/s)	Tmax (°C)	Tmin (°C)
1:00	0	0	23	23
2:00	40	4	23	23
3:00	0	0	22.7	22.7
4:00	0	0	23	23
5:00	0	0	23	23
6:00	0	0	22.6	22.6
7:00	0	0	24	24
8:00	200	4	25	24
9:00	230	4	27.5	25.6
10:00	0	0	30	26
11:00	360	6	31	26
12:00	30	6	31.6	25
13:00	40	4	32	26
14:00	40	6	33	25
15:00	360	12	32	25.3
16:00	30	14	31	27
17:00	60	16	28	26
18:00	60	6	25.7	24.9
19:00	300	5	26	25
20:00	270	2	26	26
21:00	90	5	25.4	25.2
22:00	240	2	25	25
23:00	120	9	25	25
0:00	0	0	24.7	24.7

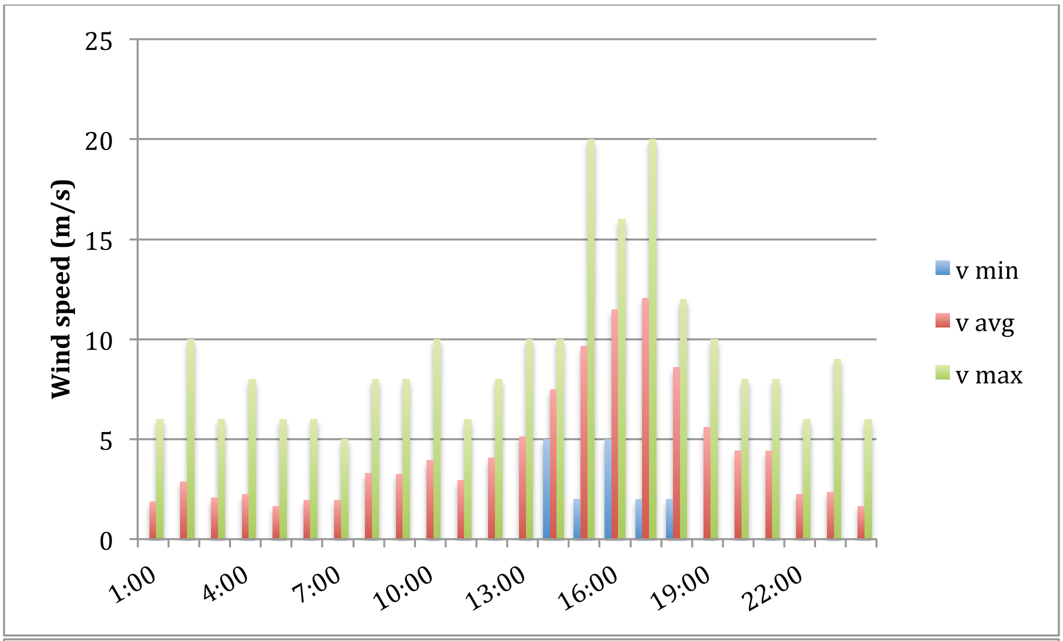
Tuesday, July 19, 2011				
Time	Direction	v (m/s)	Tmax (°C)	Tmin (°C)
1:00	0	0	25	25
2:00	30	5	24	24
3:00	0	0	23.9	23.9
4:00	0	0	24	24
5:00	0	0	24	24
6:00	0	0	23.6	23.6
7:00	0	0	25	25
8:00	0	0	27	26
9:00	360	2	28.8	26.8
10:00	300	2	31	26
11:00	360	2	31	26
12:00	360	4	32.2	25.8
13:00	30	7	33	26
14:00	20	6	34	25
15:00	360	10	23.3	25.9
16:00	360	10	31	27
17:00	360	14	30	26
18:00	360	8	29.6	26.3
19:00	360	6	28	26
20:00	330	6	27	26
21:00	330	6	27.3	26.4
22:00	360	4	27	27
23:00	0	0	27	27
0:00	330	4	27.2	26.7

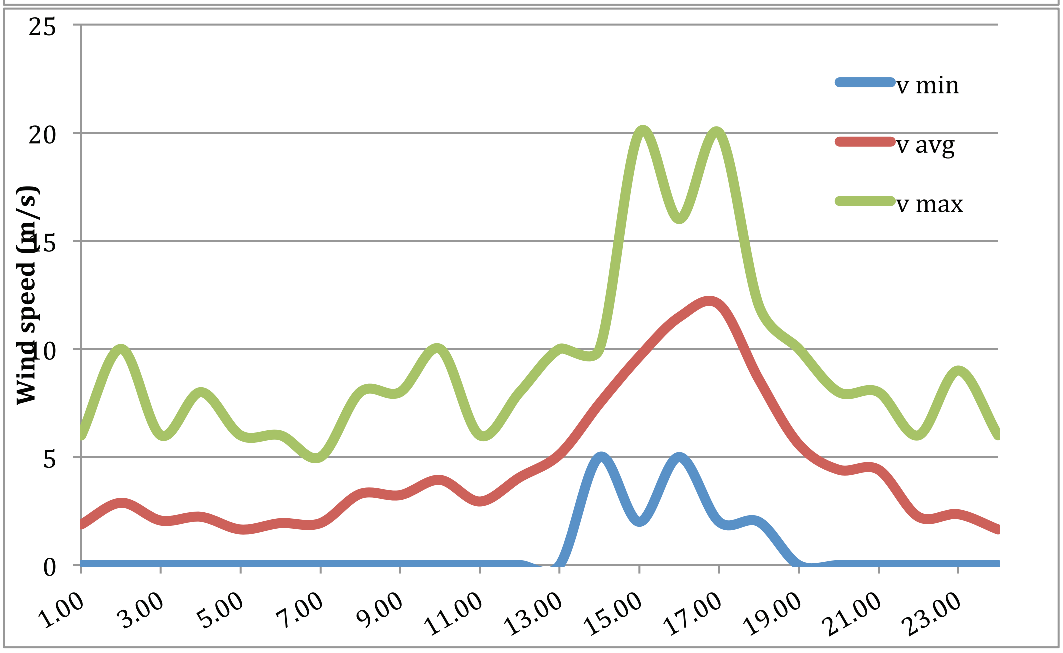
Wednesday, July 20, 2011				
Time	Direction	v (m/s)	Tmax (°C)	Tmin (°C)
1:00	360	4	27	27
2:00	360	6	26	26
3:00	270	4	25.8	25.8
4:00	360	4	26	26
5:00	0	0	25	25
6:00	0	0	25.6	25.6
7:00	230	4	26	26
8:00	200	4	28	27
9:00	240	4	29.2	26.9
10:00	270	4	31	27
11:00	210	2	31	27
12:00	360	3	32	26.7
13:00	360	10	32	28
14:00	360	10	33	29
15:00	360	10	32	27.4
16:00	360	10	32	27
17:00	360	10	31	26
18:00	360	10	29.9	26.1
19:00	340	10	29	26
20:00	120	6	26	25
21:00	160	4	24.2	24
22:00	0	0	24	24
23:00	0	0	25	25
0:00	0	0	24	24

Thursday, July 21, 2011				
Time	Direction	v (m/s)	Tmax (°C)	Tmin (°C)
1:00	190	2	24	24
2:00	0	0	24	24
3:00	0	0	23.5	23.5
4:00	0	0	23	23
5:00	0	0	24	24
6:00	0	0	23.3	23.3
7:00	150	5	24	24
8:00	160	8	27	25
9:00	200	2	28.1	24.8
10:00	230	2	30	25
11:00	40	2	31	26
12:00	0	0	31.7	26.2
13:00				
14:00				
15:00				
16:00				
17:00				
18:00				
19:00				
20:00				
21:00				
22:00				
23:00				
0:00				

A1.2 Wind speeds

From the data presented in the previous paragraph are the minimum, average, and maximum wind speeds deducted. These three values are presented for each hour of the day. This is used to know what winds speeds can be expected at certain hours of the day. This data shows that the windpipe will be the most effective between 13:00 and 21:00. Around 13:00 the average wind speeds measured increase with a maximum around 17:00, close to 21:00 the average speed is decreased to a level it stay until 13:00.

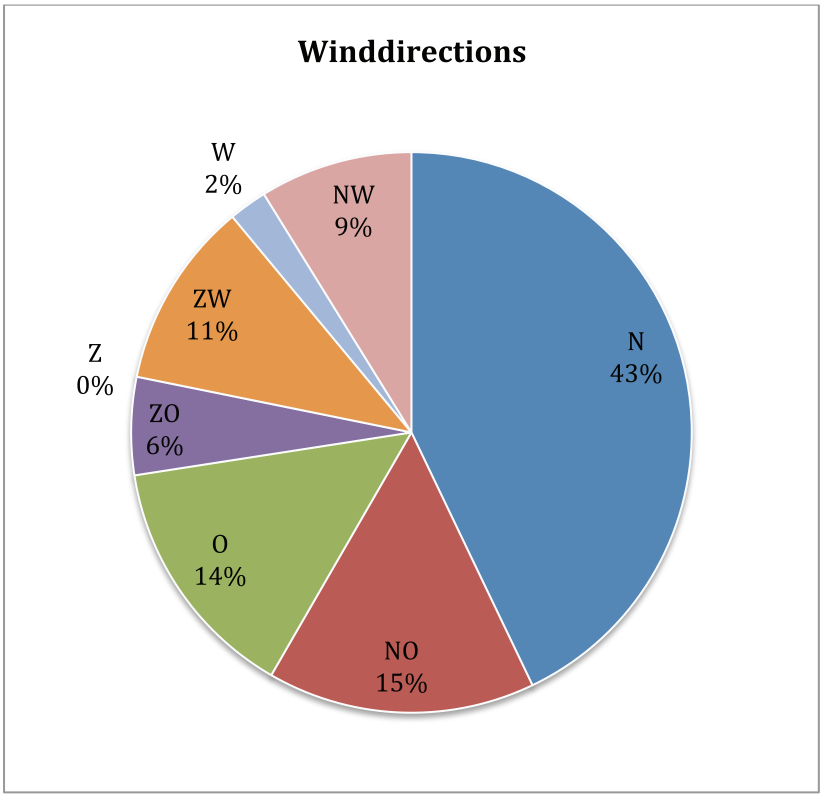




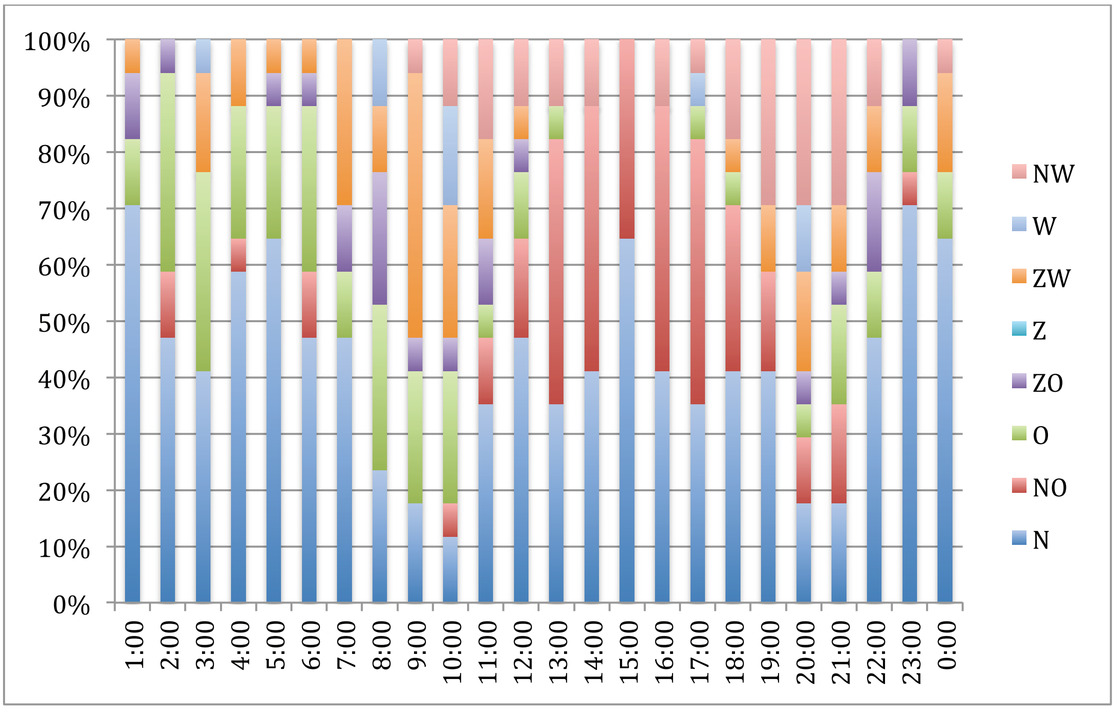
A1.3 Wind direction

The direction of the wind was given in degrees, to determine the dominant direction(s) the degrees are classified in to eight directions. These direction and the corresponding angles are presented in table X below. This classification is made for every measurement. Figure X presents the times that a specific direction is given in the data. Shown is that north is the most dominant direction followed by northeast.

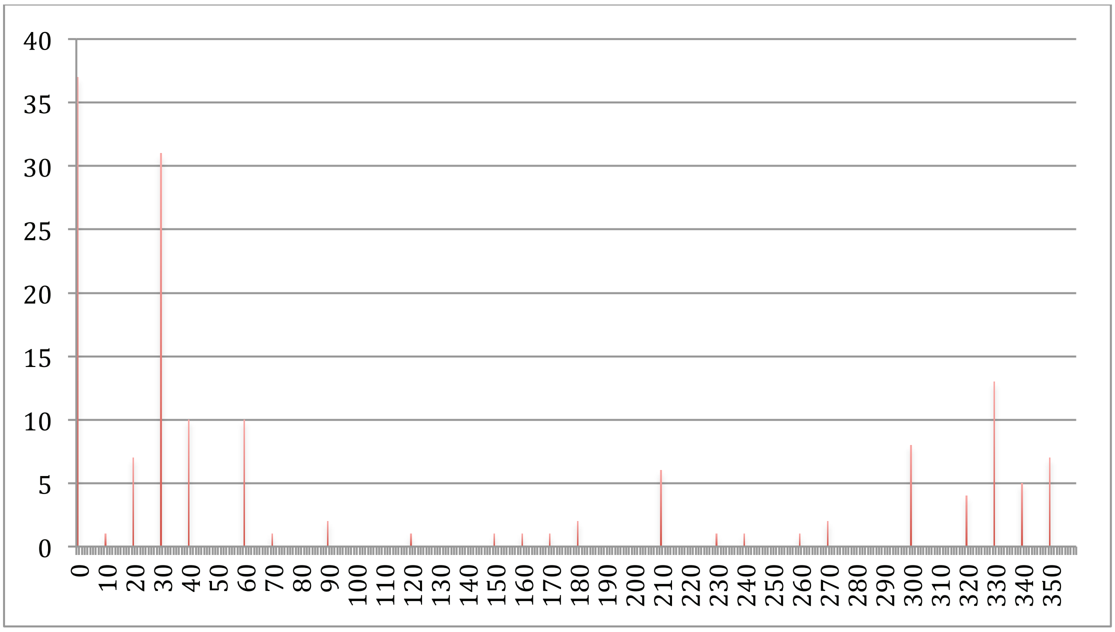
	MIN	MEAN	MAX
N	337.5	0	22.5
NE	22.5	45	67.5
E	67.5	90	112.5
SE	112.5	135	157.5
S	157.5	180	202.5
SW	202.5	225	247.5
W	247.5	270	292.5
NW	292.5	315	337.5



When the directions are presented over the time of a day it shows that the north and northeast wind directions are particularly dominant between 13:00 and 19:00. This is almost corresponding to the time that the wind speeds are at the higher level.



The effective range of an fixed windpipe is 60 degrees, it catches wind that flows in the direction of the head of the pipe, but also air the comes in at an angle between 30 degrees lower and higher. For the time period between 13:00 and 21:00 where the wind speeds are at the highest calculated is what the optimum position of a fixed head will be. In the most optimum position the pipe should be placed so it can catch the winds in the northern direction. In 66% of the time the wind is directed between 330 and 30 degrees. Below the Figure presents the amount of times the wind was directed in a specific direction. The figure shows that 0 and 30 degrees are the most common directions.


40
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A1.4 Design process windpipe

The basic requirements behind the design:

- Low construction and maintenance costs;
- Easy to install and construct;
- Largely made out of standard materials;
- Possibility to after install in to a house;
- Earthquake friendly.

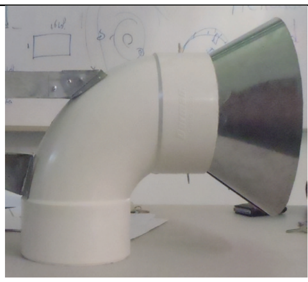
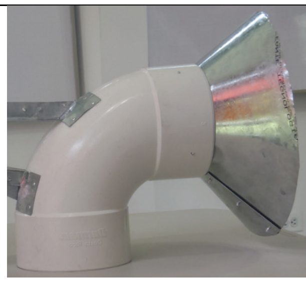
The design for the tropical wind towers is in main purpose for the lower income class. Especially these people live in closely the each other built houses with almost no outside space. Most often the walls of these houses are low and they only have a ground floor. High closed fences surround these houses.

First step; the use of pvc pipes. These are low cost easy to work with and lightweight. There is chosen for a six-inch pipe because these are the most cost effective, if the costs are compared to the area of the pipe. For example for the price of an eight-inch pipe you can buy two six-inch pipes. Which have a much bigger surface area.

Second step; selecting a head, which converts the horizontal airflow in to a vertical flow. A standard 90° curve is selected, because it has a good shape and is easy to install.

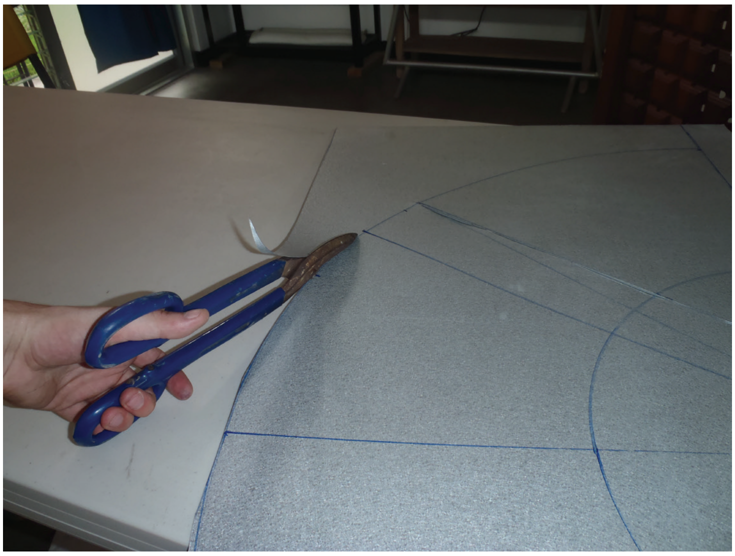
Third step; selection of a mouth to increase the inlet opening. Tested is if a the use of a mouth can increase the airflow through the pipe. The mouth is a cone made from sheet metal. This test is done with a room ventilator. Three test setups are used; one with only the head; one with a 30° angled mouth; and a 45° angled mouth. The fan created an airspeed of 15 m/s output flows are shown below. Conclusion is that the standard head performs the best. With the other mouths a lot of air bounces out. The angle is to large.

Curve	Output pipe (m/s)
0°	13.5
30°	12.5
45°	11

The test was redone with a 20° mouth. In this test the three different speeds of the fan is used to make a better comparison. These results are given below.

Curve	3	2	1
Input fan:	8.3	9.2	10.5
Output 0°	5.5	6.7	8.6
Output 20°	8	9	10.2

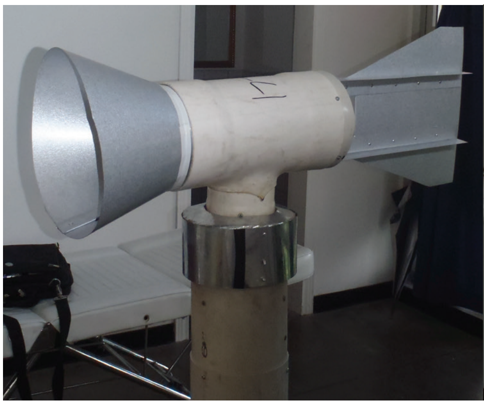
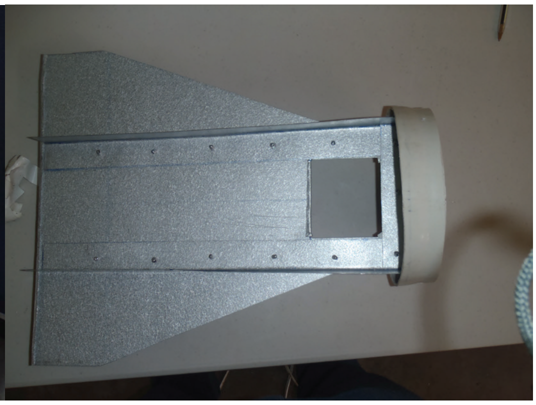


Fourth step; first outdoors test. The head and mouth are fitted to a 5 meter long pipe. Noticed was during this test that it was hard to direct the head in to the wind because the wind direction changes. The decision was made to design a rotating mechanism.

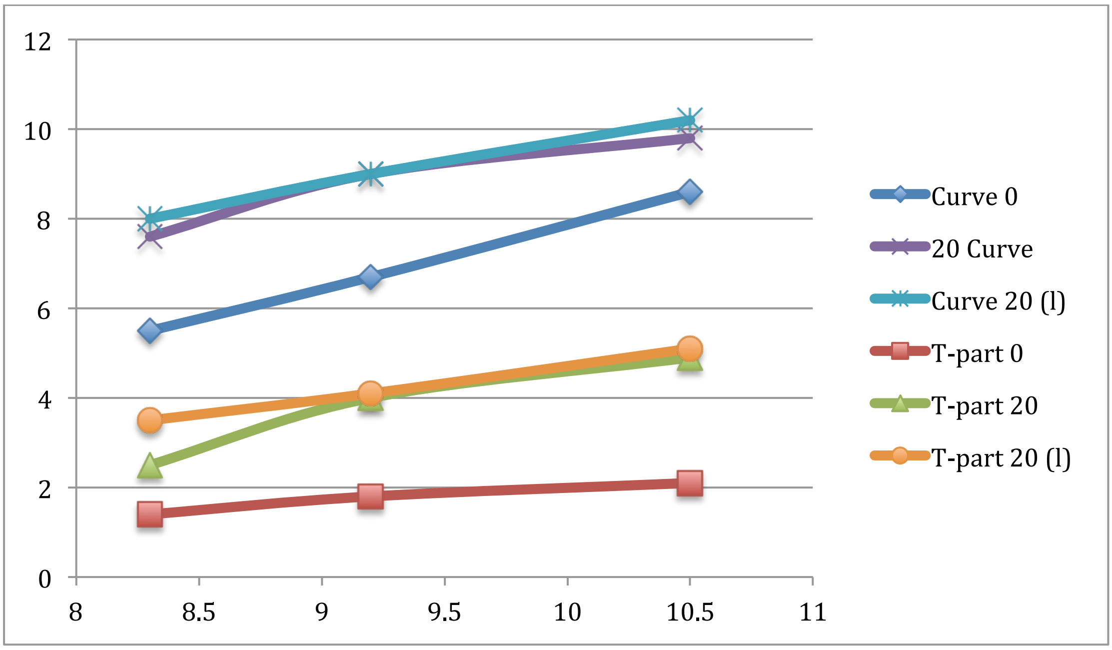
Fifth step: first design rotating mechanism. A design was made and created to make the existing 6-inch head rotating on top of the pipe. This mechanism exists of one axle to which two disc are connected. One disc is connected to the pipe and the other to the six-inch head. The outside of the top of the pipe and the inside of the bottom of the head are sanded down so there is space to rotate. During test it showed that the mechanism got stuck a lot, it was no balanced enough and the space between the head and the pipe was too little. There was to much friction. A second version was needed to overcome these problems.



Seventh step; second design. The friction needed to be reduced in this second design and the stability needed to be increased. The curved head is out of balance by nature, a T-connection part is more balanced. Chosen is to experiment with this a t-part with a closed backside. To tackle the second problem, the friction, there is chosen to fit the head inside the pipe and not around it. When the head is fitted around the gap should be small because otherwise it looses air. When the pipe is fitted inside the gap can be bigger because the air will not flow out easily. One size smaller as six-inch parts are four-inch parts. There is chosen to use a six-to-four-inch t-connection. This part has two six-inch sides and one four, so the same mouth can be used as in the previous model. The backside is close with an end cap. Because of the flat surface of the end cap it is easy to fit the tail to it. Because the four-inch connection a different rotating mechanism needed to be made. Now a more stable version was made. A gain one axle connected to rings, but the rings now were made using a mould. So they were perfectly round. A local welder made the rings.

In test the airflow through this t-connection proved to be a lot smaller as through the curve shaped head. Below the result are shown of the test. The t- and curved- shaped head with different mouths. All curved configurations performed better as the T configurations. All speeds are presented in m/s.



To try to overcome this problem the inside of the t-part was more streamlined. However this would not help, so the assumption was made that the 4-inch connection acted as a bottleneck. To test this assumption a redesign was made for the 6-inch curve. A redactor-part, which could reduce the 6-inch to a 4-inch, was used so it also could be fitted inside the pipe. With this configuration the same results were gained as with the t-connection, during indoor tests. Searched is to different materials that could be used. No better standard part could be found so these were used for outdoor tests.