THE HAITIAN DREAM

Increasing the economic, social and environmental resilience of the hot and humid, high density urban Haitian neighbourhood by the implementation of climate responsive design.

E.J. de Visser

ABSTRACT

The event of the earthquake on January 12 2010 in Haiti has caused in a disaster which has shocked the world. It resulted in an estimated amount of 250.000 casualties and left over 1.000.000 people homeless. From these numbers it is clear that Haiti needs to become more resilient to hazards to prevent in a future repetition of this disaster.

A study into Haiti's history and present day situation shows that the disaster was not a result of a single problem. Multiple problems affect the country and not all can be solved by one research. That is why this research will focus on reigniting the Haitian building industry in a sustainable way by the production and application of building products produced with locally found or grown raw materials. Through this approach jobs will be created, the environmental degradation will be stopped and solid wastes diminished because of sustainable resource management.

The choice of which building products will be produced focuses on the applicability within the local building industry which is in turn determined by the materialization of the buildings. The design of the buildings has failed in providing a safe and comfortable environment. The design of the built environment has to be changed into a climate responsive design which is resilient to hazards. We should design with the climate instead of against it.

The results of the research will be tested through a design for a high density urban neighborhood of Haiti. The design will be evaluated on specific indicators from the resilience and sustainability theory and compared with the existing situation and another design solution from NGO's.

The evaluation shows that the climate responsive design, with a materialization of sustainable building products, diminishes the solid waste significantly at the afterlife of the building from 40% to only 7%. The design provides in a thermally comfortable indoor climate by the implementation of only passive means. The design has proven to be resilient to future natural and man-made hazards and will prevent in disaster.

The research question is whether the Haitian building industry can be used as an economic growth stimulator to develop the country in a sustainable way. If the design of the thesis is implemented to cope with the urban growth of Port-au-Prince over a time period of 50 years, 9.124 housing blocks are needed. The demand for building materials will be immense: nearly 5,98 million ton. This demand will create jobs and increase the purchasing power of Haitians which will increase the wealth. The research proves that there is a huge potential for the building industry to be an economic growth stimulator and develop Haiti in a sustainable way. The development will be even more stimulated through a climate responsive design of the built environment which is resilient to hazards.

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Green Building Innovation

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URBANEMERGENCIES CASESTUDYHAITI

Tomorrow's Toussaints

this is Haiti, a state
slaves snatched from surprised masters,
its high lands, home of this
world's sole successful
slave revolt, Haiti, where
freedom has flowered and flown
fascinating like long necked
flamingoes gracefully feeding
on snails in small pinkish
sunset colored sequestered ponds

despite the meanness
and meagerness of life
eked out of eroding soil
and from exploited urban toil, there
is still so much beauty here in this
land where the sea sings roaring a shore
and fecund fertile hills lull and roll
quasi human in form

there is beauty here
in the unyielding way
our people,
colored charcoal, and
banana beige, and
shifting subtle shades
of ripe mango, or strongly
brown-black, sweet
as the suck from
sun scorched staffs
of sugar cane,
have decided
we shall survive
we will live on

a peasant pauses
clear black eyes
searching far out over the horizon
the hoe motionless, suspended
in the midst
of all this shit and suffering
forced to bend low
still we stop and stand
and dream and believe

we shall be released
we shall be released
for what slaves
have done
slaves can do

and that begets
the beauty

slaves can do.

by Kalamu ya Salaam

PREFACE

This thesis is written to describe the research conducted by the author to obtain the title of Master of Science from the faculty of Architecture of Delft University of Technology. The research is part of the graduation lab of Green Building Innovation which is part of the Building Technology chair of the faculty of Architecture.

The research is contextualized in Haiti, a country which was devastated after an earthquake in 2010. A platform of the faculty of Architecture has a focus on the rebuilding efforts of the post-disaster situation. The platform is named Urban Emergencies and has had previous case studies in, amongst other countries, Venezuela, China and Ghana. The case study of 2011 has been Haiti. A site visit of a month was part of the research process and took place in October 2011. This was made possible by Cordaid, an NGO which is active in Haiti. A report on the use of quick risk mapping to benefit site selection in post disaster rebuilding efforts was prepared by our platform and can be found attached to this thesis.

The individual research of the students within Urban Emergencies Haiti are interrelated and should in the end provide in solutions for the short-, mid- and longterm post-disaster development.

THE HAITIAN DREAM

Increasing the economic, social and environmental resilience of the hot&humid, high density urban neighbourhood by the implementation of climate responsive design contextualized in Haiti.

MSc thesis
Graduationlab of Green Building Innovation
Building Technology department
Faculty of Architecture, Delft University of Technology

E.J. de Visser
April 20 2012

ACKNOWLEDGEMENT

Around a year ago I started the MSc graduation track of Green Building Innovation within the Urban Emergencies platform and from then on devoted most of my time to the research and thesis. Looking back and reviewing the whole process I can say that it has been a rocky road, but that the results are very satisfying and that the experience of the site visit to Haiti has been of amazing value to both my thesis and my personal understanding of developing countries.
Off course there are a lot of people without whom this thesis would not have been as satisfactorily to me as it is now. First, off course my three mentors Arjan van Timmeren, Regina Bokel and Loriane Icibaci. Special thanks to Loriane for her inexhaustible amount of energy and drive to make the whole Urban Emergencies studio into a success. For having already in mind the bigger picture of the connection between several projects and for pushing me, and I think also others, to get the best results out of the research.
I would like to thank the employees of Cordaid Haiti for the good care in Haiti and making the experience unforgettable. I would like to thank Alexander Vollebregt, Taneha Kuzniecow Bacchin and Alexander Wandl for their guidance during the production of the Risk Map Léogâne report. All the members of the Urban Emergencies Haiti studio, thank you for your company in Haiti and good collaboration during the gradutionprocess. Special thanks to Laura and Richard, I am very proud on the results of our collaborative research.

Special thanks and gratitude to my parents who have made it possible for me to graduate as an MSc and who have always supported me during my whole educational period. And Bram, my ‘uitlaatklep’ and great support during the whole process.

EXECUTIVE SUMMARY

The earthquake on January 12 2010 that hit Haiti caused in a disaster of which the scale has shocked the world. This event was the motive to start the research. When researching Haiti it becomes clear that a set of problems cripple Haiti's development. The problems of Haiti can be summarized and categorized into economical, environmental and social problems. These problems form the motive for the research, but not to all will a solution be sought by the research. The problems are:

Economical problems
• High unemployment
• High illiteracy causes in a low educational level of the labour force
• Low GDP
• Import surplus
• Negative industrial growth rate
• Problems indicate that the imposed plans from the international community for the reform of the Haitian economy are ineffective
• Inactive building industry

Environmental problems
• Very low forest land coverage → deforestation → soil erosion
• Vulnerable to hazards due to an ineffective building code, improper drainage, environmental degradation
• Ineffective building code + urbanization + lack of planning → informal and high density neighbourhoods

Social problems
• Long term political instability

The scope of the research is determined by indicators from the theory of **resilience**, which is the overarching theory of the research. Resilience describes the ability to return to a reference state or maintain its basic functions after a negative hazardous event (Birkmann, 2006 and Wilbanks, 2007). Under the umbrella of resilience is the theory sustainability. Sustainability has many definitions and ways of interpretation, but in general the definition of **sustainable development** is the development that meets the need of the present without compromising the ability to future generations to meet their own needs (Brundtland Commission, 1987).

The scope of the research is defined by the following indicators:

Resilience indicators
• Increase thermal comfort
• Decrease vulnerability to natural hazards
• Off-grid buildings
• Stimulate economic growth

Sustainability indicators
• Micro climate responsive
• Affordability
• Reduce waste
• Conserve natural resources
• Maximize water efficiency
• Culture responsive
• Reduce carbon output
• Reduce toxicity
• Maximize energy efficiency
• Maximize durability

The determination of the scope of the research, of which the goal is to find a solution to some of the problems in Haiti, have resulted in the formulation of the research question.

__In the context of urbanized Haiti, can the building industry with a climatically responsive design of the high-density urban neighbourhoods be committed to ignite economical, environmental and social development which increases the resilience towards disasters?__

The research described in this thesis is part of the platform Urban Emergencies. This research is part of an collaborative research whose goal is to develop a sustainable building industry with a decentralised production of **sustainable building products** for the local market with the use of local raw materials as resources. Jobs will be created which will stimulate the economic development of Haiti. The environmental problems will be solved by sustainable resource management and CO_2 emissions will be reduced by the diminishing of the transportation distances due to the local production as opposed to the import of building products.

To obtain a true sustainable building industry the total life cycle of the building material will be researched by the collaborative research. The first step towards a sustainable building industry is selecting those raw material resources which can be obtained or grown in Haiti.

Possible local raw material resources in Haiti

Reusable	Recyclable	Renewable
-	• plastic • cement rubble	• rice (food) • hemp • coconut (food) • wheat (food) • bamboo • wood

With the knowledge of with which raw materials building products can be produced, a database was set up which contains sustainable building products.

These sustainable building products have to be implemented as the materialization of the buildings of Haiti. During the earthquake, the built environment of Haiti failed in fulfilling one of its most important tasks: offering shelter. Over 1.000.000 people lost their house. Indicated as one of the main causes of this disaster is the lack of an effective building code with seismic design standards. Especially the informal, high density urban neighbourhoods were hard hit by the earthquake. The building typology prominent in these type of neighbourhoods is the cement block house. The materialization of these buildings is odd, because the climate of Port-au-Prince is hot and humid and cement of a significant thickness, such as a cement block, accumulates heat. This effect of thermal mass is desirable in hot and arid climatic zones where high temperatures during the day are alternated with low temperatures at night. In the hot and humid climate, materialization with cement will cause in indoor thermal discomfort. The urban morphology of these neighbourhoods, materialized with cement in a very dense layout, result in the so-called urban heat island which increases the ambient air temperature with a few degrees. The urban layout in hot and humid climates should be based on the optimization of the airflow to promote ventilation of the buildings.

Concluding we can state that the current prevailing design of the built environment of the high density urban neighbourhood in Port-au-Prince is **climate unresponsive**. Research into the Haitian building typologies on urban form, architectural form, passive thermal strategies and climate responsiveness has led to the formation of a toolbox. This toolbox is supplemented by a research on the same topics in other similar climatic zones around the world.

The research into climate responsive building is also approached from the theory. The climate of Port-au-Prince is classified as hot and humid. The temperature and humidity show no seasonal variation, but there are small diurnal variations in temperature and humidity. The climatic data confirms the assumption that only cooling is needed in the buildings of Port-au-Prince.

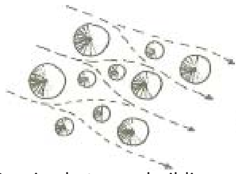
The climatic parameters in combination with contextual aspects rule out four of the five passive cooling strategies: for direct evaporation the relative humidity of the ambient air is too high; indirect evaporation by a water surface is impossible due to the danger of attracting mosquitos with a possibility of malaria or dengue; radiative cooling seems promising but there

Climate responsive toolbox for the hot and humid climate

Urban form

Haiti
- Communal living by family bonds (cultural and contextual)

Hot&humid climatic zones
- Shading of an inner courtyard
- Spacing between buildings to promote airflow

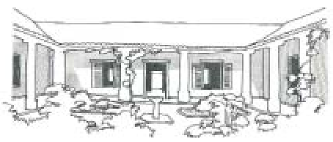

Spacing between buildings to promote airflow


Shading of an inner courtyard

Architectural form

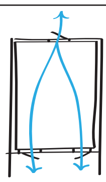
Haiti
- Vodou house layout and detailing (cultural and contextual)

Hot&humid climatic zones
- Adjusting of facade surface according to solar angles

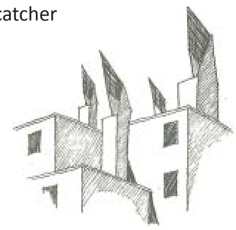

Adjusting facade surface to solar angle

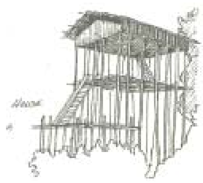
Passive thermal strateges

Haiti
- Cross ventilation
- Lightweight structure (low thermal mass) + reflective roof material


cross ventilation

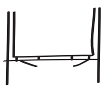
Hot&humid climatic zones
- Elevated house to utilize airflow to the fullest
- Windcatcher

Windcatcher


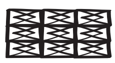

Elevated house

Climate responsiveness

Haiti
- Shaded veranda
- Shutters
- Ventilation bricks
- Reflective roof material


shaded veranda


shutters


ventilation bricks


reflective palm leaves

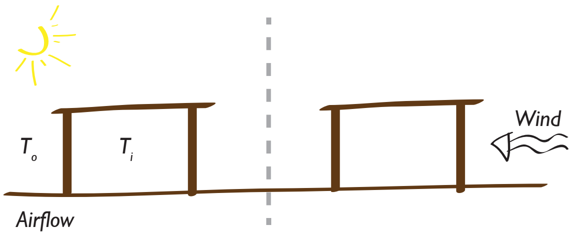
Hot&humid climatic zones
- Shaded balcony
- Shutters
- Shading of the surrounding built environment


Shading of the surroundings


Shaded balcony

is a high percentage of cloudiness during the night thus this strategy looses its effectiveness; and the last one of thermal mass does not suit the hot and humid climate due to the small diurnal temperature differences. The only possible passive cooling strategy is cooling by airflow.

Passive cooling strategy for design: airflow



The amount of cooling necessary to obtain the desired indoor thermal comfort level is determined by a range of temperature under which most people perceive it to be comfortable. These standards have been developed for the western world, but are lacking for the hot and humid climate. Through fieldwork research it was tried to formulate the **perception of tropical comfort** into a range of temperature, humidity and/or air velocity.

From the fieldwork it was not possible to determine the temperature, humidity or wind speed range for the indoor thermal comfort level in which the inhabitants of the urban high density neighbourhood of Villa Rosa would feel comfortable. The only recommendation which can be made is to promote ventilation of the indoor space to the fullest, because when both the temperature and the humidity are high the only way for the human body to loose heat is through evaporation. The potential of evaporation is dependent on the amount of airflow, the air velocity.

The findings of the research will be tested through a climate responsive design for the urban high density neighbourhood with a materialization of sustainable building products provide for by the database. The location for the design is the informal, high density urban neighbourhood Villa Rosa in Port-au-Prince. The neighbourhood is located on a steep slope and was hard hit during the earthquake. This neighbourhood is the typical concrete jungle which is seen all over Port-au-Prince.

The two main research topics of the thesis are climate responsive design and the materialization of the design with sustainable building products. There are also smaller research topics indicated by the theory of which the findings are implemented into the design. One is off course to decrease the vulnerability to hazards.

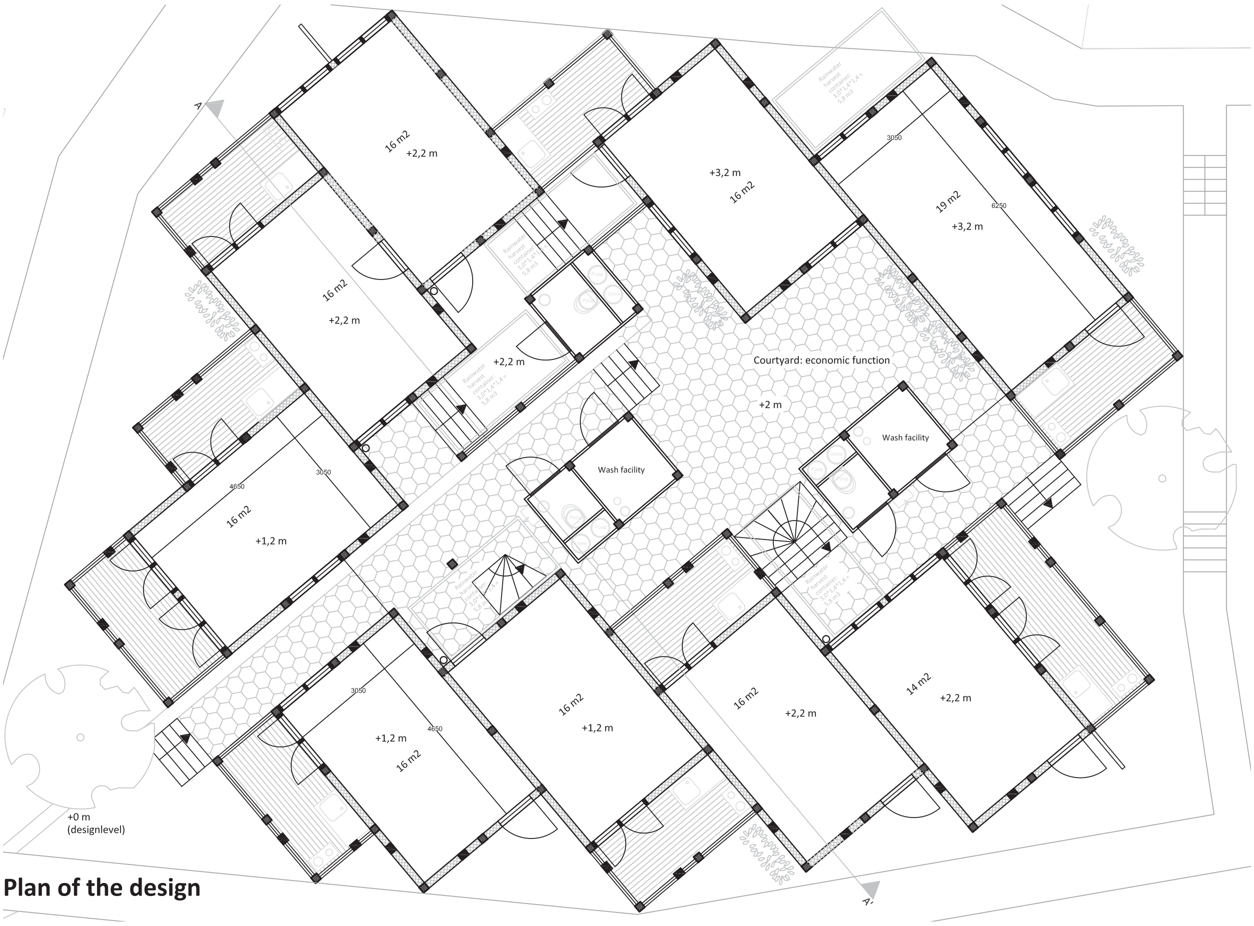
The **natural hazard** of the earthquake does not pose the greatest risk on disaster in Villa Rosa, landslides do. The third natural hazard which poses a risk are tropical storms. The outcomes of the research on how to mitigate the risk have been implemented into the design.

Man made hazards can also result in a disaster. Mitigating the risk is difficult since there is no predefined list of man made hazards. What can be done is to be as self-sufficient as possible. Therefore, the design is not connected to the infrastructure of electricity, sewage and water. It is an off-grid design. Electricity is gained by PV panels, a sewage is not necessary since all toilets are dry toilets and rainwater is stored to diminish the daily demand for water.

Cultural or contextual responsiveness is necessary for the design to be accepted by the future user. Several cultural aspects have been implemented in the design; flexibility of the construction process and the housing sizes; extra housing units for future population growth; local entrepreneurship is stimulate by extra floor space for economic purposes; and there is a possibility for the user to express cultural believes by painting the house or decorating with woodcarving.

The implementation of the research on climate responsive building into the design starts with the diminishing of the **heat gain** as much as possible. Removing the heat producing activities from the indoor space to the outdoor space will diminish the indoor heat gain. Therefore, the activity of cooking is provided for in an outdoor space at the veranda or balcony. A correct design and materialization of the building shell (facades and roof), according to the amount of solar radiation received, will reduce the outdoor heat gain.

Because of the proximity of Haiti to the equator, solar angles are high and the roof will receive most solar



Plan of the design

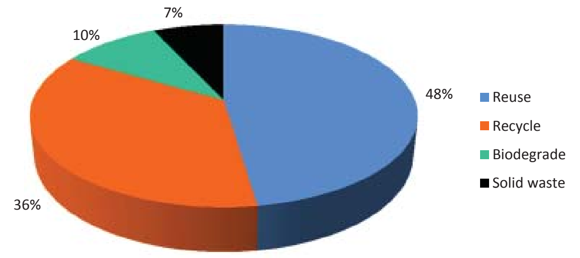
Birdseye view of the design

radiation. The chosen roof typology for the design is a double solid roof with an air cavity. The correct materialization based on thermal properties will determine the thermal performance of the roof.
Since from the analysis of the climate it followed that airflow should be directed into the house as much as possible, the facades which do not receive direct solar radiation are materialized as shutters. Those facades that do receive direct solar radiation should have a low conductivity and a low thermal mass to prevent in the accumulation of heat during the day.

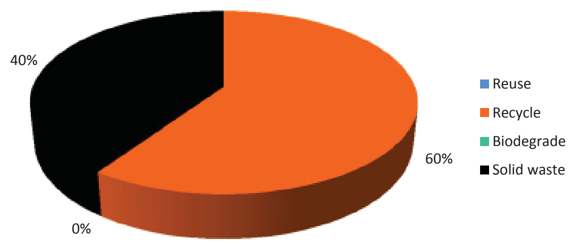
Airflow is the only passive cooling strategy which can make an indoor space thermally comfortable in the hot an humid climate. The design location is at the leeward side of a hill which makes the potential for an acceptable indoor air velocity for ventilation difficult to obtain. Another type of airflow is present at the location due to the topography of the hill. The building is designed to catch this airflow by a stepped-row housing block. The morphology of the stepped row will create high and low pressure zones and by placing the facade openings at the correct place, cross ventilation is promoted. The indoor spaces have to be single banked to ensure the cross ventilation. The design of the facade openings should focus on maximizing the ventilation and thus a choice is made for floor to ceiling high shutters.

The materialization of the building is with sustainable building products from the database. For the design of the building, with 27 housing units and supporting functions, the total demand for building materials is calculated. The amount, in mass [kg], is calculated for the total lifespan of the building which is 50 years. The lifespan of the building is in some cases longer than the lifespan of the building products. These products have to replaced and this will also be taken into account when calculating the total demand for building products.
At the end of life of the building and during the life span of the building, a waste flow of building materials is created. Compared to the existing situation the waste flow of solid waste is significantly diminished.

Afterlife of the building products of the design



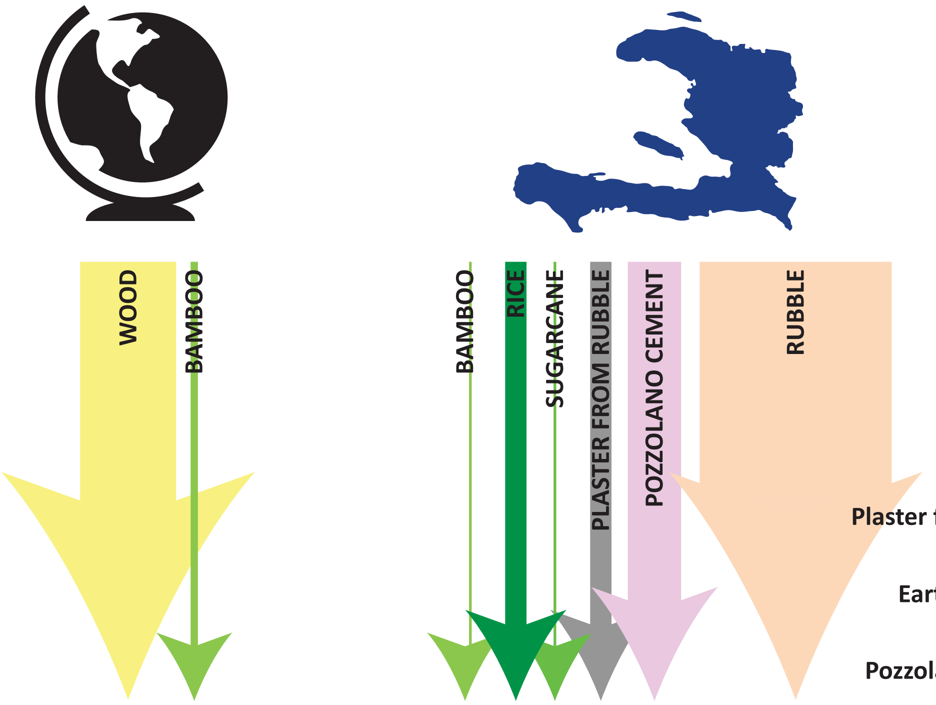
Afterlife of the building products of the existing situation/ NGO design



The goal of the research was to find solutions to some of the problems which cripple Haiti's development. The research question was wether the development of Haiti could be stimulated by a sustainable building industry which produces sustainable building products, and a climate responsive design.

The research shows that there is a huge potential for the building industry, focussing on the production of sustainable building products for the local market, to be the ignition of Haiti's development and hereby increasing the resilience towards disasters caused by natural and man made hazards. It became clear during the evaluation that a lack of data about the building products and their production processes have obstructed some of the results of the research. The total number of jobs created both during the life cycle of the building products and at the construction site could not be determined. The climate responsive design has proven to provide in a better thermal comfort level than the existing situation.

Building material input



Wood
144.233,3 kg

Bamboo
27.392,2 kg

Bamboo
894,3 kg

Rice board
31.842,1 kg

Sugarcane
3.178,9 kg

Plaster from rubble
45.792 kg

Earth or rubble
312.600 kg

Pozzolano cement
90.051,6 kg

27
UNITS

137
PERSONS

Total amount of building material
655.984,4 kg

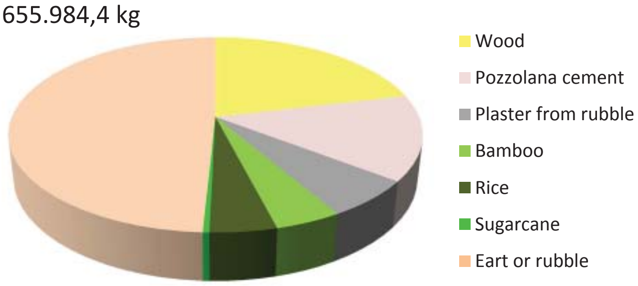
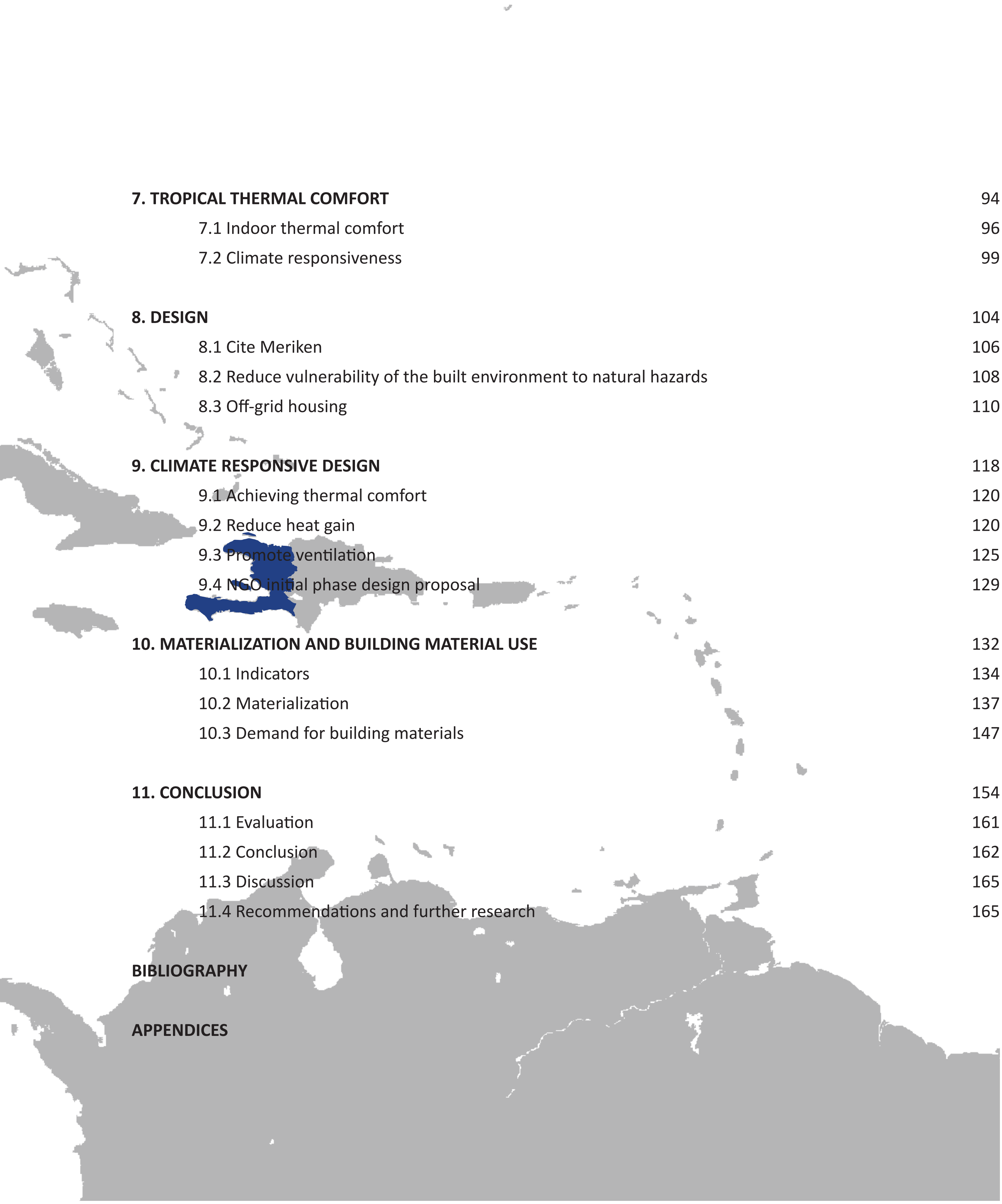
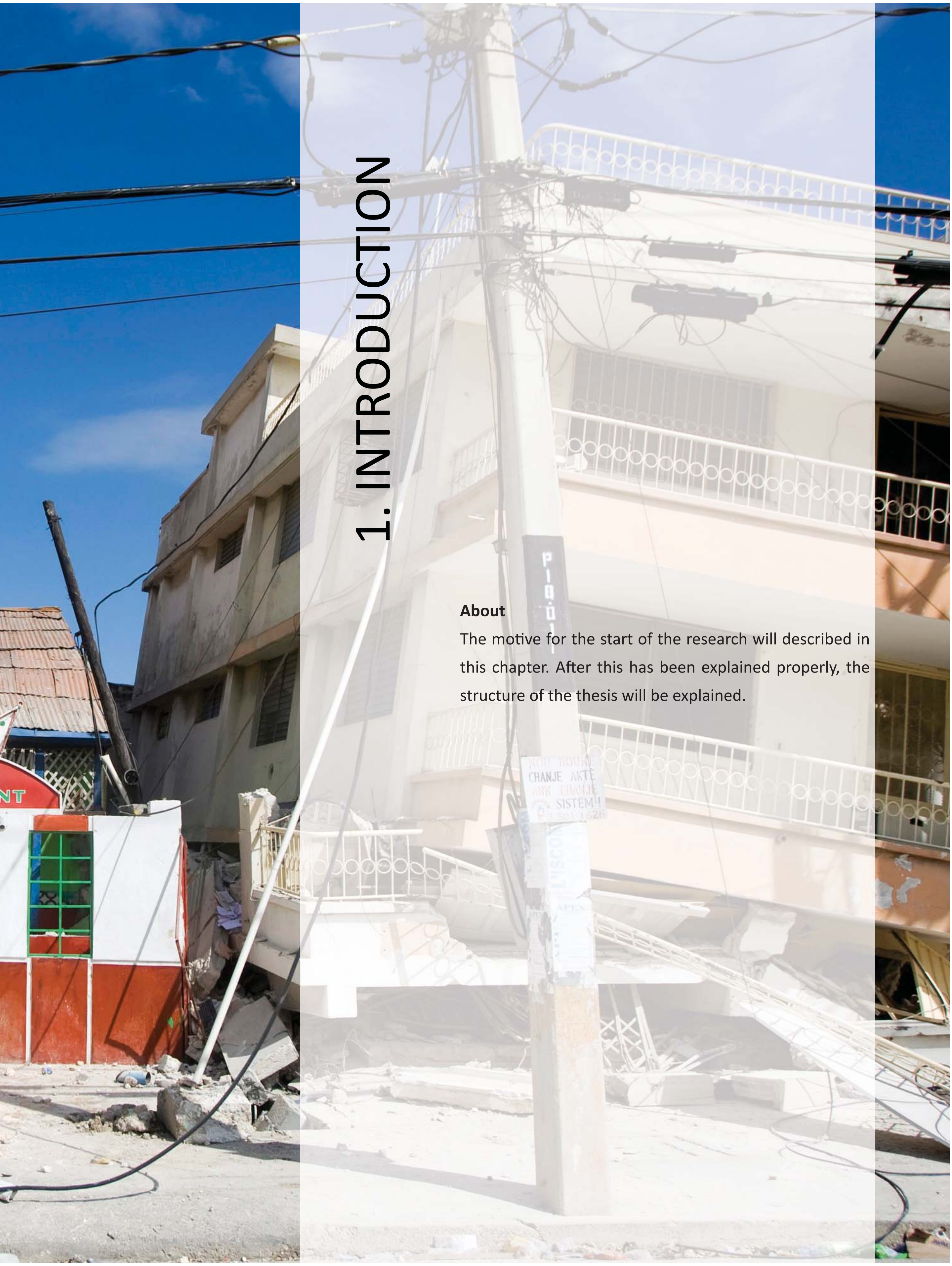


TABLE OF CONTENT




Charly
RESTO DANSA



1. INTRODUCTION

About

The motive for the start of the research will described in this chapter. After this has been explained properly, the structure of the thesis will be explained.

1. INTRODUCTION

On January 12 2010 a 7.0 magnitude earthquake hit Haiti. It resulted in a large scale disaster which shock the world. Reports about 250.000 casualties accompanied by footage such as fig. 1.0 of the devastation, were heartbreaking. Benefits to raise money for the rebuilding of Haiti were organized all around the world and the amount of money donated was immense.
What was striking is the fact that this country is in the midst of the tropical Caribbean sharing the island of Hispaniola with the Dominican Republic, a very popular holiday destination. From the footage of the aftermath of the earthquake one would not expect this country to be located in the Caribbean. Searching on the internet for images of Haiti, there seems to be only misery in the country. When the same is done for the Dominican Republic there is the envisioned image of the Caribbean as a tropical paradise with palm trees and beautiful coloured seas (fig. 1.1). One starts to question how it is possible that there is such a big difference between the two countries which share an island?

Researching more about Haiti, which is even called by some 'the island that ate itself', it starts to become clear that the earthquake and the problems occurring during the aftermath (such as cholera and political unrest) are only the tip of the iceberg of all problems which cripple Haiti's development.
Another big part of the iceberg is the environmental degradation due to large scale deforestation which has led to soil erosion. Haii is located in the Hurricane belt and when the annual tropical storms visit the island, this most of the time leads to the disaster of flooding and landslides because the soil is unable to retain the water. Very striking for the environmental degradation is the border between Haiti and the Dominican Republic (fig. 1.2). Usually, borders between countries are only political, but the one on Hispaniola is visually within the topography.

The disastrous event of the earthquake was felt hardest in the high density urban neighbourhoods of Port-au-Prince (fig. 1.3). Under the reign of the Duvalier

Fig. 1.1: Google search of the Dominican Republic (left) and Haiti (right)
Source: Google

Fig. 1.2: Border between Haiti (left) and the Dominican Republic (right)
Source: NASA/Goddard Space Flight Center Scientific Visualization Studio

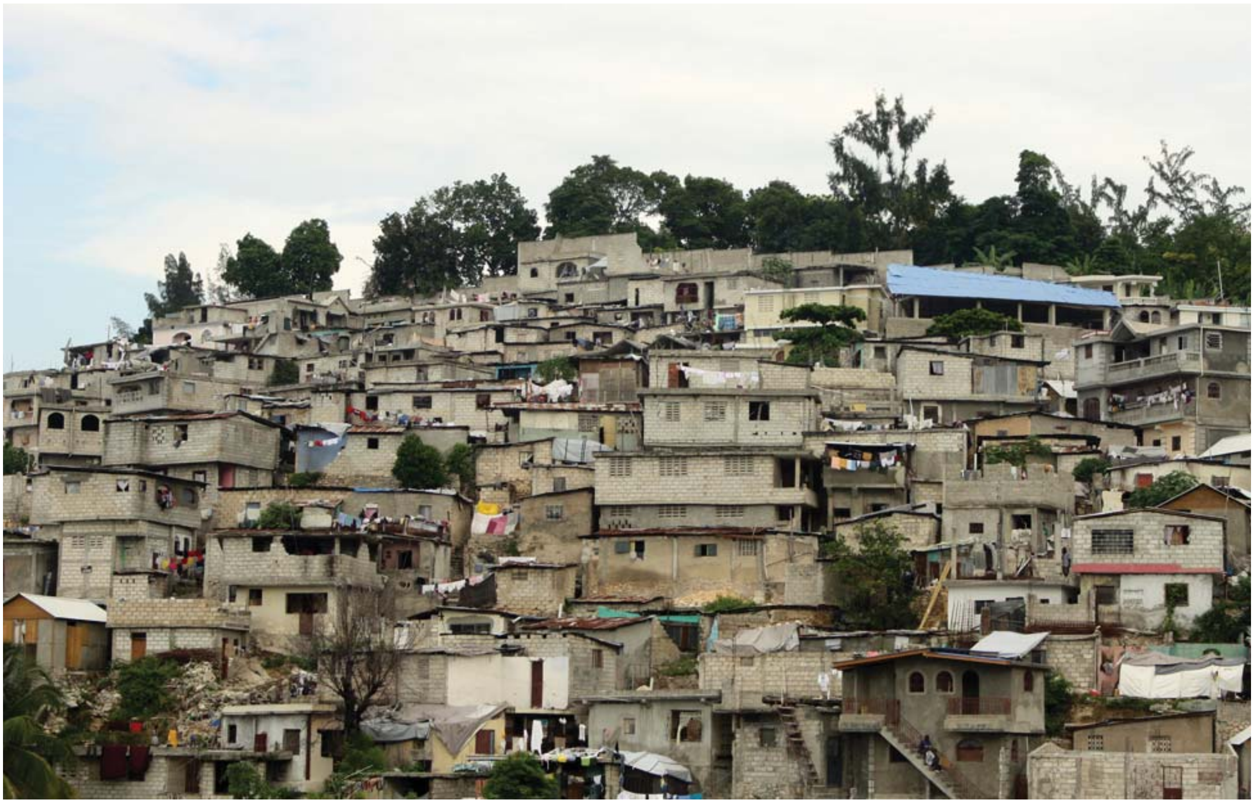


Fig. 1.3: View on Villa Rosa, Port-au-Prince
Source: Author

family, Port-au-Prince urbanised at a fast rate because of the rise in unemployment at the rural areas. Due to the lack of urban planning and an ineffective building code the informal neighbourhoods popped up like mushrooms. The lack of proper construction methods and supervising has led to the collapse of many cement buildings during the earthquake causing in the disaster. A lack of knowledge on how to build with concrete and cement in seismic active areas can be appointed to as one of the causes of the high number of casualties. Concrete in building construction is an invention of the western world and is imposed on countries such as Haiti as a cheap solution to the increasing demand of building materials. Where there is a lack of supply of natural and indigenous building materials, cement if the solution to the problem. This globally growing consumption of cement and concrete has led to the fact that the cement production is responsible for 5% of global CO_2 emissions. Next to this negative effect on the environment it is questionable wether this building material suits the climate of Haiti. A significant mass of cement accumulates heat during the day which is ideally for arid climates where hot temperatures during the day are interspersed with cold nights. For hot and humid climates with small diurnal temperature differences, such as in Port-au-Prince, the accumulation of heat during the day and the radiation at night in unwanted.

Haiti's destroyed natural capital is due to both economical and political reasons. It has led to the present day situation where almost all resources are imported and where there is no industry except for international garment factories. For Haiti to develop and start living up to the Caribbean preconception of the tropical paradise, the development of the building industry as an economical growth stimulator will be researched in this thesis. The building industry in developing countries has proven to be an industry which can stimulate sustainable development. A report by Plessis (2002) on sustainable construction in developing countries has underlined this and even states that construction in developing countries 'provides an opportunity to avoid problems currently experienced in the developed countries'.

The building industry should create employment and by using technologies which stimulate the development on the economical, environmental and social sphere. For the production of building materials, raw materials are needed. Haiti used to be the wealthiest colony of the Caribbean and some say that its agricultural yields have made Paris into the world class city it is today. Nevertheless, the deforestation and soil erosion show that this has changed dramatically and so the building industry should aim at protecting and even expanding the natural capital of Haiti. Efficient resource management should aim at reducing the use of raw materials or promote the use of renewable resources which can regrow.

The produced building products should be focussed on a use within the local Haitian market. The current design of the Haitian houses will thus have to be investigated not only for the application of other building materials, but also to increase the resilience to future disasters. Another problem is the materialization of the house design of the high density urban neighbourhoods of Port-au-Prince, which shows a lack of climate responsiveness.

The goal of the research described in this thesis is to stimulate economic, environmental and social development through a sustainable building industry.

Structure of the thesis

In the next chapter the context of the location of the research will be discussed on the political, economical and environmental historical events (chapter 2). This is crucial in understanding the cultural responses which is embedded in the research. The theory of resilience and sustainability will be delineated by the indicators which define the scope of the research (chapter 3). The research question will be formulated and the objectives for the research described. The research is part of an interrelated research within the platform of Urban Emergencies and this bigger view research will be described in chapter 4. It will focus on the introduction of a sustainable building industry in Haiti to ignite the development. The climate unresponsive houses in Haiti which are present nowadays may be preceded by building typologies that did respond to the local climate. A research into Haiti's building typologies is made in chapter 5. The climate of Haiti has to be analysed to know which thermal passive strategies can be implemented in the design on an urban and house scale level. An analysis of the climate has three layers: macro, meso and micro and will be discussed in chapter 6. The reason why climate responsive building is important is to obtain a comfortable indoor thermal comfort. This will be explained in chapter 7 together with the climate responsiveness of building typologies in similar climatic zones around the world. This chapter will be the end of the research phase. The outcomes of the research will be tested and evaluated through the design.

The design will be described in chapter 8. In a separate chapter, chapter 9, the climate responsiveness of the design will be explained. The design will be materialized with the building products from a database which contains only building products which can possibly be produced in Haiti. The materialization of the design will be explained in chapter 10. The chapter will conclude with the total demand of building products, which is an input for the larger scale, interrelated Urban Emergencies research.

The final chapter will evaluate the design of the thesis with the existing situation and/or an NGO design materialized with cement. Also the conclusions, recommendations and further research will be presented.

Fig. 1.4: The future generation
Source: Author

Fig. 2.0: Topographic road map of Haiti
Source: Rémi Kaupp, through wikimedia

2. CONTEXT: HAITI

Content

About

Haiti has a complex reality which has to be understood in order to be able to have a relevant thesis research and project. This chapter will describe the history of Haiti on the political, economical and natural hazard occurrence from the inhabitation of the Taíno Indians up to the present day situation. At the end of this chapter, the input for the research will be summarized.

2. CONTEXT: HAITI

The structural basis of Haiti's crippling poverty is a direct legacy of slavery and its aftermath (Hallward, 2004).

Haiti or *Ayti* ('mountainous place' in the Arawak language of the Taíno Indians) is known by the general public as a very poor country that has been plagued by political violence for most of its existence as an independent country since 1804. Little do they know that Haiti was once the wealthiest colony of France, the pearl of the Caribbean. Cotton and indigo grew naturally; coffee, cacoa and tobacco were of world class quality and the tobacco leaves grew larger than in any other region of the Americas (Connor, 2003). Than what happened to this country that it got into such a state of despair? Long time political instability can be pointed out as one of the factors. But one can also doubt wether the international aid and involvement has positively influenced Haiti's development. A time line of Haiti's history on major events in politics, economic policy and natural hazards from 1492 - 2011 (fig. 2.3) gives insight into the turbulent history of this country. The chapter will conclude with statistics on the current state of affairs regarding the topographic, economic and demographics of Haiti in comparison to the Dominican Republic and the Netherlands. The purpose is to get an understanding of the contextual (social, economical and environmental) factors influencing the research.

2.1 General history

When Columbus set foot on Haiti in 1492 there were five different kingdoms of indigenous inhabitants on the island of Hispaniola (now: Haiti and the Dominican Republic). The indigenous inhabitants are the Taíno Indians and at the time of Columbus there was a total population of about 1.3 million (Connor, 2003). The Spanish colonized the island and forced the Taíno's to work in their silver mines. In under a decade the Taíno's were either worked to death or they died by European diseases and thus the import of slaves began. Charles V (ruler of the Holy Roman Empire) authorised the importation of 15.000 slaves in 1517. Due to political issues in Europe, the French, with Bertrand d'Orgeron as the appointed governor, eventually became the ruler of Saint-Domingue (west part of Hispaniola) in 1665. The treaty of Ryswick assigned the colony to France in 1697. The French turned Saint-Domingue into an agricultural colony when starting in 1705 with the cultivation of sugar, which was already imported by the Spanish from the Canary Islands, and during the 1760s with coffee production (World History Archives, 1995). In 1685 the king of France, Louis XIV or the Sun King, wrote the Code Noir which defined the conditions of slavery. This book turned slavery into a racial matter and not pure economically any more. Before the book was published, poor whites also worked as slaves at the plantations (Connor, 2003). The people brought in from Africa as slaves, most of them if not all from Guinea, outnumbered the white over 100 to 1 at the plantations (Connor, 2003). The barbaric situation in which the slaves were living and by being seen more as animals than humans by their masters, led to a revolt in 1791. The jealousy by the British and the Spanish over the wealthy colony added up to the conditions that eventually led to the Haitian revolution. This was both a political revolution and a social revolution since this was the first and only time slaves were successful in a revolt. It turned out to be a power struggle between the French, Spanish, British and an army of freed slaves led by Toussaint l'Ouverture. Deception and cooperation between the four parties

Fig. 2.1: Jean Jacques Dessalines
Source: http://www.biography.com/people/jean-jacques-dessalines-9273005

led to the defeat of the colonial powers and the total control of Hispaniola by l'Ouverture. Napoleon was unrelenting and send a new fleat of 30.000 men led by Charles Leclerc to Haiti to regain the power over the colony. He succeeded and l'Ouverture was deported to France where he died in 1803 in imprisonment. Another revolt by the Haitians plus an outbreak of disease amongst the French soldiers, led to the final defeat of the French and the foundation of Haiti as an independent and free country. Jean Jacques Dessalines (fig. 2.1) declared on 1 January 1804 the republic of Ayiti, or Haiti.

In the continuing struggle for power, Dessalines was assassinated on 17 October 1806. The country was then divided in a kingdom in the north directed by Henri I; and a republic in the south directed by Alexandre Pétion, an *homme de couleur*. President Jean Pierre Boyer, also an *homme de couleur* and successor to Pétion, managed to reunify the two parts of St. Domingue and extend control over the western part of the island.

The example of Haiti, an independent country formed by a slave uprise, led slave-dependent Britain, France, and the United States to economically isolate Haiti. This stifled Haiti's economic development, and made the country vulnerable to a variety of forms of economic blackmail that continually drained her treasury. This was the first in a series of external factors contributing to the backward development in Haiti.

In July 1825, King Charles X of France sent a fleet of 14 vessels with troops to try and reconquer the island. Under pressure, President Boyer agreed to a treaty by which France formally recognized the independence of the nation in exchange for a payment of 150 million francs, an indemnity for profits lost from the slave trade, the colony and the loss of soldiers.

2.2 Politics after independence

After losing the support of Haiti's small elite class, Boyer was ousted in 1843. A long succession of coups followed his departure. National authority was disputed by factions of the army, the elite class, and the growing commercial class, increasingly made up of numerous immigrant businessmen: Germans, Americans, French and English.

In 1915 the U.S. Marines occupy Haiti ostensibly to protect their citizens from civil unrest. The occupation lasts until 1934 during which they 'abolished the clause in the constitution that had barred foreigners from owning property in Haiti, took over the National Bank, reorganized the economy to ensure more 'reliable' payments of foreign debt, expropriated land to create their own plantations, and trained a brutal military force whose only victories would be against the Haitian people' (Hallward, 2004). From their actions it seems like there was a lot more involved then just protecting the Haitian people. A period of political conflict and unrest followed untill ex-doctor François Duvalier

Fig. 2.2: The Duvaliers, left Baby Doc and right Papa Doc
Source: REX FEATURES, through http://www.telegraph.co.uk/news/worldnews/centralamericaandthecaribbean/haiti/8264430/Haiti-25-years-on-from-Baby-Doc-Duvalier.html

	POLITICS	ECONOMIC POLICY	NATURAL HAZARDS
before 1492	**Taíno indians** Five kingdoms ruled by a cacique.	Feudal governance system.	
1492	**Spanish colony** Hispaniola discovered by Colombus.	Main economic purpose was the **mining** of silver and gold. Introduction of sugar cane to Haiti.	
1697	**French colony** Treaty of Ryswick formally assigned the colony to France. Renamed to Saint-Domingue.	Shift of economic purpose towards **agriculture**. Colony flourished with the production of	
1791 - 1804	**Haitian revolution** Led by l'Ouverture and Dessalines.	**Semi-feudal** economic system.	
1790s - 1860	Conflict	**Industrial revolution** Manual and animal labour replaced by machine based manufacturing.	
1825	**Boyer signs treaty with France** Loss of support from the Haitian elite resulted in a coup d'etat.	Payment of 150 million Francs. Haiti unable to do so starts borrowing from French banks. Adjusted to 90 million Francs in 1838 to be paid over a period of 30 years.	
1842	Conflict		**at Cap-Haïtien** Death: 10.000 Affected: unknown
1915 - 1934	**US occupation** Trained a brutal military force.	Ensured that foreigners were allowed to own property in Haiti. They took over the National Bank. Reorganized the economy to ensure more 'reliable' payments of foreign debt. Expropriated land to create their own plantations.Transformed the economic system into **semi-capitalism**.	
1935			***Five*** Death: 2.150 Affected: unknown
1954	Conflict		***Hazel*** Death: 1.000 Affected: 250.000
1957	**François Duvalier elected as president** Ruled as a dictator. Papa Doc established his own murderous militia, the Tonton Macoutes. Ruled with the support of the international community. Oppressed his political opponents.		
1963			***Flora*** Death: 5.500 Affected: unknown
1968			**drought** Death: 0 Affected: 210.217
1971	**Jean-François Duvalier inherits the presidency** Baby Doc used Voodoo to intimidate a nation predisposed towards superstitions and with the highest levels of illiteracy and poverty world wide. Fled the country in 1986 to France.		
1974			**drought** Death: 0 Affected: 507.000
1977	Conflict		**drought** Death: 0 Affected: 450.000

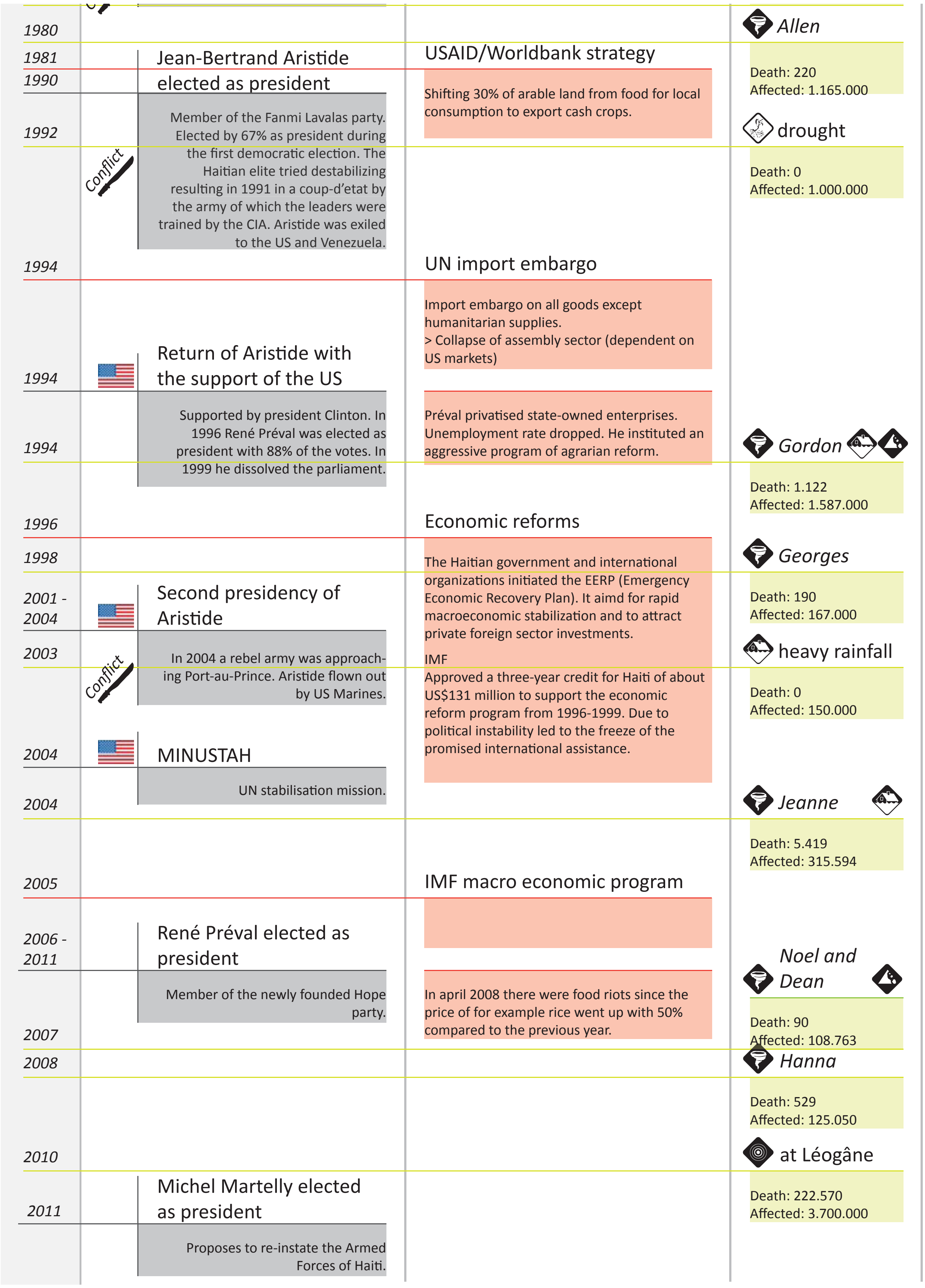


Fig. 2.3: Haiti's history on major events in politics, economic policy and natural hazards from 1492 - 2011.
Source: by author.

(fig. 2.2) won the presidential elections in 1957. He established his own murderous militia: the Tonton Macoutes. During a reign of fourteen years, declaring himself the divine incarnation of the Haitian nation as Papa Doc, he terrorised his people. Throughout his reign he gained international support as an ally against communism, but oppressed his political opponents with violence. After his death in 1971 his son Jean-François, Baby Doc (fig. 2.2), took over and he enjoyed even more enthusiastic foreign support (Hallward, 2004). The Duvalier family dictatorship lasted from 1957 till 1986 and foreign aid and elite corruption soared, but for the mass of Haitians pauperization and political oppression continued undiminished (Hallward, 2004). The very small Haitian elite has had a very big influence on the politics of Haiti which becomes clear when Jean-Bertand Aristide (fig. 2.4) was elected as president in 1990 during the first democratic election. This election was held after Baby Doc fled the country in 1986 in the midst of a popular rebellion against his regime. Aristide was a Catholic priest who was born in poverty and became a man of the people. The Haitian elite, some say strongly supported by the US, tried to destabilize Aristide's government from the beginning on. Chomsky (ZNet, 2004) and a US former official (Aristide and the Endless Revolution, 2005) state that Washington (the US government) 'was appalled by the election of a populist candidate with grass-root constituency'. An observation by Bellegarde-Smith that 'the fear of democracy exists, by definitional necessity, in elite groups who monopolize economic and political power' seems to be true for Haiti, since profitable industries in Haiti are either property of US companies or Haitian elites. Aristide attempted to carry out susbstantial reforms, which brought passionate opposition from Haiti's business and military elite. In September 1991 the army, a left-over from the US occupation supplemented with the FRAPH which was founded by the CIA (ZNet, 2004), performed a coup d'état and Aristide had to flee the country. In 1994 Aristide returns to Haiti with the support of US president Clinton, but on the condition that Aristide adopts the program of the president candidate (a former World Band official) that had lost the 1990 presidential election in Haiti to Aristide (ZNet, 2004).

Fig. 2.4: Jean Bertrand Aristide
Source: Rapadoo Observateur

In 1996 René Préval was democratically elected president with 88% of the votes. He privatised state-owned enterprises and the unemployment rates dropped. In 1999 he dissolved the parliament due to constant conflict with the OPL (Organisation de Peuple en Lutte) in parliament. He did finish his presidential term and resigned in 2001 (presidency is five years in Haiti).

Aristide was elected as president for a second time in 2001. As a legacy from 1994 there was an import embargo which was now reinforced by the US who did not want Aristide in office (Aristide and the Endless Revolution, 2005). However, despite of this economic embargo Aristide was able to accomplish more than the Duvalier dictatorships and all the others in the past: the country went from 34 secondary public schools towards 138, a university was build to educate doctors (there was 1,5 doctor per 11.000 people) and violence rates dropped.

In 2004 there was another coup d'état due to a rebel uprise and Aristide was flown out by US Marines to Africa. There is a lot of speculation about who was behind this rebel uprise. Some claim that the US had armed 'rebels' from the Dominican Republic who than crossed the border and started the uprise. From 2006 - 2011 René Préval was president for a second period. In the aftermath of the earthquake in 2010, Michel Martelly was elected as president and he still holds office today.

2.3 Economical situation

The 150 million francs to be paid as a compensation to France (reduced to 90 million francs in 1838) is probably the most important factor in the establishing of Haiti as a systematically indebted country which 'justified' foreign interventions. Haiti could only make the payment by borrowing money from French banks at extortionate rates (Hallward, 2004). The demand was eventually brought back to 90 million Francs, but it still consumed around 80% of the annual financial budget of Haiti. Some say that this is where the environmental problems of the grand scale deforestation started: 'From French colonizers' coffee and sugar plantations to the swaggering timber industry of the 19th and 20th centuries' (The daily beast, 2010). Haiti tried to pay the debt to France in any possible way. The deforestation has caused severe problems since Haiti is subjected to annual tropical storms which leads to floodings and landslides affecting the Haitian population (fig. 2.3). The largest contributor to the deforestation nowadays is the wood chopping for charcoal, the fuel in Haiti for cooking.

Right after the independence of Haiti, an economical system was adopted where landowners collected a share of the land's produce in exchange for tenancy (World History Archives, 1999), a semi-feudal system. The industrial revolution (1790s-1860s) brought major changes to the world by replacing manual labour or animal labour with machine-based manufacturing. It increased wealth for all and introduced capitalism as an ideology. This all happened on continental Europe and in Haiti the effects were noticed by the eventual change to a semi-capitalist economic system. This system was accompanied by American built factories for the industrial production of sugar (the Hatian American Sugar Company, HASCO) and sisal. The Haitian farmers were driven off their land and forced to work in these factories. The danger to HASCO and other American business interests in Haiti was allegedly one of the factors which led to the U.S. Marine invasion of the country in 1915 and the continued U.S. occupation until 1934. During this occupation laws were adjusted to 'benefit' the economic growth and stability. Concluding we can say that the US turned Haiti into a semi-capitalism economic system to benefit mostly their own economy.

During the dictatorship of the Duvalier family it's estimated that 30.000 Haitians were killed. The US however, continued military and economic aid to this government. It is said that this foreign investment did not bring prosperity to the country, and that poverty even soared. Due to a strategy by USAID and the Worldbank in 1981, the agricultural production of rice was shifted to producing cash crops for the international, mostly American, market.

When Aristide returned to Haiti, after being exiled, in 1994 he had to agree with the implementation of the IMF structural adjustment program. This involved 'further reductions in wages that had already sunk to starvation levels, privatization of the state sector, reorientation of domestic production in favour of cash crops popular in North American supermarkets and the elimination of import tariffs (Hallward, 2004). Haiti used to be self-sufficient in rice production but these economical strategies got the Hatian rice market flooded by subsidized Americain grain (Hallward, 2004 and Unreported World, 2009). Haitian rice farmers were unable to compete and so lost their source of income. In 1985 Haiti imported 7.000 tonnes of rice, in 2002 this rose to 220.000 tonnes. Similar situations occurred within the poultry industry and sugar industry of Haiti. To prevent an agricultural collapse an expansion of the light manufacturing and assembly sector was proposed. In the late 1970s dispite the very low wages (some only 11 cents/hour) and a virtual ban on trade unions it had already resulted in an employment of 60.000 people in this industry with mainly American companies. But at the turn of the century only around 20.000 people were still employed in this industry due to even cheaper labour in southeast Asia (Hallward, 2004).

During the second presidency of Aristide (2001-2004) the country was for the second time in its history completely boycotted by the international community. In 1994 there was already an embargo on the import of goods and this was supplemented by the IMF not paying the promised $131 million to support the economic reform program. Despite the lack of funds, Aristide accomplished quite a lot which was already described in the previous paragraph.

2.4 Haitian building industry

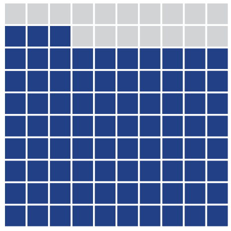
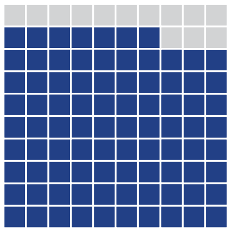
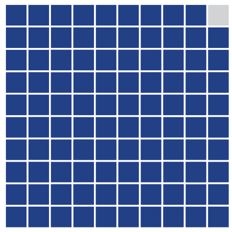
After the earthquake in 2010 it became obvious that the Haitian building code was very ineffective. According to Arup (2010) there are no existing building codes or regulations in Haiti and they propose to use the international standards although they 'assume a degree of sophistication in the construction industry that does not exist in Haiti'. As for the building industry, it follows the same path as the other industries: everything is imported. There used to be a profitable cement industry but during the privatisation of state-owned enterprises in 1994 it became property of probably the Haitian elite. As with the sugar industry, the production was stopped and cheap cement was imported. According to Langenbach (2010), bricks were produced in the area of Port-au-Prince in the early part of the 20th century.

2.5 Statistical data on Haiti and the Netherlands

The events in the past have crippled the Haitian economy to a point where they are completely depended on foreign aid and imports. With an unemployment rate of 41% in 2010 (CIA Worldfactbook), a literacy of only 53% in 2003 and 80% of its population living below the line of poverty (2003 estimate), some top-down strategies should be replaced by bottom-up strategies (wether from the Haitian government as opposed to the international community or the Haitian people themselves).

The demographic data of urbanization in Haiti of the coming years will pose an even greater pressure on the building industry. The creation and implementation of an effective building code is crucial if one wants to prevent another major disaster such as the earthquake in 2010. The lack of a thriving building industry does however also offer opportunities to a revival of the building industry by the possibility of starting the production of sustainable building materials.

The main source of the now following statistical data is the CIA World Factbook.

Demography	**Haiti**			**Dominican Republic**			**the Netherlands**		
Total population (July 2012 estimate)	9.801.664			10.088.598			16.730.632		
Age structure (2011 estimate):	*% of total*	*Male*	*Female*	*% of total*	*Male*	*Female*	*% of total*	*Male*	*Female*
0-14 years	36	1.748.677	1.742.199	29,5	1.493.251	1.441.735	17	1.466.218	1.398.463
15-64 years	60	2.898.251	2.947.272	64	3.251.419	3.120.540	67	5.732.042	5.624.408
65< years	4	170.584	212.949	6,5	300.245	349.458	16	1.141.507	1.484.369
Annual rate of urbaniza-tion [%] (2010-2015 estimate)	3,9			2,1			0,8		
Population urban/rural Rural Urban									
Agricultural population *Source: UN, 2011*	5.984.000			1.142.000			409.000		
Literacy rate [%] (2003 estimate) Definition literacy: age 15 and over that can read and write Illiterate Literate									

Source, if not stated: CIA World Factbook

Environmental	**Haiti**	**Dominican Republic**	**the Netherlands**
Land area [km^2]	27.750	48.670	33.893
Land use (2005):			
Arable land [%]	28,11	22,49	21,96
Permanent crops [%]	11,53	10,26	0,77
Other [%]	60,36	67,25	77,27
Forest area [%] *Source: UN, 2011*	4	41	11
Annual rate of change in forest [%] *Source: UN, 2011*	-0,8	0	0
Climate	Tropical; semiarid where mountains in east cut of traid winds	Tropical maritime; little seasonal temperature variation; seasonal vari-ation in rainfall	Temperate; marine; cool summers and mild winters

Source, if not stated: CIA World Factbook

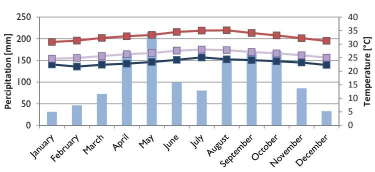


Fig. 2.5: Climate data Port-au-Prince
Source: Moeller, 2011

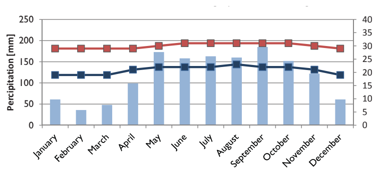


Fig. 2.6: Climate data Santo Domingo
Source: BBC Weather, 2011

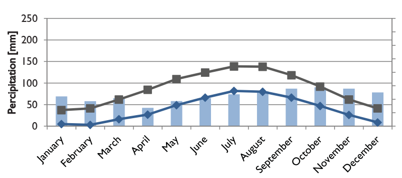
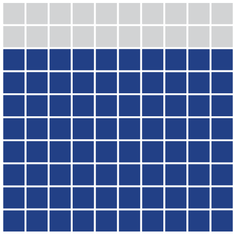


Fig. 2.7: Climate data Rotterdam
Source: KNMI, 2011

Economy	**Haiti**		**Dominican Republic**		**the Netherlands**	
GDP (Gross Domestic Product) [$] (2011 estimate)	12.440.000.000		93.230.000.000		705.700.000.000	
GDP per capita [$] (2011 estimate)	1.200		9.300		42.300	
Population below poverty line [%] (2003 estimate) Above Below						
Labour force (2010)	4.810.000		4.732.000		7.785.000	
Labour force by occupation (2005 estimate):	[%]		[%]		[%]	
Agriculture	38,1		14,6		2	
Industry	11,5		22,3		18	
Services	50,4		63,1		80	
Unemployment rate [%] (2011 estimate)	40,6		13,3		5,2	
Industries	Textiles, sugar refining, flour milling, cement, light assembly based on imported parts		Tourism, sugar processing, ferronickel and gold mining, textiles, cement, tobacco		Agroindustries, metal and engineering products, electrical machinery and equipment, chemicals, petroleum, construction, microelectronics, fishing	
Industrial production growth rate [%] (2011 estimate)	-4,8		1,5		0	
Exports [$] (2011 estimate)	690.300.000		7.792.000.000		576.900.000.000	
Export commodities	Apparel, manufactures, oils, cocoa, mangoes, coffee		Ferronickel, sugar, gold, silver, coffee, cocoa, tobacco, meats, consumer goods		Machinery and equipment, chemicals, fuels; foodstuffs	
Export partners (2010 estimate)	*Country*	*[%]*	*Country*	*[%]*	*Country*	*[%]*
	US	90,2	US	52	Germany	26
	Canada	4	Haiti	13,6	Belgium	13
	France	1,5			France	9,2
					UK	7,7
					Italy	4,9
Imports [$] (2011 estimate)	3.275.000.000		18.380.000.000		514.100.000.000	
Import commodities	Food, manufactured goods, machinery and transport equipment, fuels, raw materials		Foodstuffs, petroleum, cotton and fabrics, chemicals and pharmaceuticals		Machinery and transport equipment, chemicals, fuels, foodstuffs, clothing	
Import partners (2010 estimate)	*Country*	*[%]*	*Country*	*[%]*	*Country*	*[%]*
	US	51	US	44	Germany	15,5
	Dominican Republic	19	Venezuela	7	China	12,6
	China	11	China	6,1	Belgium	8,3
			Mexico	4,9	US	6,8
			Columbia	4,8	UK	6,2
					Russia	5,6
Export - Import [$]	-2.584.700.000		-10.588.000.000		62.800.000.000	

SUMMARY

The problems of Haiti can be summarized and categorized into economical, environmental and social problems. These problems form the motive for the research, but not to all will a solution be sought by the research. The scope of the research will be determined in the next chapter.

Economical problems
• High unemployment
• High illiteracy causes in a low educational level of the labour force
• Low GDP
• Import surplus
• Negative industrial growth rate
• Problems indicate that the imposed plans from the international community for the reform of the Haitian economy are ineffective
• Inactive building industry

Environmental problems
• Very low forest land coverage → deforestation → soil erosion
• Vulnerable to hazards due to an ineffective building code, improper drainage, environmental degradation
• Ineffective building code + urbanization + lack of planning → informal and high density neighbourhoods

Social problems
• Long term political instability

Fig. 2.8: View on coastline, Septieme Gerard
Source: Author

Fig. 2.9: Small scale banana plantation
Source: Author

Fig. 2.10: Rural house made from natural materials
Source: Author

Fig. 2.11: Cement block production
Source: H.C. Janse

Fig. 2.12: Informal urban neighbourhood near the coast
Source: Author

Fig. 2.13: Informal neighbourhood on a hill slope
Source: Author

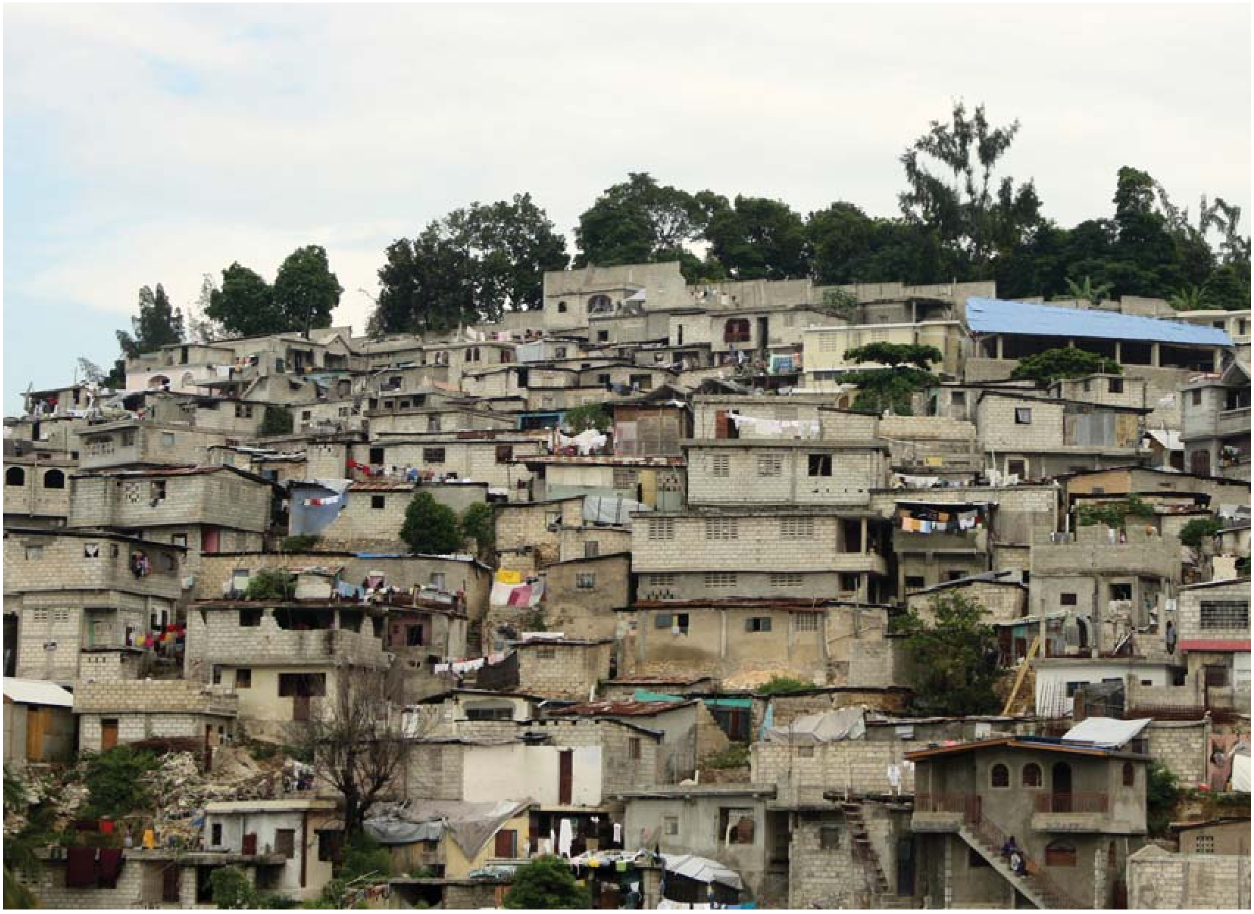
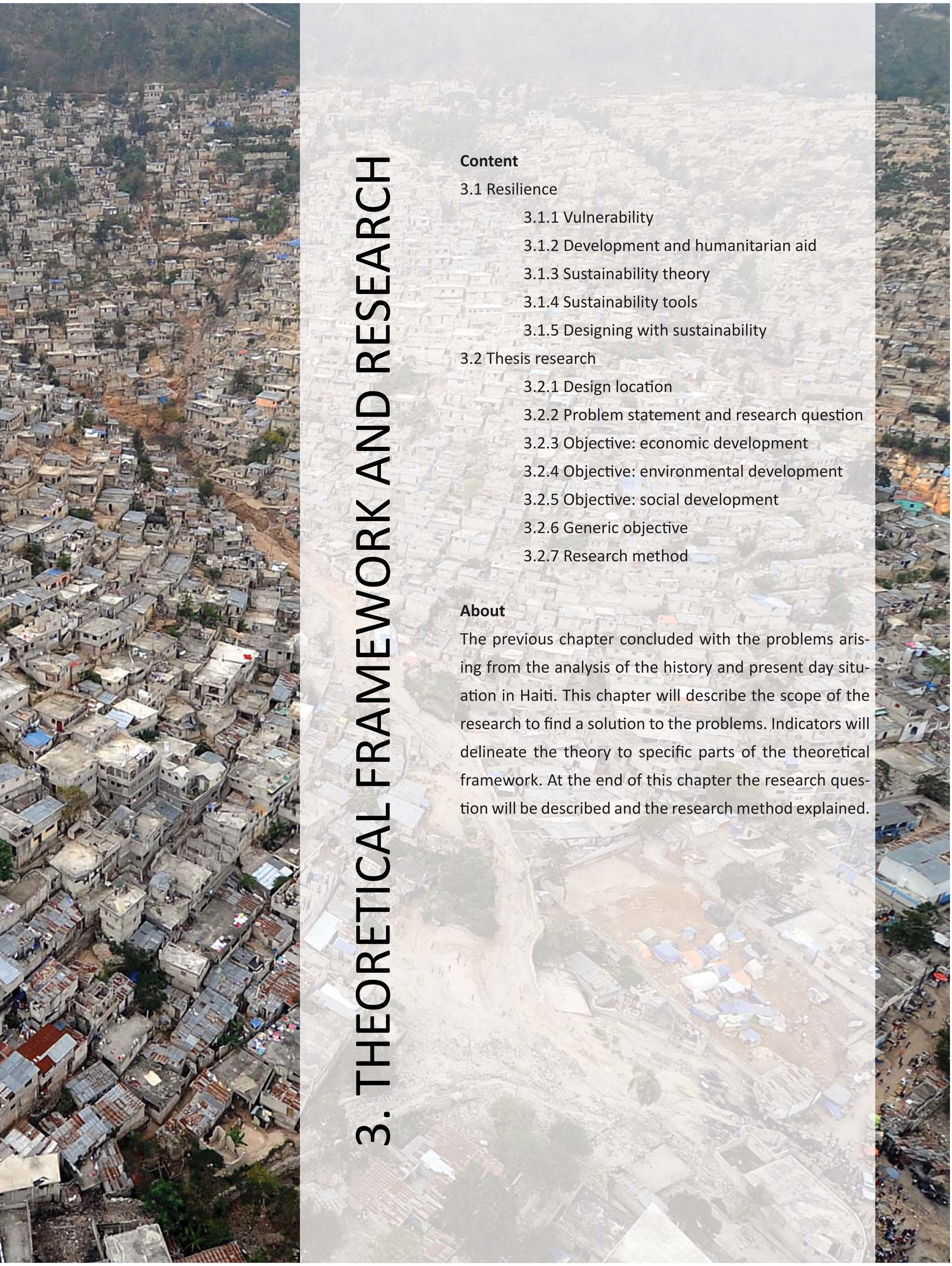


Fig. 2.14: Gingerbread house
Source: Author

Fig. 2.15: Solid waste collection point
Source: Author

Fig. 3.0: Aerial view of Port-au-Prince
Source: US Navy



3. THEORETICAL FRAMEWORK AND RESEARCH

Content

About

The previous chapter concluded with the problems arising from the analysis of the history and present day situation in Haiti. This chapter will describe the scope of the research to find a solution to the problems. Indicators will delineate the theory to specific parts of the theoretical framework. At the end of this chapter the research question will be described and the research method explained.

3. THEORETICAL FRAMEWORK AND RESEARCH

Hazards only become disasters when people's lives and livelihoods are swept away.
-Kofi Annan- (Birkmann, 2006).

The motive for the start of this research was the event and aftermath of the earthquake on January 12 2010 in Haiti. Fig. 3.1 shows the impact of the Léogâne earthquake in the number of casualties against the magnitude juxtaposed with other major earthquakes in the world. Clearly, Haiti was hard hit with a high number of casualties by an earthquake not belonging to the upper regions of the magnitude range. The almost famous and commonly used phrase *earthquakes do not kill people, buildings do* applies to Haiti. Reports by international organizations suggest that the scale of the disaster was a result of 'poor construction and materials, lack of planning and building regulations and a *lack of awareness* that earthquakes were a significant hazard in Haiti' (Arup, 2010). The UN even states that this disaster was 'largely preventable using existing knowledge of seismic activity and expertise in building construction' (Thummarukudy, 2010). From

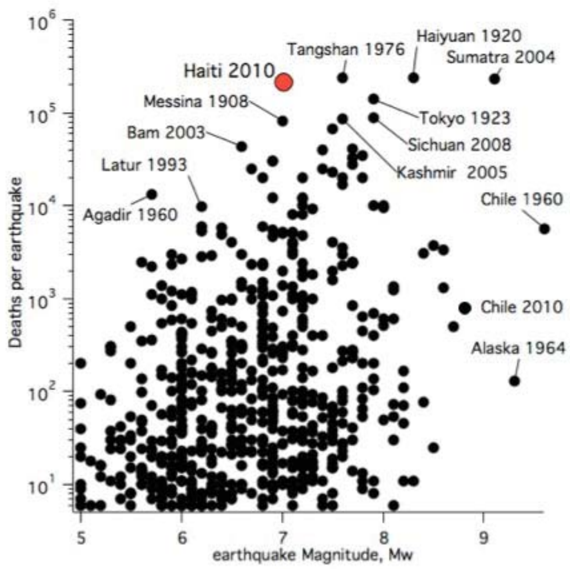


Fig. 3.1: Earthquake magnitude against number of deaths
Source: University of Colorado

findings in the previous chapter we can conclude that this is only the tip of the iceberg which is Haiti's problems. The problems concluded with in chapter 2, cripple the Haitian society and are slowing down development. To these problems a solution has to be found. It is clear that Haiti is in need for a sustainable economic development. Also, if we want to prevent for future (natural) hazards to have the same impact, the Haitian society must become more resilient to them. The lack of awareness described by Arup (2010) shows that an assessment of which risks on hazards are prominent in Haiti, is necessary to make. After the risks are determined, by for instance a risk map, measures can be taken to reduce the vulnerability towards these risks and thus increase the resilience. These measurements can be a strategy, policy or a design for the built environment.

The research in this thesis is embedded in a theoretical framework which is shown in fig. 3.2. The resilience theory is the overarching theory of which sustainability and development aid are part. Humanitarian aid focuses on alleviating the suffering in the short term and has no long-term vision. It is therefore not within the resilience umbrella. Fig. 3.2 also shows the indicators which are research topics within the theoretical framework in this thesis and will be explained later.

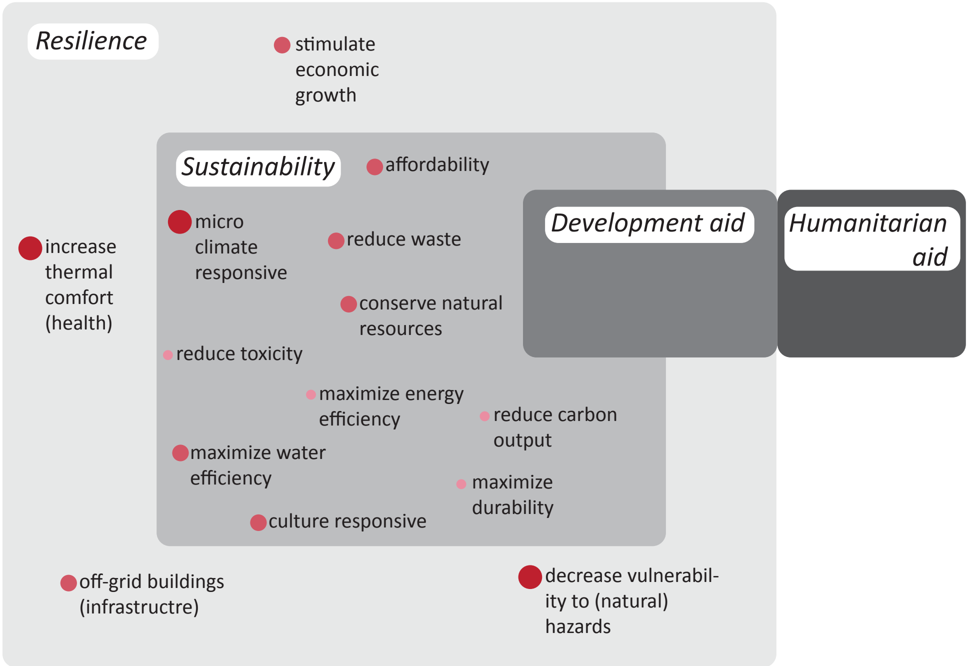


Fig. 3.2: Theoretical framework with main indicators
Source: Author

3.1 Resilience

Boscher and Godschalk state that ‘attaining urban and economic resilience will demand a paradigm shift in the way in which security policy is written and how built environment professionals add risk mitigation measures to their everyday practices’ (Coaffee, 2008). Resilience is defined in various ways, but the general definition is that it describes the ability to return to a reference state or maintain its basic functions after a negative hazardous event (Birkmann, 2006 and Wilbanks, 2007). This ‘hazardous event’, or disaster, can be basically anything that has a negative effect on a functioning system. For instance, if a train breaks down at a track and there is no other available track, other trains cannot pass and thus the system is vulnerable. The time it will take for the system to return to its reference state is as long as the repair of the train will take. If there is another track available this time span to return to the reference state is much shorter and the system is more resilient to the negative effect of a train breakdown. During the Léogâne earthquake the built environment proved to be very low resilient to the risk: the collapse of buildings, the loss of life and a very slow recovery process where international help was much needed.

Obviously, resilience is a very broad theory which can be applied to any system, thus it has to be delineated for the scope of this thesis. The delineation is done by using indicators. Sustainable development of the Haitian building industry and built environment are the main themes of the research and thus the indicators will focus on this.

3.1.1 Vulnerability

The resilience of a system is measured by the vulnerability or coping capacity. As can be found in chapter 2, Haiti has suffered a great deal from the events of natural hazards (fig. 2.3). Due to environmental degradation, secondary effects of these natural hazards have worsened: (annual) tropical storms (hazard) result in landslides and floodings (secondary effects) which can be attributed to the soil degradation because of deforestation. Specific parts of Haiti are vulnerable to the risk of certain natural hazards. But it is not only the natural hazards that Haiti is vulnerable to, also man-made hazards such as an energy crisis or an negative event which causes in the disruption of the infrastructure of drinking water pose a danger. Determining the vulnerability of a community or system combined with the knowledge of hazards is the starting point of disaster risk reduction (DRR) strategy. In this way the outcomes of this research can be used to formulate

policies or guidelines for the design of the built environment. Disasters should be viewed as a 'result of the complex interaction between a potentially damaging physical event and the vulnerability of a society, its infrastructure, economy and environment, which are determined by human behaviour' (Birkmann, 2006).
Vulnerability is used to describe a community's physical, economic, social or political susceptibility to damage as the result of a hazardous event of natural or man-made (anthropogenic) origin (Cardona quoted in Birkmann, 2006). But according to Wisner (2004) the vulnerability are 'the characteristics of a person or group and their capacity to anticipate, cope with, resist and recover from the impact of a natural hazard.' We see that Wisner also takes into account the possibility of a community or area to be resilient towards the hazard. Birkmann (2006) rightfully states that there is no universal definition of vulnerability and that different disciplines have developed their own definitions. These different disciplines have also developed their own framework on how to evaluate vulnerability. Birkmann (2006) has analysed some of these frameworks and this resulted in the development of the BBC conceptual framework (fig. 3.3). The advantage of this framework is that it can be implied without the occurrence of a hazard. It 'takes into account the opportunities to reduce the various vulnerabilities before risk turns into catastrophe' (Birkmann, 2006). The framework consists out of three spheres: social, environmental and economic which is an equivalent of the people, planet, profit for sustainable development. The framework implements the formula:

Risk = Hazard * Vulnerability

The framework 'underlines the need to view vulnerability within a process (dynamic), which means focusing simultaneously on vulnerabilities, coping capacities and potential intervention tools to reduce vulnerabilities (a feedback-loop system)' (Birkmann, 2006). The main focus of the framework is not on a risk assessment, but on the different elements or spheres. In this model we see that a specific change in politics, such as an early warning system, will reduce the vulnerability

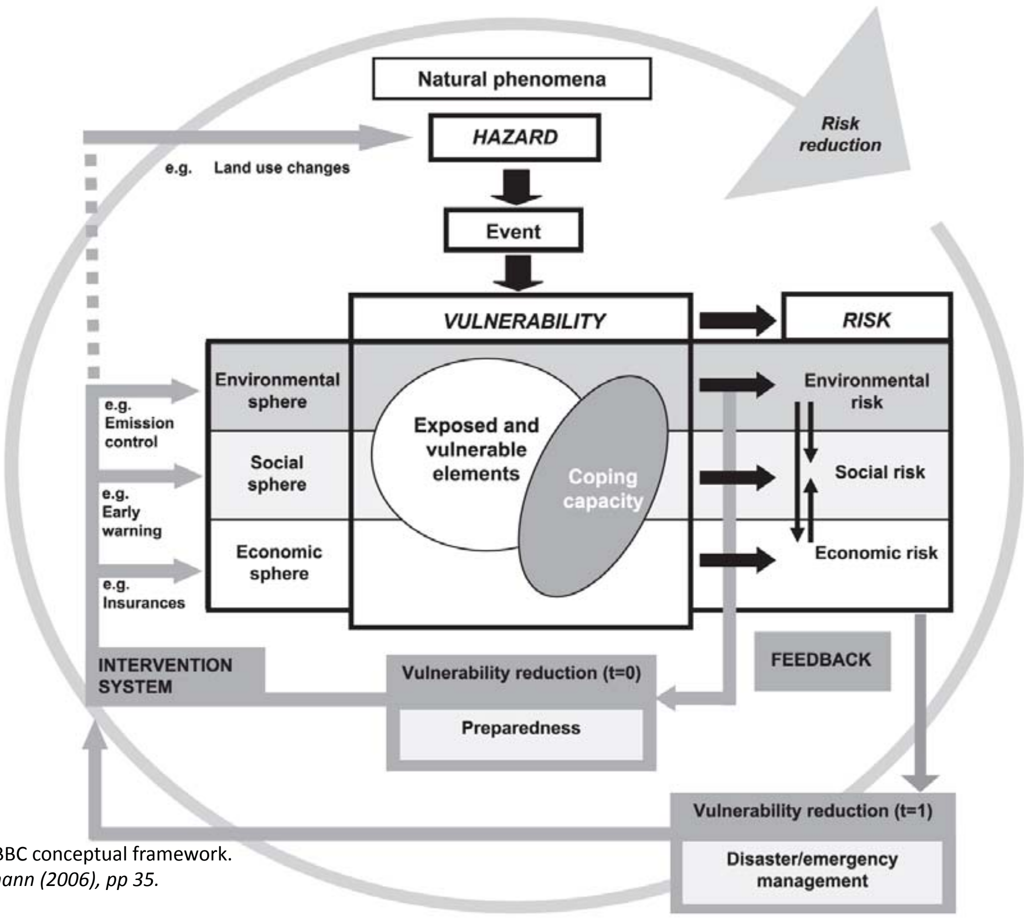


Fig. 3.3: The BBC conceptual framework.
Source: Birkmann (2006), pp 35.

and increase the coping capacity to the risk on a future hazard.
A hazard is defined by the UN/ISDR as a ‘potentially damaging physical event, phenomenon and/or human activity, which may cause the loss of life or injury, property damage, social and economic disruption or environmental degradation (Birkmann, 2006). Natural hazards have been discussed before, but there are also man-made, or anthropogenic, hazards such as sociological hazards (wars, terrorism or civil disorder) and technological hazards (structural collapse or power outage) which can cause in disaster.
To design for mitigating risk, the risk first needs to be known. Risk maps are a powerful spatial tool to visualize the vulnerability to natural hazards of a community or an area. The goal is to improve the resilience of an area by mapping through GIS (Geographic information system) the different risks and combinations of risks. These can be analysed and will provide a guideline for design and for forming policies for development. These maps will not only consist of geographic information, but also social and economical data. The NATHAT (Analysis of Multiple Natural Hazards in Haiti) report (Mora, 2010) aims to guide the actions which give priority ‘to new conditions that create sustainable resilience, in addition to a culture of prevention to ensure the integration of risk management in all future development programs.’ The preliminary results of their research show that the natural hazards with the highest risk on disaster are associated with a high amount of precipitation. But they state that ‘other natural hazards must always be taken into account’ and the ‘vision for risk management should be centred around a multi-hazards situation’ (Mora, 2010).

3.1.2 Development and humanitarian aid

The motive for this research was the Léogâne earthquake that devastated large parts of the capital of Haiti, Port-au-Prince, and the Léogâne area. International aid was already provided before the earthquake by for example the UN, who provids in food aid and a military stabilisation force named MINUSTAH. Fig 3.4 shows the aid in USD per capita in 2007. Haiti is coloured green which means that it received 50-100 per capita. From the statistical data provided in chapter 2 we know that the GDP per capita is $1200 (2011 estimate). This means that the international aid accounts for between 4-8% of the GDP which might be less than expected.
This provided international aid, from before the earthquake, can be labelled as development aid. It is distinguished form humanitarian aid since it is aimed at alleviating poverty in the long term, rather than alleviating suffering in the short term. Religious institutions during the middle ages were the first providers of humanitarian aid to the poor. Modern day humanitarian

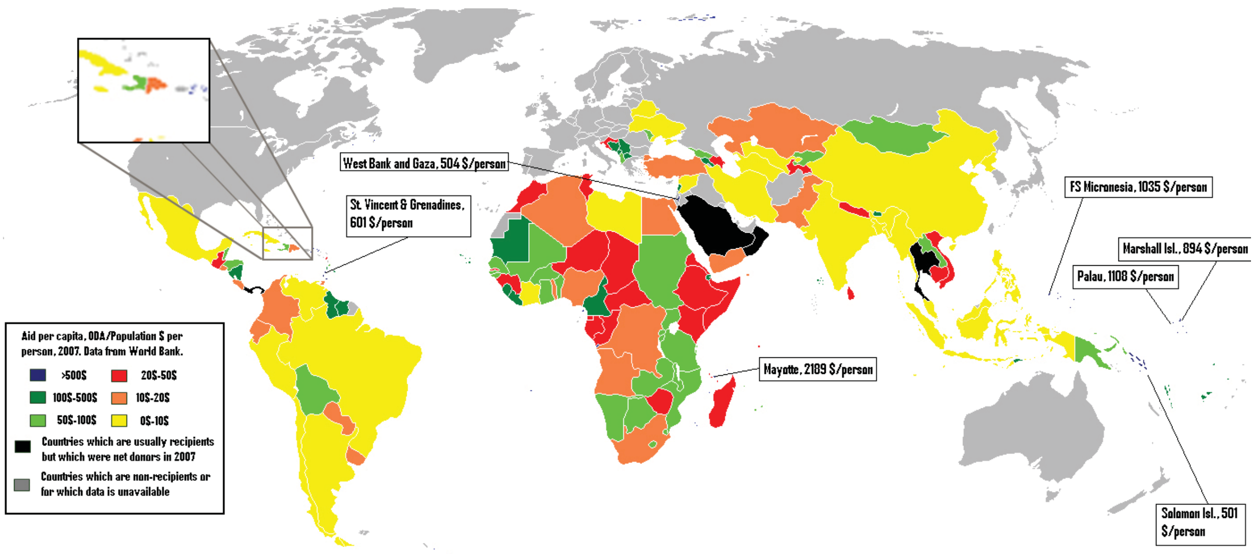


Fig. 3.4: Aid per capita
Source: World Bank

aid had its foundation when Henry Dunant initiated, after witnessing suffering at the battlefield, the establishment of the Red Cross in 1859 (Hilhorst, 2007).

For the rebuilding of Haiti after the earthquake, a group of NGO's, the Red Cross and the Red Crescent Movement have developed the Sphere Project (2011). In this handbook there is a 'set of universal minimum standards in core areas of humanitarian response' contextualized in Haiti. This handbook can be very helpful when determining a set of requirements for the design of the house.
After the earthquake of January 12 2010, NGO's providing humanitarian aid flooded Haiti. After a disaster hits an area the recovery process has the following phases:

Phase 1: Emergency Relief (saves lives)
0-6 months
Phase 2: Rehabilitation (providing essential services)
6 months-2 years
Phase 3: Reconstruction
5 years

Both humanitarian and development aid are involved in the post-disaster recovery process. The first phase is focussing through humanitarian aid on alleviate the suffering on the short-term. During the second and third phase, development aid makes its entry into the process. Development aid seeks to 'financially support the development of underlying socioeconomic factors which may have led to a crisis or emergency'.
The goal of the recovery process is to return to a pre-disaster situation with a higher level of resilience towards future risks. This can be achieved by performing a disaster risk reduction (DRR) assessment to gain knowledge about the vulnerability of a community or area to hazards. Knowing these vulnerabilities policies and plans can be made to address this for development.

3.1.3 Sustainability theory

The UN stated in 2005 that sustainable development, poverty reduction, good governance and disaster risk reduction are mutually supportive objectives (Birkmann, 2006). But what is the definition of sustainable development and how is it achieved?
In 1983 the Brundtland commission was established by the UN to unite countries to pursue sustainable development. In 1987 a report by the commission was published and sustainable development was defined as 'development that meets the needs of the present without compromising the ability to future generations to meet their own needs' (Brundtland Commission, 1987). This is a very noble goal, but the definition lacks an explanation of the process of achieving sustainable development. Redclift (2005) argues that the needs of future generations change, a fact which the word *development* actually also implies, and that different cultures may have different needs. With a world population developing on prosperity, there will be a larger demand for goods and a change in their needs. He states that 'if our objective is the sustainable yield of renewable resources, than sustainable development implies the management of these resources in the interest of the natural capital stock' (Redclift, 2005). So efficient resource management is necessary to meet with the needs of the future generations. If we make sure that resources will stay available for future generations we do not have to question ourselves what their needs will be. Efficient resource management offers corporates a guideline to improve the design of their product and to minimize wastes.
Changing Course by Schmidheiny (1992) has conceptualized the phases through which corporate involvement in the environment had passed: the prevention of polution in the 1970s, measures to encourage self-regulation in the 1980s and a concern to incorporate sustainability into business practices in the 1990s (Redclift, 2005). From then one, the relation with the environment became a central part of corporate governance. In our capitalist world, sustainable initiatives unfortunately only work when they provide in profit. Critics of this corporate 'greening' state that cleaner industries are only a redistribution of risks to other locations and the process is not as transparent as some corporates promote (Redclift, 2005). An example of an allegedly sustainable development is the large-scale cultivation of soybeans in Brazil to produce biodiesel. This cultivation has caused for the logging of 'native

tropical vegetation' or rainforest resulting in massive deforestation, pesticide overuse and slavery (Bickel, 2003). Also, this cultivation of soybeans has ousted other forms of agriculture resulting in a mono-culture.

Sustainability approaches

Starting out as a corporate concept of how to integrate sustainable development, the designers and planners of the built environment have taken over the sustainability approach and adjusted or expanded it. The most important ones will be discussed.

The TBL (Triple Bottom Line) approach tries to find a synergy between the three elements that form the goal of sustainability and was developed by John Elkington. It was developed to integrate sustainability into the business agenda. The triad is defined as *social* (or social equity), *environmental* (or environmental protection) and *economic* (or economic growth). The social element aims on the business practices towards labour and the social impact of the business. Fair trade is an approach that fits in this element of the TBL since it aims to improve trading conditions. The environmental element aims to not harm the environment and/or to diminish the impact. Ecological Footprint, LCA and no ecologically destructive practices (overfishing, depleting of resources) are all tools within this element to evaluate a company or product on the environmental performance. The economic element focuses on the economic impact the organization has on its economic environment.

There have been developed a lot of diagrams that represent the interdependency of the three elements. Fig 3.5 shows two of them where the left one is considered to be weak since it does not show how the three main spheres of sustainability are interrelated. It implies an isolated goal definition for each of the three dimensions, neglecting the linkages between them (Birkmann, 2006). The diagram on the right represents a clear hierarchy and interdependency between the three dimensions and is considered to be the strong representation of the TBL approach.

According to McDonough and Braungart (2002) focusing solely on the triple bottom line 'can obscure opportunities to pursue innovation and create value in the design process.' They aim for a change in the design philosophy and process rather than making an existing product with less materials. The fractal ecology triangle (fig. 3.6) offers a tool to visualize that their approach is not a balancing of the three elements (the TBL approach), but a dynamic interplay to generate value (McDonough, 2002). The fractal honours the needs of all three elements, which they compare with capitalism, socialism and ecologism. They see rich relationships rather than inherent conflicts. This will lead to eco-efficiency where waste = food, sun is the only source of energy and the design is made with respect towards biodiversity. These are the three basic rules of the cradle to cradle principle, also developed by McDonough and Braungart.

Brezet (1997) states that with industrial ecology the focus is on the reuse of waste streams: waste can be a valuable input for another process. This is within the same line of thought with the Cradle to Cradle approach of McDonough and Braungart (2007). Brezet

Fig. 3.5: Triangle of sustainability, the weak (left) and the strong (right)
Source: Elkington

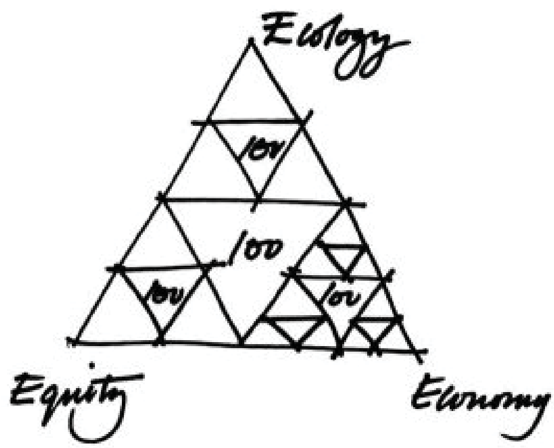


Fig. 3.6: Fractal ecology
Source: Braungart, 2007, pp.

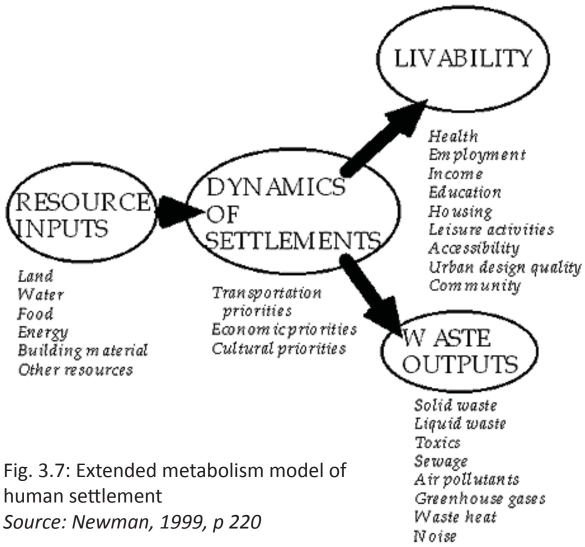


Fig. 3.7: Extended metabolism model of human settlement
Source: Newman, 1999, p 220

focuses on the relevance of ecodesign for businesses. The closing of the cycles of wastes not only has a positive effect on the environment, but can also be an interesting principle for profit-making businesses. For all theories that have the aim to change our way of treating the environment it holds that businesses have to be able to make a financial profit out of it.

While the previous description of an approach towards sustainable development was more focussed on corporate and product design, the approach of urban metabolism focuses on the flows within a city (fig. 3.7). It implies that we should start looking at our cities and their surroundings as ecosystems. An ecosystem is the complex of living organisms, their physical environment, and all their interrelationships in a particular unit of space. To interpret this on our cities, according to Newman (1999) we must find the inputs and outputs, or wastes, of energy and materials and analyse its pathways (flows). Its goal is 'to reduce the city's use of natural resources and production of wastes while simultaneously improving its livability.' We need to close the cycle of resource management and restore the balance and interdependency with nature. The analysis of the pathways of materials in urban metabolism is a material flow analysis (MFA).

3.1.4 Sustainability tools

These approaches towards sustainable development make use of tools that quantify and qualify products on their sustainability. Unfortunately, there is not only one tool that has been developed and used. Spiegel (1999) makes the refreshing remark that 'we are a litigious industry in a scientific society. We like to measure, monitor, assess and label. Green buildings and green building materials are no exception. This decade has seen a veritable flood of green rating systems and assessment tools, each vying for public recognition and industry acceptance. Some of the tools will be described.

The LCA (Life Cycle Analysis) tool analyses a product from cradle to grave and assesses the environmental impacts. It analyses the relevant energy (embodied energy), water, waste and other outputs such as CO_2 emmissions (Rider, 2011) and material input throughout the 'life' cycle of a product.

With more and more companies claiming their products to be sustainable, product certification tools have developed. An example is the FSC (Forest Stewardship Council) forest certification which implies that the wood for timber products is obtained through responsible forest management.

3.1.5 Designing with sustainability

The sustainable development approaches and methods are implemented in the design process. Some of these sustainable design processes will be described.

According to Yeang (2008) we must seek the integration of the built form with their context, using elements of the earth and vegetation in such a way that the built environment appears to be part of the natural environment. By *ecomimesis* we must design our built environment in a way that the materials are continuously reused and recylced. When this is not possible, they must be seamlessly and benignly reintegrated into the natural environmental cycles and processes and not dumped as waste.
Bioclimatic design refocuses on providing high quality passive design of buildings through new technologies in the building envelope and in its form and fabric (Hyde, 2008). One main feature of climate responsive design is to use passive climate control systems rather than rely on active energy systems that consume nonrenewable resources. For its form, inspiration can be

found in vernacular architecture that belongs to regions with similar climatic conditions to the design location. They may contain passive cooling, heating and ventilation strategies that can be applied in modern houses in an urban setting.
From studies it proved that urban settlements around growing cities are adopting a specific style of building which can be found to have aspects of vernacular architecture. Linking bioclimatic design with features of the local vernacular could create a design method for an appropriate domestic architecture for urban settlements (Labaki, 1997).

3.2 Research

Chapter two ended with a summary of a set of problems present in Haiti as input for the research. The first part of this chapter has described the theoretical framework which indicates the solution towards solving the problems. The solution is to make Haiti more resilient to hazards, but the way how to do it is what's important and which will be described in the next chapters. The indicators delineate the theory to those parts relevant to the research. They will be described below.

Resilience Indicators

Indicator: Decrease vulnerability to hazards

When the vulnerability is reduced, the risk on disaster from a hazard will be reduced (outcome of the formula: Risk = Hazard*Vulnerability). To reduce the vulnerability a risk map has to be made for an area to visualize the natural hazards that pose a risk. When knowing which natural hazards pose a risk to an area, the design of the built environment can respond to this.
Reducing the risk on disaster from man-made hazards is more difficult to identify due to nature of the hazard. Some indicators will try to decrease the vulnerability to certain man-made hazards such as an energy crisis.

Indicator: Increase thermal comfort

During the earthquake, the informal high density neighbourhoods of Port-au-Prince (fig. 3.0) were subjected to collapse the most. They are not the slum neighbourhoods near the sea coast, but low-income neighbourhoods that are built on the slope of the spurs of the Massif de la Selle on the south side of Port-au-Prince. As can be seen from fig. 3.0 the predominant building materials are cement for the walls and a roof of CRS of galvanised iron. Considering that the climate of Haiti is hot and humid this is odd and out of place. Cement of a reasonable thickness absorbs heat during the day and will radiate this during the night causing in higher indoor temperatures. Roof sheeting of metal heats up significantly during the day due to direct solar radiation and will increase the indoor air temperature. The building materials applied do not respond to the climatic conditions and worsen the indoor living conditions. But Port-au-Prince is not an exception, the favelas in Rio de Janeiro (fig. 3.8) and the barrios in Caracas (fig. 3.9) show a similar building material use in a similar climate. An increase of thermal comfort will improve the living conditions. The sustainability approach of climate responsive building will be implemented to achieve this.

Fig. 3.8: Favela in Rio de Janeiro
Source: www.ourmaninbrazil.com

Fig. 3.9: Petare barrio in Caracas
Source: http://www.shalomministry.org/venezuela_2011.htm

Indicator: Stimulate economic growth

Due to political instability and a negative influence of some international aid through economic reform programs, local capacity building should be stimulated. This is a bottom-up approach where local and effective institutions are established that encourage investment and economic growth. In Haiti there are already projects with local capacity building that focus on the agricultural sector. For this research, the building industry will be ignited since it has a lot of potential with a growing urban population and hopefully in the future a growing wealth and an increased purchasing power. It has proven to be very powerful in the development process of countries. Haiti now does not have an active building industry and unfortunately building materials are all imported. By proposing sustainable building products, environmental issues will be noted.

Indicator: Off-grid buildings

Mentioned earlier were the difficulties to reduce the vulnerability to man-made hazards due to the unpredictability of the disaster effects. To some the vulnerability can be decreased by an off-grid building design. This implies that the building is independent of the infrastructure of energy (electricity), water and sewage.

Sustainability Indicators

Indicator: Micro climate responsive

To reach the goal of increasing the indoor thermal comfort, the sustainability approach of a climate responsive design will play an important part. The climate has to be researched to understand the factors that play a role in the determination of the indoor thermal comfort. Possible passive thermal strategies that are suitable within the Haitian climate have to be set. Researching other countries with a similar climate can result in climate responsive features for the house design.

Indicator: Maximize water efficiency

Providing in drinking water is becoming a major problem in the world, also in Haiti. Maximizing the water usage efficiency both in the built environment and the building industry will relieve some of the pressure on the system. For the design for the built environment water efficiency is met by using raining water for some purposes. During building material production processes water is used for several reasons. Using less water, or through efficient use, will reduce the pressure on the system and increase the resilience.

Indicator: Culture responsive

The design for the built environment has to be accepted by local population. If it is not accepted the design will not be used to its fullest potential and the resources will be wasted. Research into the needs and wants of the local population is necessary.

Indicator: Affordability

As with the previous indicator, this indicator is contextualized. What is affordable in the Netherlands or even the Dominican Republic is different from that in Haiti. The affordability is closely related to the purchasing power and thus the GDP and economic growth of Haiti.

Indicator: Reduce waste

Reduce, reuse, recycle are the three R's when talking about the reduction of waste. So first, the demand for resources should be reduced, secondly as much as possible products have to be reused and if this is not possible the waste should be recycled. Since we are focussing on the building industry, the production of building materials has to researched on the three R's strategy. Also, at the end of life of a building these three R's play an important role.

Indicator: Conserve natural resources

The importance of efficient resource management and saving the earths resources for our children has been discussed previously. From chapter 2 we know that the natural capital and ecosystems of Haiti have been destroyed for a large part. Conserving the natural resources is thus of great importance. Through sustainable forest management the ecosystem and natural resources will be reserved. Since wood is an important building material research into a combination of both is necessary.

Indicator: Reduce carbon output

Carbon output is one of the main responsible factors that contribute to climate change. It is of great importance to reduce this. However, due to the increasing of the prosperity of the world population and the increasing demand for energy, the CO_2 emissions are increasing. The emissions are, amongst other causes, caused by the burning of fossil fuel due to transportation and the production of building materials. An analysis of the life cycle of building materials will reveal the CO_2 emissions.

Indicator: Reduce toxicity

Reducing toxicity does not need an explanation. Asbestos sheets are a good example of a building material which turned out to be toxic and thus this product is banned in Europe. Toxic components pose a great danger to the health of human beings and ecosystems. Great care should be taken when selecting building materials for the design.

Indicator: Maximize energy efficiency

As with the water efficiency, maximize the energy efficiency will decrease the pressure on the energy system. If this is a system run on fossil fuels it is of even more importance due to the resilience to man-made hazards and the CO_2 emissions. Haiti has high solar radiation values which provide in a change to implement PV panels to provide in energy. Taking into account that the prosperity of the population will increase, so will the energy demand in the future.

Indicator: Maximize durability

The longer a material or building product will last, the lesser resources for new materials are needed. The durability of a product depends on the kind of climate it is exposed to. UV-radiation, moist, fungus, these are only some examples of factors that determine the durability.

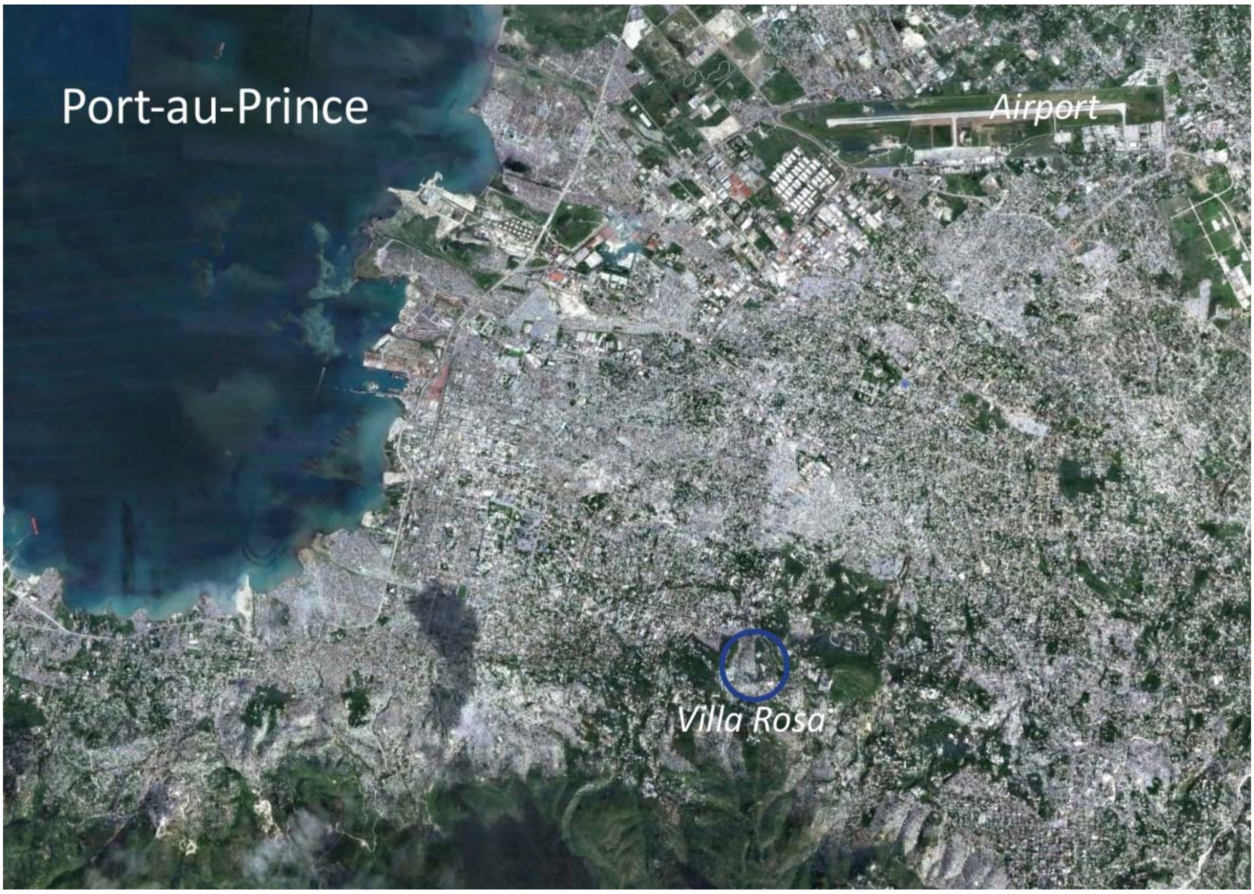


Fig. 3.10: Port-au-Prince, aerial photo with location of Villa Rosa neighbourhood
Source: Google Earth

Fig. 3.11: Villa Rosa, Port-au-Prince
Source: Google earth

3.2.1 Design location

The indicators will direct the research to certain parts of theory. The outcomes of the research have to be tested to answer the question whether the solution to the problems stated in chapter 2 are found. The testing will be done through a design in a high-density urban neighbourhood of Port-au-Prince.

Villa Rosa is such a neighbourhood (fig. 3.10). Due to informal planning, without proper drainage, infrastructure and building typologies, the neighbourhood is vulnerable to natural hazards and thus an ideal case for testing the research outcomes.

During the earthquake in 2010 Villa Rosa suffered severe damage. A part of this neighbourhood, Cite Meriken, will be the location for the implementation of the research into a design. The neighbourhood lies on the border of two cities: Port-au-Prince and Pétionville. The inhabitants have jobs in both cities and they belong to the upper range of the low-income class.

Villa Rosa did not start off as the conrete jungle it is today. During the Duvalier period three families were living on the grounds of Villa Rosa. After the departure of the Duvaliers, these families began to sell plots without the issuing of title deeds (Cordaid, 2011). The neighbourhood in its physical present has only existed for around 30 years.

Villa Rosa 'shares' a spur of the Massif de la Selle with another neighbourhood named St. Maries (fig. 3.11). From the top we see a clearly visual separation between 'concrete jungle' Villa Rosa and the green oase of St. Maries, which is a church community. This separation is a physical wall made of natural stone and cement blocks. Villa Rosa is a pedestrian accessible neighbourhood with only a vehicular road at the top of the hill (access through St. Maries) and at the bottom (connection to Route Canape Vert) which is a dead end road. More information about the neighbourhood will be provided in the design chapter of this thesis.

3.2.2 Problem statement and research question

The political, social and environmental problems of Haiti were summarized at the end of chapter 2. An attempt to solving these problems will be made through this research. The outcomes of the research will be implemented in a design which will be compared and evaluated on the indicators in comparison with the existing situation.

The indicators, which delineated the theory, offer a framework with a direction of solution for the research process. It is clear that the vulnerability of the high density neighbourhoods has to be decreased dramatically to support economic, environmental and social development and to increase the resilience to future natural hazards. Redclift (2005) states that the 'precarious nature of many developing countries, their continued indebtedness and poor governance, have made it difficult to enforce higher environmental standards.' However, in this research a different approach will be researched where the local people are involved.

The research question is:

In the context of urbanized Haiti, can the building industry with a climatically responsive design of the high-density urban neighbourhoods be committed to ignite economical, environmental and social development which increases the resilience towards disasters?

3.2.3 Objective: economic development

Haiti's economic growth has long been at a low level. The objective for the research is to **ignite the economic development through a sustainable building industry**. From the historical context we can conclude that the top-down approach with economic reform programs have not brought the desired economic development since the unemployment rate is still high and 80% of the population is living below the poverty line of $1 per day. Local capacity building is a bottom up strategy which is already implemented for the agricultural sector (TechnoServe, 2009). Local capacity in the building industry can be maximized by producing sustainable building products with locally available raw materials.

3.2.4 Objective: environmental development

Environmental degradation has been the catalyst to some natural phenomena in causing a disaster with the loss of life and soil erosion as an outcome. Deforestation and loss of ecosystems is the catalyst. The

cultivation of crops that benefit the food production and/or serve as raw materials for sustainable building products is the desired approach to stop the environmental degradation and soil erosion. Forest regeneration and sustainable forest management should be implemented to both serve the regeneration of the ecosystems of Haiti and the demand for timber of the building industry. Efficient resource management is a must within the Haitian context since so little resources are available. Also, toxic emissions caused by the building industry should be diminished.
For the built environment the objective is to decrease the vulnerability hazards and increase the resilience to the direct and secondary disasters. An off-grid (no connection to the city infrastructure of energy, water and sewage) housing solution would be the most resilient towards certain natural or man-made hazards. In the case of Haiti this is an objective since it will improve the resilience dramatically.

3.2.5 Objective: social development

A socio-economic objective is to increase the purchasing power and GDP of the Haitians by creating jobs in the building industry. An objective of the climate responsive design for the high density neighbourhood is to increase the thermal indoor comfort and thus the health of the occupant.

3.2.6 Generic objective

The generic objective is to find a solution for the climate unresponsive building materials and typologies that crowd the southern cities in the world that deal with an huge influx of inhabitants (urbanization). Cities such as Port-au-Prince (fig. 3.0), Rio de Janeiro (fig. 3.8) and Caracas (fig. 3.9).

3.2.7 Research method

To answer the research question and structure the research, a research method was developed. The research method is shown in fig. 3.12. This method has actually no specific location so it can be applied to other case studies as well. It is designed to meet the generic objective, but offers also the contextual input for the design. The method consists out of the following steps:

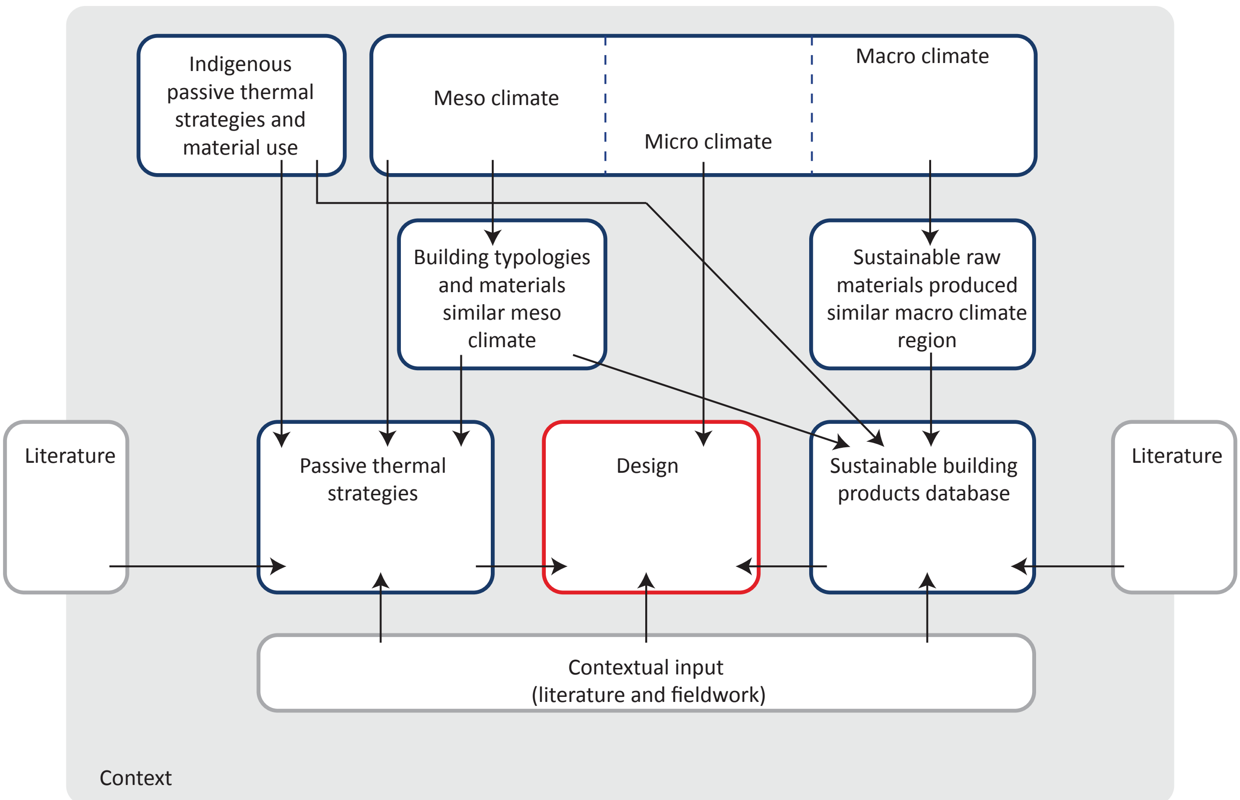


Fig. 3.12: Research method

Indigenous passive thermal strategies and material use (chapter 5)
Through the ages mankind has adjusted its houses to the local climate, the building typologies and material use were climate responsive and built with local materials. It is because of globalization, urbanization, the introduction of mechanical climate control installations and new materials that we seem to have forgotten how to design in consistence with the local climate. Especially in the developing countries, where the tide of industrialization and westernization has swept away traditional architecture (Harman, 1995).
An analysis of the indigenous building typology can provide in passive thermal strategies in accordance with building materials that still suit the climate. If natural hazards occur on this specific location, as is with Haiti, this is an aspect to be analysed for the indigenous typologies and the typologies of similar climatic regions.

Classify the climate (chapter 6)
The climate has generally speaking a constant annual lapse where seasons can be defined and through it a classification can be made. The climatic data of a specific location gives insights into which passive thermal strategies can be applied. The micro climate is a direct input for the design.

Building typologies and materials similar meso climate (chapter 6)
A classification of the meso climate defines a region in the world which shares this same climate characteristics. The building typologies used in the regions may be suitable to modify and use for the design. Therefore, case studies and analysis have to be made.

Sustainable raw materials produced or grown in similar climatic regions (chapter 9)
The production and application into the built environment of sustainable materials around the world is increasing. Raw materials are needed to produce these building products. The raw materials may already be present at a location, but they may also lack. We have to take a look at the production of sustainable materials in similar climatic regions to find suitable options for the production of raw materials. The materials that are grown (renewables, such as wood) in these regions may even help to stop environmental degradation. It is important that when the raw materials are being extracted for building material production, it should never be in such an amount that it will destroy the ecosystems. Sustainable resources management is a must. Agricultural waste is an example of a potential sustainable material that needs processing before it is a building material. Research into other similar potential building materials is relevant to form a database of building products.

Literature
An important source of information is literature. Relevant research and best case practices offer new views on the topics of the research.

Passive thermal strategies (chapter 6)
The output for passive thermal strategies from the indigenous building typologies, the building typologies from similar climatic regions and from literature is combined in a so-called toolbox. This toolbox can be extended throughout the design process and is to feed the design with possible solutions. The meso climate will provide in climatic data which will exclude some passive thermal strategies.

Sustainable building products database (chapter 9)
Some building products (materials) that are used in the indigenous building typologies and typologies from similar climatic regions match the indicators to be included in the database. The database includes, amongst others, the thermal properties and possible usage within the building. There is also input coming from the sustainable building products that can be produced or grown in the surrounding of the location and from literature.

Contextual input (chapter 7)
The context of the design gives input where it is needed and this depends on the design assignment. Specific contextual input can for example be a list of certain demands from a client.

The method described can be applied to any location. However, this does not apply to all design process approaches. The design produced with this method has a strong link with the local climate. It is a climate responsive design where the choice of building materials is very important.

SUMMARY

This chapter described the theory of the scope of the research. The theory of resilience is the overarching theory and under it's umbrella is the sustainability theory. The scope of the research is defined by the indicators which are part of the theory.

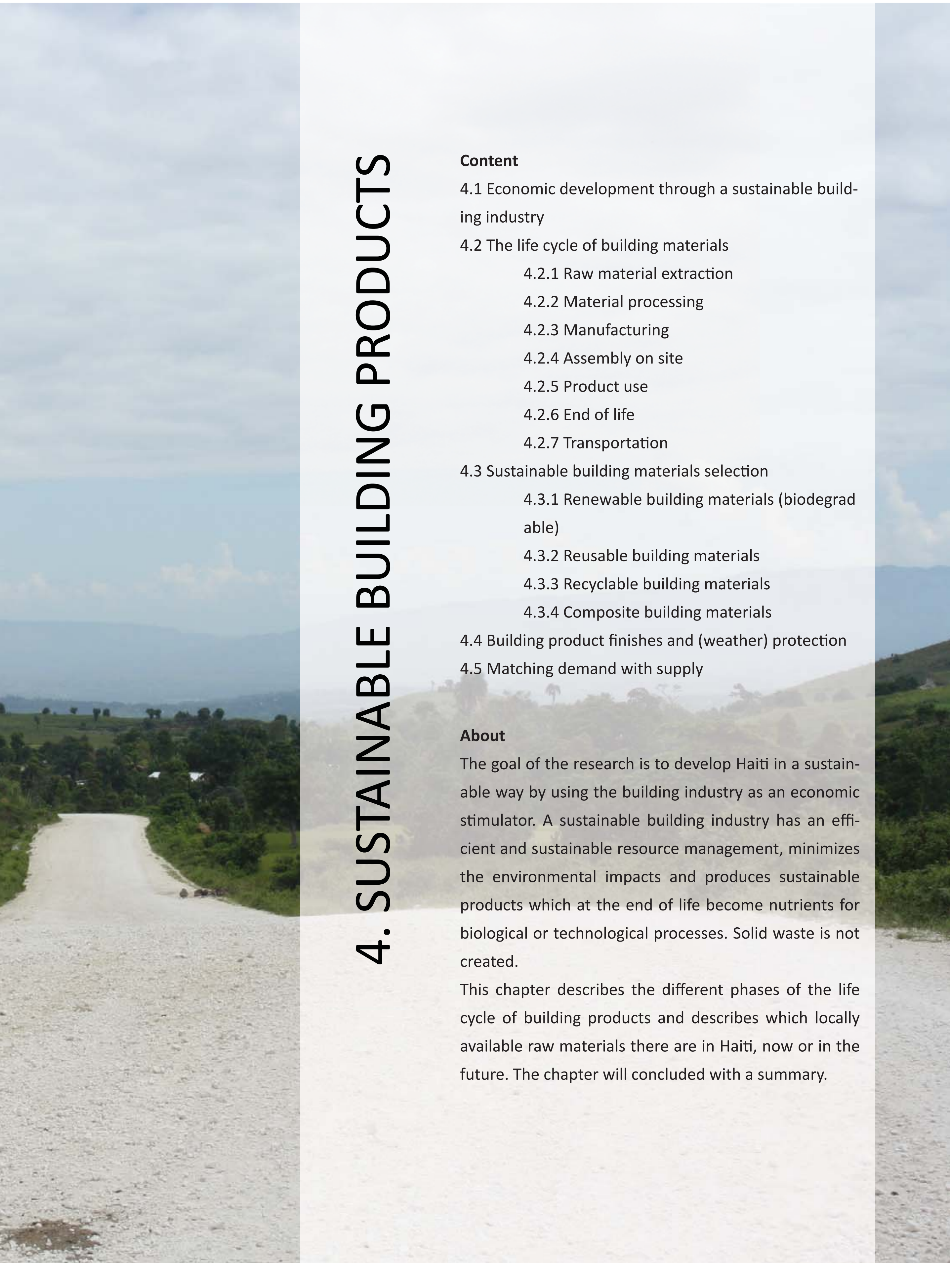
Resilience indicators
• Increase thermal comfort
• Decrease vulnerability to natural hazards
• Off-grid buildings
• Stimulate economic growth

Sustainability indicators
• Micro climate responsive
• Affordability
• Reduce waste
• Conserve natural resources
• Maximize water efficiency
• Culture responsive
• Reduce carbon output
• Reduce toxicity
• Maximize energy efficiency
• Maximize durability

The scope of the thesis and selection of those problems from chapter 2 which will be adressed, have led to the research question.

In the context of urbanized Haiti, can the building industry with a climatically responsive design of the high-density urban neighbourhoods be committed to ignite economical, environmental and social development which increases the resilience towards disasters?

Fig. 4.0: Landscape north of Port-au-Prince
Source: Author



4. SUSTAINABLE BUILDING PRODUCTS

Content

About

The goal of the research is to develop Haiti in a sustainable way by using the building industry as an economic stimulator. A sustainable building industry has an efficient and sustainable resource management, minimizes the environmental impacts and produces sustainable products which at the end of life become nutrients for biological or technological processes. Solid waste is not created.

This chapter describes the different phases of the life cycle of building products and describes which locally available raw materials there are in Haiti, now or in the future. The chapter will concluded with a summary.

4. SUSTAINABLE BUILDING PRODUCTS

"If the industrial development of Europe and America has been rapid, at what rate will not the tropics advance!"
Fry, 1982

The Brundtland commission (1987) defined sustainable development as 'development that meets the needs of the present without compromising the ability to future generations to meet their own needs'. Through sustainable and efficient resource management and the use of renewable energy it is possible to meet this goal. In the ideal situation there is no waste generated during processes except for biodegradable waste.

For the total development of Haiti, and any other country for that matter, the economy (income per capita and purchasing power) should develop first to stimulate other forms of development. With an unemployment rate in Haiti of 41% and illiteracy of 47% (CIA factbook) there is an additional problem, next to unemployment in it self, with the educational level of the labour force. Schumacher (1973) states that 'development does not start with the goods; it starts with people and their *education*, *organisation* and *discipline*. All three must evolve step by step, and the foremost task of development policy must be to speed up this evolution. All three must become the property not merely of a tiny minority, but of the whole society.' Therefore foreign investment in Haiti in a way like a South Korean garment manufacturer is going to do, should be limited. They are creating a 250-hectare industrial park in northern Haiti which will export clothing to the US. The goal is to create 20.000 jobs at the park and another 113.000 through cottage industries (The Associated Press, 2011). According to an article by the Associated Press (2011) critics say that this is not the best way to create jobs, but that it is a beginning. Other companies have preceded the South Korean company and it is questionable whether it was with good intentions for the people of Haiti. These kind of projects should be limited since, amongst other negative aspects, it does not educate the labour force.

The reignition of the Haitian building industry with an efficient and sustainable resource management to stimulate economic development is the goal of this research. The research will try to match Haiti's (potential) quantities of natural resources with the quantity of the building products demand by the building industry and vice versa. The research is part of the Urban Emergencies Haiti studio which has as a goal to link the spatial dimension with the social and economic progression during the search for solutions for the short, mid- and longterm post-disaster development in Haiti. An interrelated project (fig. 7.1) has the goal to develop the Haitian building industry in a sustainable way to stimulate economic growth. The carrying capacity of the Haitian land will be determined and thus the

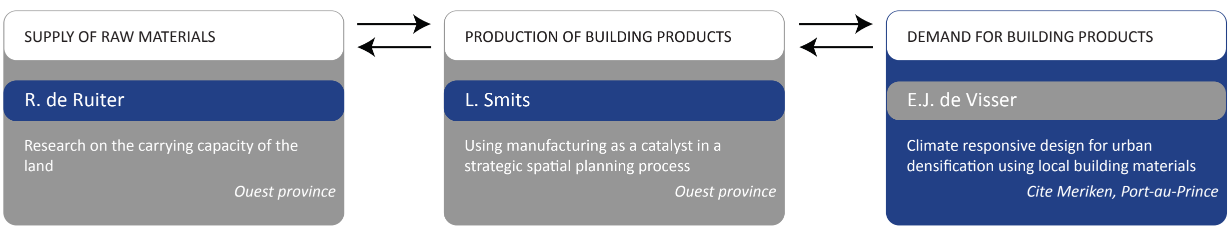


Fig. 4.1: Interrelated research in UE Haiti studio
Source: Author

annual amount of available raw materials for building product production. Due to the environmental problems, sustainable resource management is necessary to restore or protect ecosystems and soil degradation. The side of the demand for building products will be researched and described in this thesis. The place where the demand and supply meet each other is the production place. Different indicators such as population density, raw material production site and accessibility determine the best place for a production place. The result of this interrelated research will be an evaluation of the possibilities for a sustainable building industry in Haiti. Research questions arise, such as: Which building products and thus raw materials have a high potential to be an economic growth stimulator? What will be the environmental impact? Will enough jobs be created to decrease somewhat the unemployment rate? Will the end product be affordable for Haitians? At the end of this thesis the results from the interrelated research will be discussed.

4.1 Economic development through a sustainable building industry

The building industry is one of the most polluting industries in the world, but it offers a great potential for economic growth in developing countries such as Haiti. First some facts about the pollution: in the US, the construction and demolition debris counts for 40% of the total landfill volume. It is calculated that 5% of global CO_2 emissions comes from cement production. It is estimated that of the flows of resources, 50% is directly or indirectly related to the building industry (Dobbelsteen, 2001 after Haas, 1997). This pollution is part of the unsustainable and inefficient resource management of the building industry. To understand where this pollution is coming from we must analyse the system, the life cycle of building products, from start till end. The different stages of the system of the production of building products should be analysed on environmental impact.

A goal of this research is increasing the economic resilience of Haiti to hazards, natural and man-made. From the historical analysis on Haiti (chapter 2) we can conclude that only centralized economic reform programs have been instructed by the international community and/or the Haitian government. Up till now, they have not brought the so desperately needed economic growth. Another approach is in line with the thoughts of a movement emerging during the ‘70s named the Alternative Technology. The movement, of which Fritz Schumacher is a key figure, advocates for more ‘appropriate’ technologies instead of transferring capitally-intense technologies from the industrialized world to the developing world (Smith, 2005). They have developed a vision in reaction to the fundamental problems of the industrial society (fig. 7.2) to bringing about an ecological society (Smith, 2005). The large-scale centralized projects, established by the Haitian government, are opposed to the small-scale decentralized projects proposed by the AT movement. An example of a successful decentralised project is an award winning project in Cuba by CIDEM (Center for Research and Development of Structures and Construction Materials). The project is focussed on developing and implementing technologies to support change at the local level (BSHF, 2012). These changes included a fundamental shift from centralised production based on long-distance transportation, to the local production of building materials in order to reduce energy and transportation costs. Reason for this fundamental shift was the energy crisis in Cuba after the collapse of the Soviet Union. The centralised production of building materials was no longer able to supply a steady stock of building materials which led to a decrease in new housing construction (BSHF, 2012). The project aims through the production of innovative and environmentally sustainable building materials to create jobs

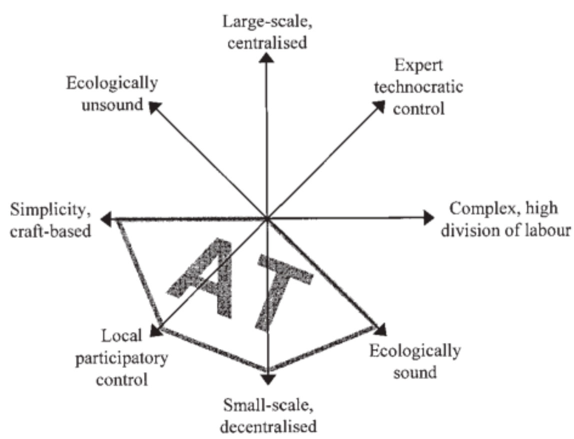


Fig. 4.2: Alternative Technology framework for technology development.
Source: Smith, 2005 pp. 111

and stimulate the building industry. This project has so far resulted in over 5.000 new build or renovated houses using the so-called ecomaterials and created over 200 jobs directly (producing the materials) as well as many others indirectly (BSHF, 2012).

In the context of Haiti there are also other factors that enlarge the need for sustainable resource management of the natural capital. Its longtime wood logging has led to an area land use for forest of only 4% (UN: Rural Population, Development and the Environment, 2011) causing in soil erosion and desertification. In times of heavy rainfall these areas are prone to flooding. Next to these environmental problems, it also means that there is no wood and timber available for the building industry causing in the import of wood. Food insecurity is another major problem affecting Haiti. This can be considered as odd due to the climate of Haiti and the history of being the *Pearl of the Caribbean*.
According to Van den Dobbelsteen (2001) there are three environmental problems which threaten the existence of life: depletion of natural resources, degradation of ecosystems and degradation of the human health. Unfortunately, all are present in Haiti and action has to be taken to stop this threat. Thus the goals for the building industry are:

• Decrease unemployment rate
• Increase educational level
• Producing building materials for the local (national) market
• Decrease food insecurity
• Protection and expansion of Haiti's natural capital

The first three goals are derived from AT theory and the present economical situation of Haiti (chapter 2). The last two are related to the environmental context. Haiti is for the largest part of its food security depending on imports and the environmental problems put a large emphasis on protecting, and expanding when possible, the natural capital of Haiti.

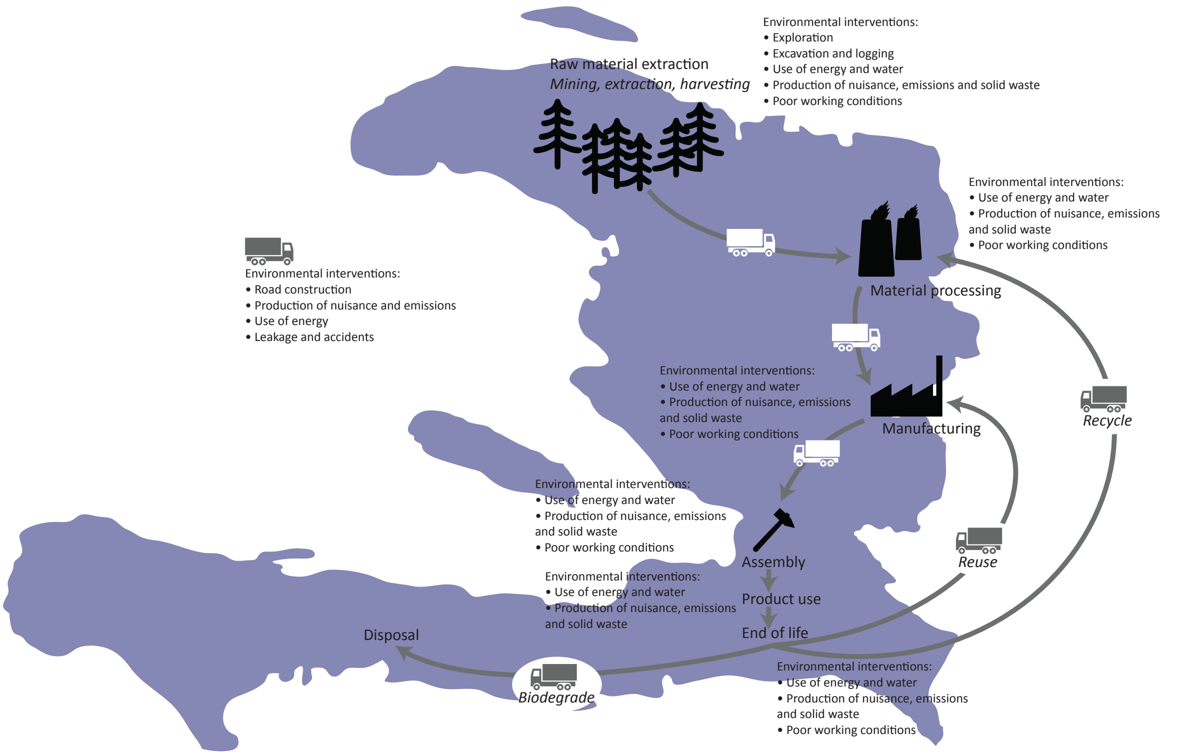


Fig. 4.3: Life cycle of a building material. Note: place indicators on the map are not the actual locations.
Source: After Rider, 2011 pp. 79, modified by the author

4.2 The life cycle of building materials

To understand the factors which influence the environmental, economical and social impact, we need to analyse the life cycle of a building product. First we need an understanding of the different phases involved in the production and after life of a building product with a focus on the environmental impact. The life cycle of a building product is different than that of a building and has a longer time span. For a building the user phase is the most important and longest phase, but for building product the most important is the production and the end of life phase to evaluate the environmental impact.

There has not been consensus amongst literature which environmental impacts belong to what phase, in particular the transportation emissions and the use of energy. Also for the after life of a product, when recycled, it is not determined if the recycle energy input should be attributed to the first product or to the new one. Also, certain companies that produce building materials claim that their product has a negative carbon emission impact. However, they most of the time do not specify as to how they calculated the LCA and which phases they took into account. Full disclosure of the method is most of the time not given and this makes an environmental impact analysis cumbersome. It is therefore necessary to understand what the phases of the life cycle of a building material are to make an own environmental impact analysis. Fig 4.3 shows the life cycle of building materials and their environmental interventions.

4.2.1 Raw material extraction

The cycle starts with the raw material extraction in the form of mining, extraction or harvesting. According to the Bureau des Mines et de l'énergie d'Haïti, Haiti is 'very rich with soil treasures, they just don't know about it'. They state that intense mining is a possible industry. From the economic activity map (fig. 4.4) we can see that there used to be mining of bauxite (aluminium ore) by an American company Reynolds Metals Inc. from 1957-1982 and copper by a Canadian company named SEDREN S.A. from 1960-1971 (VCS Mining LLc, 2011). Due to political issues mining has not made progress for some decades, but recently

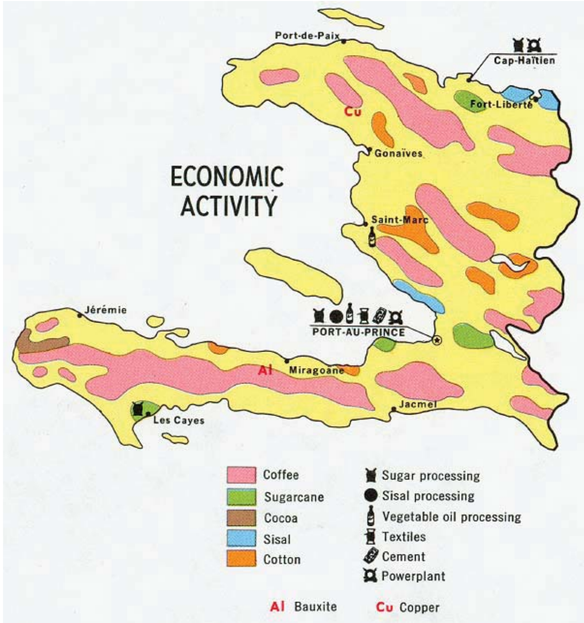


Fig. 4.4: Economic activity Haiti, 1970
Source: Army Geospatial Center

companies were granted permits for mining copper, gold, silver, nickel and PGM (platinum group metals). There are recent studies into silver, calcium carbonate, lignite, marble, jasper and Pozzolane. From the economic data of the neighbouring Dominican Republic we see that ferronickel and gold mining is one of the industries most prominent in the country and thus responsible for some part of the GDP. Haiti could profit from the knowledge of production processes. From fig. 4.4 we clearly see that the crops that made Haiti a wealthy colony were still grown in 1970: cofffee, sugarcane, cocao, sisal and cotton. This indicates that the soil was still nutritious at that time, which was during the Duvalier period.

Raw materials such as clay or salt can be extracted from the soil of Haiti. There have not been found data for the industrial production of these raw materials,

Fig. 4.5: Mud cookies
Source: www.dipity.comredleg82Haiti-Cite-Soleil

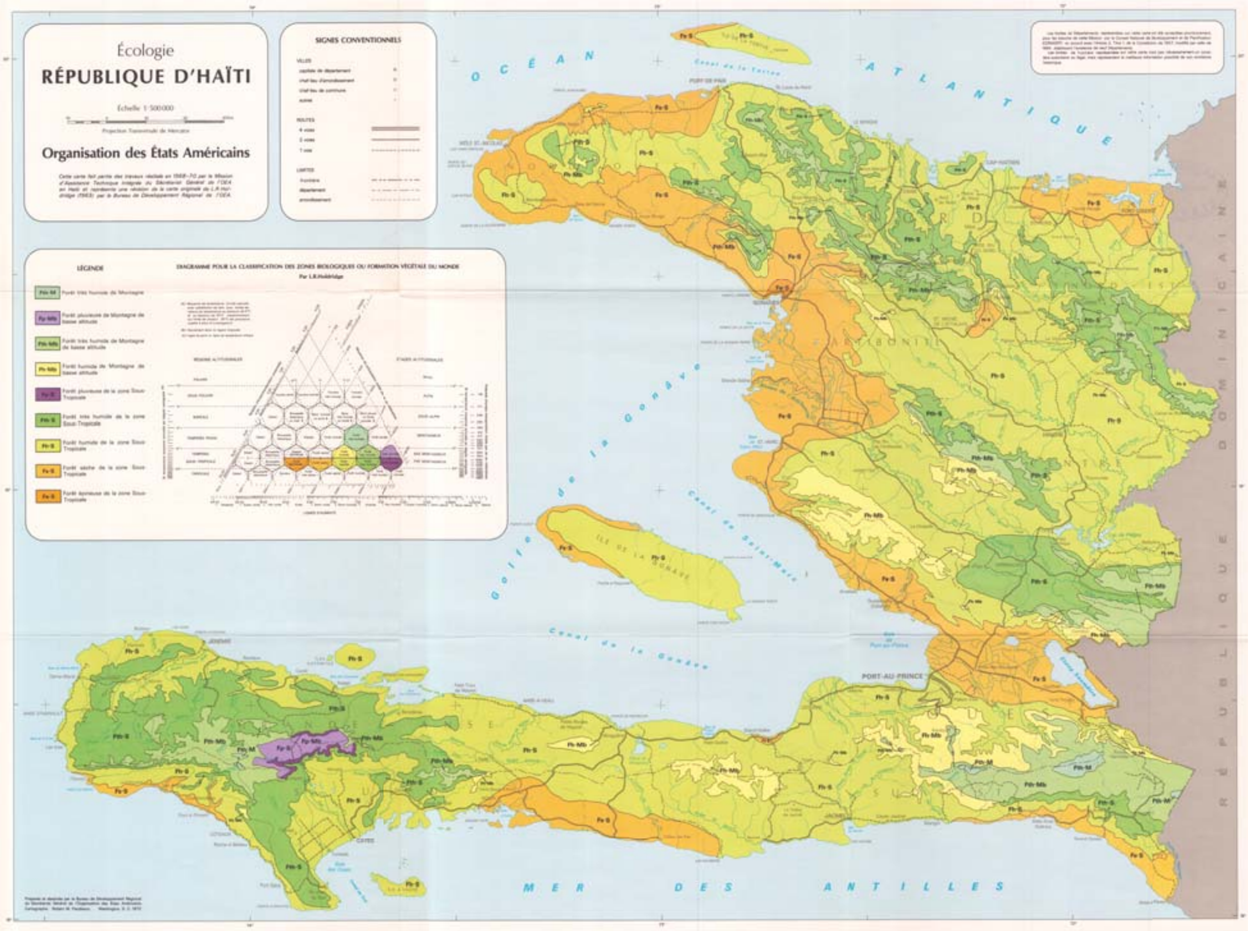


Fig. 4.6: Ecology map Haiti
Source: Army Geospatial Center

but clay is for sure found in Haiti since there have been several reports about very poor Haitians eating so-called mud cakes (fig. 4.5) to stop the hunger (Carrol, 2008).

The mountain ranges of Haiti have modified the macro climate into diverse ecosystems. Forests offer wood that can be used for timber as a building product, but due to heavy logging most of the forest has disappeared. Fig. 4.6 shows the ecology of Haiti with the orange zones being subtropical dry broadleaf forest, light green zones being subtropical moist broadleaf forest, dark green zones being subtropical very moist broadleaf forest and purple zones being subtropical rainforest. This shows that Haiti used to have varied ecosystems with different tree species.

Another potential raw material for the production of building products is agricultural waste. The potential is great since in the first place it produces food and thus helps solving the problem of food insecurity and than from the waste you can create a building material. Waste from crops such as wheat, rice, coconut, sugar cane and corn can be used to manufacture building products.

The environmental impacts during this phase are according to Van den Dobbelsteen (2001):

Environmental impact during the raw material extraction phase	Research
Exploration	No soil degradation (loss of quality and productivity) > crop rotation. No disturbance of existing ecosystems.
Excavation and logging	Sustainable resource management > no depletion of resources but regeneration and/or protection of the natural capital.
Use of energy and water	As low as possible and promotion of the use of renewable energy sources.
Production of nuisance, emissions and solid waste	As low as possible.
Poor working conditions	Fair trade principle with improved trading and working conditions.

The goal of the research is to keep the environmental impacts as low as possible. During this phase, special care should be taken into not depleting the natural resources. Responsible raw material extraction is a must for sustainable development.

4.2.2 Material processing

The raw materials need processing into useful materials for the manufacturing phase. For instance, raw wood has to be sawn into boards and raw ore has to be processed such as molding or casting. To reduce the environmental impact by CO_2 emissions it is best to keep the transportation distances between the raw material extraction and the material processing small. However, it needs to be within the vicinity of several other supporting functions such as a labour force and the manufacturing industries. Smits (2012) deals with these problems in her research.
According to Van den Dobbelsteen (2001) the environmental impacts during material processing are:

Environmental impact during the material processing phase	Research
Use of energy and water	As low as possible and promotion of the use of renewable energy sources.
Production of nuisance, emissions and solid waste	As low as possible. Substitute toxic products/components/processing techniques.
Poor working conditions	Fair trade principle with improved trading and working conditions.

To increase the durability of certain materials measures are taken which are often toxic and thus pose a great danger to the human and environmental health. There are alternative products which can be used to serve the same purpose but do not have the same recognition as the traditional ones. Examples of these kind of components are PBT (Persistent, Bioaccumulative and Toxic) compounds. They do not break down by natural processes and are highly toxic in small quantities (Rider, 2011). Examples are PVC and lead solders. These compounds should be avoided.
The life span without these measurements may be similar to the life span of the building and thus the question should be whether it is even necessary at all.

4.2.3 Manufacturing

Different processed materials are brought together to be manufactured into a building product. This phase resembles the previous phase and thus the environmental impacts are:

Environmental impact during the manufacturing phase	Research
Use of energy and water	As low as possible and promotion of the use of renewable energy sources.
Production of nuisance, emissions and solid waste	As low as possible. Substitute toxic products/components/processing techniques.
Poor working conditions	Fair trade principle with improved trading and working conditions.

4.2.4 Assembly on site

After a building product is finished it is transported to the building site where it becomes part of the building. During the assembly on site, mechanical fastening is preferable to adhesive/solvent welding bearing in mind the future recyclability (Spiegel, 1999) and reusability in the end of life phase.
According to Van den Dobbelsteen (2001) the environmental impacts during the assembly or renovation are:

Environmental impact during the assembly on site phase	Research
Use of energy and water	As low as possible and promotion of the use of renewable energy sources.
Production of nuisance, emissions and solid waste	As low as possible.
Poor working conditions	Working conditions should be monitored by the contractor.

4.2.5 Product use

The use phase has in theory the longest time span. It might happen that a building material fails before the end of life of the building and has to be replaced. Renovation or replacement of the material causes in yet more environmental impacts and increases the use of resources. During the product use phase the indoor air is exposed to the building products which could result in the creation of a bad indoor air quality which can lead to illness. Again, the fact has to be stressed to not implement products which contain VOCs and PBTs. In the appendices is a ‘black list’ of material components that pose a threat to the health of the environment. According to Van den Dobbelsteen (2001) the environmental impacts during the product use phase are:

Environmental impact during the product use phase	Research
Use of energy and water	As low as possible and promotion of the use of renewable energy sources.
Production of nuisance, emissions and solid waste	No toxic emissions, nuisance and solid waste as low as possible.

4.2.6 End of life

The life span of a building is most of the time shorter than the technical life span of a building product (Dobbelsteen, 2001). Therefore, it might be possible to reuse the product as a whole or recycle parts of it. Reusing would result in no solid waste and the product would enter a new life cycle at the manufacturing or assembly phase. If this is not an option, it might be possible to recycle the product into new virgin materials or downcycle the product. If there is no possibility of reusing or recycling of the product it becomes solid waste. If this is the case the product should be biodegradable. Only than the nutrients come back into the biosphere cycle of biological processes and there is a sustainable resource management.

It is possible that the biodegradable waste will serve as biomass (plant material and animal waste) to obtain energy from it.

According to Van den Dobbelsteen (2001) the environmental impacts during the end of life phase are:

Environmental impact during the end of life phase	Research
Use of energy	As low as possible and promotion of the use of renewable energy sources.
Production of nuisance, emissions and solid waste	No toxic emissions, nuisance and solid waste as low as possible.
Poor working conditions	Working conditions should be monitored by the contractor.
Landfill or incineration	Optimise the reuse and recycle of the product. Only biodegradable solid waste.

When having the goal to make sure that all products can be recycled, reused or are biodegradable, the input of the raw materials should be adapted to meet this goal. The building materials should be designed for dismantling and recycling instead of just being consumer goods and at the end landfill volume.

4.2.7 Transportation

Between the phases of the life cycle of a building product there is a need for transportation which has an environmental impact. The distance between the phases of the life cycle determine these environmental impacts which are mainly CO_2 emissions. According to Van den Dobbelsteen (2001) the environmental impacts during the transportation phase are:

Environmental impact during the end of life phase	Research
Use of energy	As low as possible and promotion of the use of renewable energy sources.
Production of nuisance and emissions	Minimize transportation distance and thus CO_2 emissions
Road construction	-
Leakage and accidents	-

The amount of production of carbon emissions (CO_2) through the use of non-renewable energy by for example trucks and ships, is determined by the distance between the life cycle phases. It has long been a common goal of countries to reduce the carbon emissions, but grand scale changes remain unexecuted. By diminishing the transportation distances between the life cycle phases this can be obtained. Rider (2011) underlined that by buying locally manufactured products the carbon impact will be reduced.

4.3 Sustainable building materials selection

By implementing locally produced sustainable building products in the building industry of Haiti the economic growth will be stimulated. Carbon emissions caused by large transportation distances will be reduced. Producing building products with locally available raw materials is a goal of the research. Knowing Haiti's history on environmental degradation this is going to limit the options. When compiling a database with building products that can be locally produced in Haiti the second step will be selecting the appropriate materials for the design. Selection criteria or indicators are defined for the decision making process. These indicators are:

• Availability (no depleting of natural capital)
• Toxicity
• Affordability
• Embodied energy
• Water usage
• Durability (resistivity to UV, moisture and termites)
• Thermal performance
• Mechanical performance

The indicators will be elaborated on in chapter 9.

Affordability is an important indicator and depended on the target group within the context of the design. Wienecke (2010) states that 'in poor communities technological innovations must be inexpensive and minimal of risk. Thus to be relevant, the demand for products must be within the purchasing power of the consumers.' Haiti can overall be considered a poor community and thus affordability is an indicator with much weight to it.

The last two indicators are only expected from specific materials. For instance the mechanical properties apply to those materials used as structural elements. The sustainable building products will be gathered in a database with all the indicators and material properties. The sustainable building materials that will be gathered are found through research in literature and the building industry of countries with a similar climate.

4.3.1 Renewable building materials (biodegradable)

Building products which at the end of life phase will be disposed should be biodegradable. For this building material category, it is important to keep in mind from the beginning of the production process that at the end of life the product should be biodegradable. And thus no toxic chemicals should be added to the product since they pollute the environment. Renewable building materials are biodegradable since they are grown from biosphere nutrients. Rapidly renewable materials are natural, non-petroleum based building materials that have harvest cycles under ten years, examples are bamboo, straw, cork, linoleum, wool and cotton (Rider, 2011).

Wood

As mentioned before, Haiti's forest coverage has declined dramatically to only 4% (UN: Rural Population, Development and the Environment, 2011) of the total land use. A small portion of Haiti (with the highest precipitation values) is tropical rainforest, the other forest used to be dry and moist broadleaf forest (fig. 4.6). In trying to restore the ecosystems (complex set of relationships amongst the vegetation, micro-organisms, water, soil and animals), which have disappeared with the logging of the forest, the indigenous species should be replanted. Reforestation projects are already being implemented in Haiti to increase the resilience to soil erosion and landslides. The Pinus Occidentalis, or Haitian Pine, used to dominate the forests of Haiti. The tree can be found at elevations from sea level up to +1500 [m] and the tree can reach a height of 25-35 [m] (FAO, 2007). The tree is termite resistant, which is very favourable in Haiti. Van Lengen (2007) states that many wood species growing in the humid tropical regions are long-lasting and resistance to insect. A fact which favours the implementation of this wood specie into the design of the built environment to ensure durability. According to the FAO (2007) the annual wood production potential is 5-10 [m^3/ha]. The distribution of the Haitian Pine is very limited which can be seen from fig. 4.7. The research and thus knowledge about this pine is very limited with only one research found by the author in the Dominican Republic. It showed that the mechanical properties, medium strength and medium density, of the pine make the timber appropriate for a structural application (Amarillas, 2012). Due to the very limited distribution, the long growing

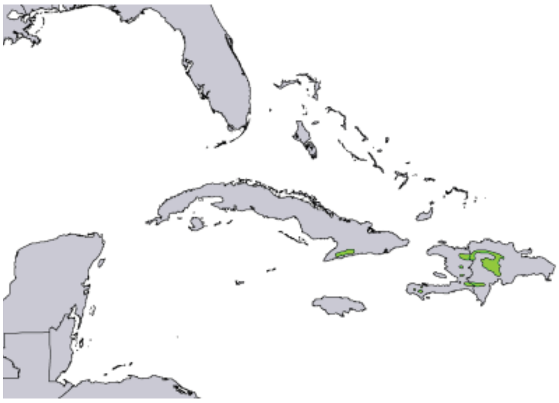


Fig. 4.7: Distribution map of *Pinus Occidentalis*
Source: USGS, after Critchfield and Little (1966)

time (around 25 years) and the need for reforestation it is unlikely to start applying this pine as a structural building material at this moment. However, for the time being, wood can be imported so that the education about building with wood can be started, but only under the condition that reforestation programs and 'plantations' of Haitian Pine are started.

Other applications of wood are fibre boards (MDF and HDF), composite boards, particle boards and plywood. According to Rider (2011) there are two points of attention with wood concerning the environmental impact: formaldehyde is often used as a binding resin and there is a possibility of toxic finishes, coatings and VOCs present in the product. Formaldehyde and Urea Formaldehyde (UF) are substance of glues and adhesives and are carcinogenic. Best option is to use No-added formaldehyde (NAF) of which axamples are MDI (methylene diphenyl isocyanate) and PVA (polyvinyl acetate), but these are still petroleum based. Recent studies into soy-based adhesive technology has promising results (Jang, 2011). It consists mainly out of soy flour and a small amount of a curing agent ECH-NH_3 which can be independent from petrochemicals (Jang, 2011). The soy-flour based resin applied in wood products is not yet available. For now, we have to do with the second best option which is the NAF adhesive.

To increase the durability of wood products there are three primary methods: creosote pressure-treated wood, pentachlorophenol pressure-treated wood and inorganic arsenical pressure-treated wood (Sustainable Sources, 2012). All of the processes involve dangerous chemicals. Research into less toxic processes has led to the use of borates in New-Zealand and Australia (Sustainable Sources, 2012) which offers great protection against insects and also improve the fire retarding. It is unfortunately a new technology and thus costly.

Grass

A renewable building material which is becoming more popular every day is bamboo. It is a very fast growing material and possesses mechanical material properties which makes the material suitable to apply as a structural material. Next to a structural application it is also possible, amongst others, to being implemented as roofing sheets (in a woven structure), flooring and as a particle board.

In Costa Rica, a country in Central America with a similar climate as Haiti, the *Guadua angustifolia* specie of bamboo is being grown on a large scale (Guadua Bamboo, 2012). Results about the yields and mechanical properties are promising and this building material should definitely be taken into account for application into the design. The application of bamboo as a building material for the roof is CBRS (Corrugated bamboo roofing sheets). They are produced by pressing together woven bamboo mats that have been impregnated with an adhesive resin in a pressing machine (fig. 4.8). The main advantages of this technology are: 'environmentally friendly, quieter in the rain, durable with a high resistance to weathering and insect attack (INBAR 2006). INBAR (International Network for Bamboo and Rattan) is providing in a transfer of technology model which focuses on the educational tools.

Fig. 4.8: CBRS producing method
Source: INBAR, 2006, pp. 1

Another raw material belonging to the grass species which has a big potential as a sustainable building material is hemp. The wooden stalk of hemp is used in several compositions of building materials. It is a fast-growing versatile plant which improves the soil, can be grown without pesticides and of which all parts of the plant are usable (not all in the building industry). Legal issues may pose problems to the production of hemp related building products. The versatility of the plant make it also possible to be applied as an insulation material, a fibre board, as a block and as a plaster.

Agricultural waste

Food insecurity is indicated in this research as a problem in Haiti. Producing, as much as possible, building products with as a raw material input agricultural waste, would serve two causes at once. Rice and wheat are two potential crops which can be grown in Haiti and as a waste product has straw which can be used as a raw material for a building product. For example, boards similar to wooden fibreboards but without the formaldehyde are being produced from rice straw.

Another application of wheat straw as a building material is a prefabricated wall element which has a high thermal insulation value (fig. 4.9). Although very suitable as a building material in the more temperate and cold climatic regions of the world, it is not suitable for the Haitian climate which will become more clear during the course of this research.

The coconut is a very versatile crop: the fruit and milk provide in food and as a raw material for building materials the husk, composed out of coir and pith, of the coconut can be used. A wide range of (building) products can be made from the coir: fibre boards, textiles, coir fibre insulation and compressed binderless board. This last product is being developed in the Philippines on a semi industrial scale (van Dam, unknown). The reason that this board can be produced without a binder is the presence of lignin in the coconut pith which acts as a thermosetting binder resin for the coir fibres (van Dam, unknown). If a coconut tree is logged the wood can also be used for timber purposes. This is not desirable since it then loses the main purpose of providing in food.

Fig. 4.9: Concept of straw bale prefab wall element
Source: http://www.modcell.com/concept/

Bio-based plastics

There is no clear consensus about the exact definition of bio-based plastics. By a Working Group for Safer Chemicals and Sustainable Materials bio-based plastics are defined as 'plastics in which 100% of the carbon is derived from renewable agricultural and forestry resources such as corn starch, soybean protein and cellulose' (Alvarez-Chavez, 2011). PLA (polylactic acid or polyactide) is an example of a bio-based plastic made from sugar and finds its application in the packaging industry. This group of sustainable materials has not found its way into the building industry but is very promising. For the context of Haiti and the goals set at the beginning of this chapter, the technology for producing these plastics is to complicated and requires a high educational level.

Earth construction

When reading about implementing local available building material, earth construction is often named. It definitely has great potential, but not for within the context of Haiti. The climate is hot and humid and shows little diurnal variation in temperature. Earth constructions store heat and this is not wanted in a passively climatized house in this climate. For the hot and arid zones around the world, with a high temperature difference between day and night, this type of local material is perfect. Also, the material does not perform well when having to deal with the natural hazards that are present in Haiti.

4.3.2 Reusable building materials

A part of the building materials will still be reusable when the building has reached its end of life since the technical life span of the material probably is longer. It is also possible that the building material will be re-used in a different composition. If a building material is reusable is depending on the durability of the material, but also the way the user treats it during the user period and the way it was assembled on site.

4.3.3 Recyclable building materials

Recycling is the processing of used materials into new products. Well-known examples are glass, paper and plastics. The goal of recycling is to reduce the waste and to reduce the production and consumption of virgin resources. When being in Haiti it is clear that they have a solid waste problem. There is a very poor waste collection system and people most of the time just burn the waste which releases many toxic chemicals into the air.

Certain plastics have the potential to be recycled into a building material. In the Ukraine, resin bonded roof tiles are produced from recycled plastics (30%) and sand (70%). There are even experiments with houses 100% materialized of recycled plastic (BBC News, 2010). A new developed material TPR (Thermo Poly Rock) from recycled plastics and minerals is used as a structural building product.

Due to the collapse of many buildings during the earthquake there is a waste problem of rubble, particularly in Port-au-Prince. Some NGO's have sought for options to recycle the rubble and use for new construction purposes. Because of the low quality of the rubble it cannot be used to produce structural elements such as cement blocks. Recycling options are paving blocks and veranda fenestration.

4.3.4 Composite building materials

Although less bad is not good (Braungart, 2007) it can be the path towards the good. There are many building products which are composed of a sustainable material such as a natural fibre in combination with cement. Especially for the structural building materials there are not yet many 'good' options. Fibres that reinforce cement can be bamboo (roofing sheets), coir (CCCB, Coconut Coir Cement Board) and bagasse. Bagasse is a secondary (waste) product of the processing of sugarcane. It is often used as a biomass source of energy, but can also be used as a raw material for building material purposes.

4.4 Building product finishes and (weather) protection

When building materials are assembled on site onto the building they often receive a finish which can be very unsustainable and even toxic in some cases. Finishes include adhesives (for example the gluing of the floor), caulking or sealing of joints (to mitigate moisture, sound, airflow, fire-stopping), paintings and coatings.

Paints consists out of four components: the binder (the base of paint which can be oil, water or latex), the pigment, the solvent and the filler. There are natural binders for paint which have been used for ages. These include chalk, lime, flour and animal or vegetable glue.

Wood preservation has already been discussed briefly before, but also bamboo and other vegetable building products can get affected by termites. There are non-toxic materials to protect against insect and rot. These are manure, creosote or borax (already discussed at the wood section of this chapter) which can be dissolved in water to facilitate the treatment of wood (Van Lengen, 2007). Other options are whitewash, beeswax or linseed oil.

To prevent insects from affecting the house at the user phase there are also sustainable measures which can be taken (Van Lengen, 2007):

1). Make a mixture of hot peppers, rolling tobacco and cumin. Burn a small amount of the mixture and close the house for a few hours. Eucalyptus incense also works.

2) Around the house, near the walls, grow a garden of plants with fragrances that repel insects such as citronella, basil, common rue and germander.

3) Paint areas with most flies, such as the stable or the kitchen, in blue.

4.5 Matching demand with supply

When the database of sustainable building materials is composed and the design is materialized, the demand for building products can be calculated. Also the carrying capacity of the land (De Ruiter, 2012), which is the supply, and the production capacity (Smits, 2012) will be determined.

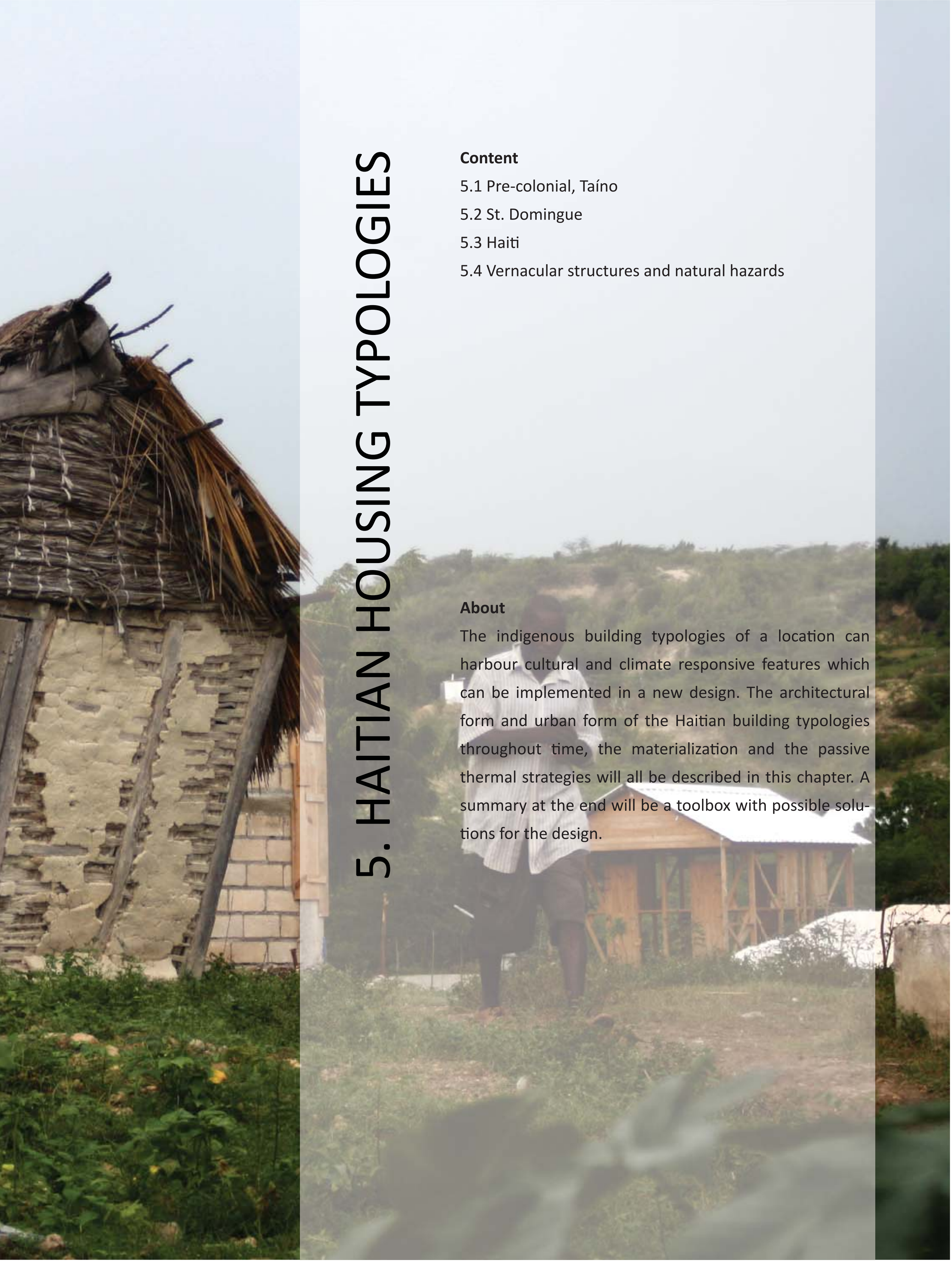
For the calculation of the demand for building products, we have to take into account the future population growth and the urbanization rate.

SUMMARY

The goal of the interrelated research within the platform of Urban Emergencies is to develop a sustainable building industry with a decentralised production of sustainable building products for the local market with local raw materials as resources. Jobs will be created which will stimulate the economic development. For the success of a sustainable building industry the total life cycle of the building material will be researched by the interrelated research. The first step towards a sustainable building industry is selecting raw materials which can be obtained or grown in Haiti.

POSSIBLE LOCAL RAW MATERIAL RESOURCES IN HAITI

Reusable	Recyclable	Renewable
-	• plastic • cement rubble	• rice (food) • hemp • coconut (food) • wheat (food) • bamboo • wood



5. HAITIAN HOUSING TYPOLOGIES

Content

About

The indigenous building typologies of a location can harbour cultural and climate responsive features which can be implemented in a new design. The architectural form and urban form of the Haitian building typologies throughout time, the materialization and the passive thermal strategies will all be described in this chapter. A summary at the end will be a toolbox with possible solutions for the design.

5. HAITIAN HOUSING TYPOLOGIES

Vernacular architecture often represents the result of many years of optimization in relation to the resources of materials and labour, the activities carried out within and around the dwelling, the social organisation of the household and the climate (Evans, 1980)

Indigenous architecture harbours, as the quote above agrees, many years of optimization in relation to the resources of materials and the relation towards the local climate. Knowing Haiti's history (chapter 2), there are architectural influences from the indigenous Taíno Indians, Spanish colonists, French colonists and the African Diaspora (mainly from Guinea). They took with them their architectural styles and cultures and modified them to the local Haitian climate. It can be argued that there is no true Haitian architectural style, or that it is a mix and cross combination of the different cultures that influenced Haiti. The first part of this chapter will elaborate on the different architectural styles of the different historical influences from the Taíno Indians to the African Diaspora. Extra focus will be on the climate responsive building features that respond to the local climate, and also the applied passive thermal strategies.

5.1 Pre-colonial, Taíno

When Columbus arrived at Hispaniola, there were five different kingdoms of Taíno Indians on the island (fig. 5.1). The Taíno society was divided into four elements: the naboria (common people), the nitaíno (sub-chiefs), the bohique (priests/healers) and the cacique (chieftains) (Salmon, 1999). This was a hierarchical society, and while there was only one cacique who was paid a tribute (tax) to oversee the village, there were other levels of sub-chiefs, who were not paid, but did hold positions of honour. They were liable for various services to the village and cacique. The Taíno used two primary architectural styles for their homes. The common people lived in circular buildings with poles providing the primary support (caney). The buildings were covered with woven straw and palm leaves to reflect the solar radiation (fig. 5.2). They housed 10-15 men and their families. The caciques had unique housing which were rectangular and featured a small porch (fig. 5.3). Despite the difference in shape and size, the materialization was similar. The houses did not contain much furniture. People slept in cotton hammocks or on mats made of banana leaves. They also made wooden chairs with woven seats, couches and built cradles for their children (Salmon, 1999). In addition to the houses, the typical Taíno village contained a flat

Fig. 5.1: Map Hispaniola with five kingdoms
Source: By author, based on literature

Fig. 5.2: The caney hut as used by the common Taino
Source: Irving Rouse 1992, through http://jamaicanechoes.wordpress.com/2010/05/05/today-is-taino-day-2010/

Fig. 5.3: The bohio hut as used by the caciques, the chiefs of Taino villages
Source: Irving Rouse 1992, through http://jamaicanechoes.wordpress.com/2010/05/05/today-is-taino-day-2010/

court in the centre of the village which was used for ball games and various festivals, both religious and secular. The houses were built around this court.

5.2 St. Domingue

In 1697 St. Domingue became a French colony. Under the French reign, Cap-François, now Cap-Haïtien and in between also named Cap Français, became the capital of the colony. The city is located at the northern coast of Haiti and was already founded in 1677 by Bertrand d'Ogeron, a Spanish colonist, because of the natural harbour of its location (Crain, 1994). It became the hub of the booming plantation economy of the 18th century. Through sugar, coffee, cotton and indigo the city gained its wealth, which was fed by the African slave trade. By the middle of the century, the city was displaying its wealth through its grand buildings and the fine dress of the colonists, it was the 'Paris of the Antilles' (Crain, 1994).

The city was subjected to repeated fires and earthquakes. Until the devastating fire of 1734, most of the buildings were constructed of vegetal materials and built of posts in the ground, *poteaux-en-terre.* After the fire it was required that the vegetal building materials were replaced by masonry construction (Edwards, 1996).

Fig. 5.4 shows the urban map of the city. Clearly visible is the grid structure of which the origin dates back to antiquity. According to an article by Aurbach (Ped Shed, 2006) a modified form of a castrum (military camp or town) served as the prototype for new cities established in the overseas colonies by the Spanish colonists. King Phillip II of Spain wrote the *Laws of the Indies* in 1573 to guide the construction of these new cities. These laws specified 'a square or rectangular central plaza with eight principal streets running from the plaza's corners' (Ped Shed, 2006).

In 1803 the city was completely burned down by the orders of Toussaint l'Ouverture, since he did not want to see the city fall into French hands (Crain, 1994). However, the grid structure remained and is still clearly visible today in the urban plan of the old part of present-day Cap-Haïtien. This grid structure can also be found in other parts of Haiti, such as Port-au-Prince and Pétionville. Port-au-Prince was founded in 1749 and became the capital of Saint Domingue in 1770. Its plan is based on a grid, with a number of irregular, randomly located streets (Crain, 1994).

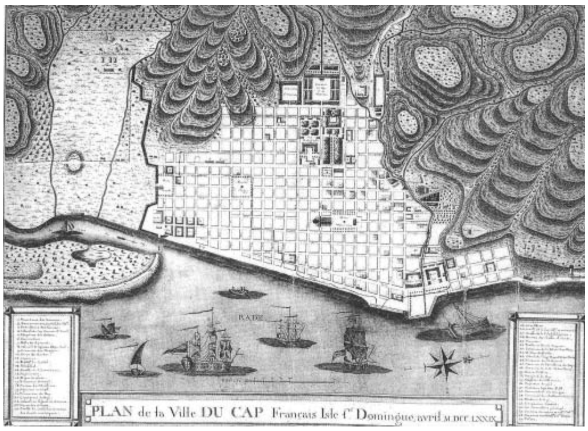


Fig. 5.4: Map of Cap Français in 1779
Source: http://framespa.univ-tlse2.fr/actualites/zelie-navarro-espace-residentiel-et-integration-sociale-le-cas-des-administrateurs-coloniaux-de-saint-domingue-au-xviiie-siecle-38053.kjsp

Fig. 5.5: View on Cap Français
Source: Selve, 1881

Zoom in on left part

On a zoom in on fig. 5.5, a view on Cap Français from 1881, we see a building typology which can be categorized as an urban dwelling. It seems to be either a three storey structure with a pitched roof or a two storey structure of which the top floor has a larger floor to ceiling height than the bottom storey. This last option would harbour the climatic responsive feature of the stack effect if air outlets are provided at the top. The indoor spaces are defined by a shaded veranda indicating a response to the local climate.

The colonization also brought other building typologies to Haiti which were found on the countryside: the plantation houses and their related structures such as the slave houses. The common layout of a plantation is shown in fig. 5.6. The total plantation can be seen as

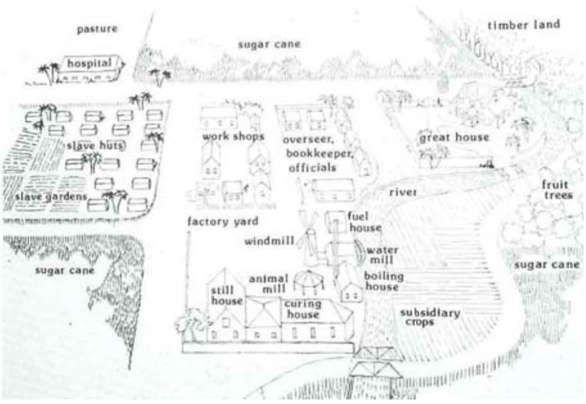


Fig. 5.6: Typical arrangement Caribbean plantation
Source: Crain 1994 pp. 52

a small village with the master's house, the crop fields, the workshops, a hospital, the houses of the overseer and other officials, the slave huts and the buildings where the crops were processed. The slave huts are within a walled part of the plantation grounds. Next to working on the crop fields, the slaves also had to provide in their own food, which they grew within the walled space.
A preserved house of a former plantation owner in Haiti is the Leconte plantation house in Larue (fig. 5.7). Due to the Haitian revolution, most of the former plantation houses have been destroyed and thus this is a unique building for the Haitian architectural body. The Leconte house was constructed using only hand-forged nails and strap iron hinges. Its "briques

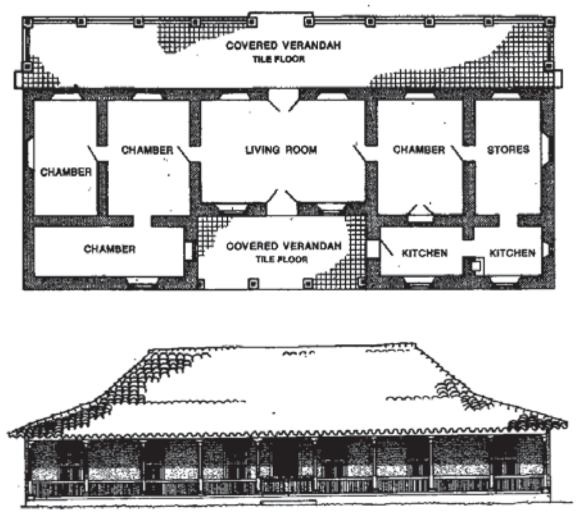


Fig. 5.7: Plan and elevation of Leconte plantation house in Larue build ca. 1760
Source: Edwards, 1996

entre poteaux" walls are supported with classical corner pilasters, similar to the town houses of Cap Haitian (Edwards, 1996). The plan shows a symmetrical layout with a core module, a near-square room in the centre and narrow rooms of equal width on each end. On the front there is a shaded veranda and at the backside of the house there is a veranda which is enclosed on three sides. The house seems to be a product of the import of the architectural style popular in Europe (symmetrical plan, use of pilasters) and a response to the local climate with the addition of the veranda's. Thin Roman style bricks (Edwards, 1996) were used for the walls. The house lacks a proper foundation and it rests directly on the ground.

When the Africans were brought to Haiti as slaves to work at the plantations, they took their architectural language common to their homeland with them. At the plantations they built their own huts, with mud and wattle as primary building materials. Their huts were narrow buildings with gabled entrances, stucco walls, thatched roofs, and shuttered windows so they could enjoy the only privacy allowed to them (fig. 5.8). They wrote African motifs into the exterior framing of their homes to express their culture. This is still found at some rural parts of Haiti (fig. 5.14).
The building typology they used to build their houses descends from West-Africa. It is a two-room house called a *Yoruba*. In Haiti this typology transformed into

Fig. 5.8: Slave quarters at a sugar plantation, St. Domingue early 19th century
Source: http://www.food.com/bb/viewtopic.zsp?t=167952&view=next&sid=689c0c599c3dc813b05b2d498e400c4c

a *Cailles* by adding a front porch (fig. 5.9). During the Haitian Revolution some French colonists together with their slaves fled Haiti to the southern states of the US. In the US this typology transformed into a *Shotgun* house.

Very rarely slaves were able to escape the horrors at the plantation and flee into the mountains were they joined other former slaves and sometimes even Taínos. They lived together in a community system which is called a *Lakou*. It refers to a clusters of homes where the members worked cooperatively and provided for each other with financial and other forms of support (Edmond, 2007). This typology is prominent in Haitian culture and also found, in a way adjusted to the modern times, in the high density urban neighbourhood Villa Rosa in Port-au-Prince. A survey conducted by Cordaid (2011) shows the family bonds within the urban dwelling blocks in the neighbourhood.
The original Lakou system at the rural Haitian areas has changed due to the pressures of increased poverty and landholding fragmentation brought about by the globalization of capitalism. One of the harmful impacts of these changes in the Lakou system is the disruption of parenting. This difficult shift has fallen largely on the shoulders of Haitian mothers. The move from multiple mothering, wherein several women in the Lakou shared in the caring and supervision of young children, to individual mothering, wherein single mothers are now the sole caretakers, constitutes a major social change that needs to be understood within the cultural context of the Haitian framework (Edmond, 2007).

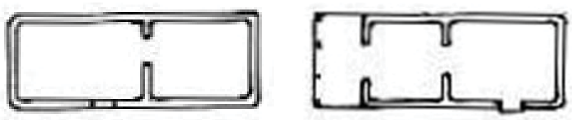


Fig. 5.9: Plan *Yoruba*, left, and *Cailles*, right
Source: North by South, 2011

5.3 Haiti

The availability of wood as a building material was decreasing after the independence due to several factors which are discussed in chapter 2. In 1923, 60% of the land was still covered with forest, in 2006 there was only 2% left (FAOSTAT). The indigenous tree specie, the Haitian pine, was used in an unprocessed way as the structural frame of the houses (fig. 5.10). Wood had always been a main natural source of building materials, but when the availability declined other resources had to be found.

Rural

The rural landscape of Haiti is dominated by houses that vary in style from one region to another. Observations conducted by the author at the rural areas near Léogâne and in urban Port-au-Prince, describe four rural building typologies and three urban building typologies. They are distinct typologies due to a different materialization and/or plan.

Fig. 5.10: Residence frame rural Haiti
Source: Crain 1994, pp. 123

Fig. 5.11: Ti Kay typology at rural Haiti
Source: Author

Fig. 5.12: Cross ventilation in Ti Kay typology
Source: Author

The building typologies found at the rural areas are mainly single-story, two-room houses, usually with a front porch, named the *Ti Kay* (Small house) typology (5.11). Due to the positioning of doors on opposite sides of the indoor spaces, cross ventilation, a passive thermal strategy, is created when both doors are opened (fig. 5.12). Other climate responsive features are the shaded veranda and the stack effect. The stack effect is created due to the pitched roof with shutters placed at the top to exhaust the warm air (fig. 5.14).

A simple building typology found is the *Ajoupas* or wattle and thatch house (5.13). This typology is a single-room house and has a low ceiling height. The building materials used are a thick pack of palm leaves for the roof and a facade of woven sugarcane fibres or wooden strips. This typology probably resembles the slave huts during the colony period.

In the dry, treeless areas, houses are constructed of rock or wattle and daub with mud or lime exteriors. In other regions, walls are made from the native palm; in still other areas, particularly in the south, houses are made of the Haitian pine and other local hardwoods. When the owner can afford it, the outside of a house is painted in an array of pastel colors. Mystic symbols are often painted on the walls, and the awnings are fringed with a colourful hand-carved trimming (fig. 5.14).

When deforestation started affecting the availability of wood as a building material, other resources were found: cement and CRS of galvanised iron. Although more present in the urban areas, there were quite some houses observed by the author at the rural ar-

Fig. 5.13: Ajoupas or Wattle and thatch house at rural Haiti
Source: Crain 1994, pp. 70

Fig. 5.14: Wood carving decoration
Source: Author

Fig. 5.15: Cement house at rural Haiti
Source: Author

Fig. 5.17: Gingerbread house in Port-au-Prince
Source: Author

eas which were made out of cement (blocks). Fig. 5.15 shows a house made of cement blocks with a roof of CRS sheets. The shaded veranda is a feature kept from the more vernacular (non-engineered) building typologies. Clearly visible are the cement blocks which are perforated to promote ventilation.

Urban

After the Haitian revolution, much of the eighteenth-century architecture was destroyed in the urban areas. Mixed occupancy is a characteristic of congested urban areas in Haiti, where residential units occur above commercial spaces (fig. 5.16). Living areas open onto upper balconies, and solid shutters are provided to cover all openings (Crain, 1994).

An unique example of Haitian architecture in the urban context are the Gingerbread houses (fig. 5.17). Haitian architects travelled to France in 1895 to study architecture and when they came back they adapted the French resort style to Haiti's tropical climate (Langenbach, 2010). They are found throughout the whole country, but the largest concentration and finest examples are in a small area southeast of downtown Port-au-Prince. The architectural style is a melange of international influences and is uniquely Haitian. They have a timber frame, filled with brick and adorned with carved wood on the facade and roof banks, high ceilings and large openings onto vast porches.

The houses were designed to take advantage of the airflow and shade but to exclude precipitation. The large windows and doors opposite of the indoor rooms provide in cross-ventilation. Because of the high ceilings, the warm air can rise without affecting the indoor thermal comfort and it will be exhausted by the shutters (fig. 5.18). This typology is very valuable since it is the only true Haitian architectural typology which is not found anywhere else in the world.

In 1925 the style of gingerbread houses came to an end when the mayor ordered all buildings to be made of masonry, reinforced concrete, or iron to prevent fire from causing a disaster. (Langenbach, 2010).

Fig. 5.16: Mixed-occupancy urban building, Cap-Haïtien
Source: Crain 1994, pp. 90

Fig. 5.18: Indoor of a Gingerbread house in Port-au-Prince
Source: William Daniels / Panos for TIME

This decision by the major has opened the way for a materialization of cement. In combination with massive urbanization and a lack of planning and building code this has led to the experience of Port-au-Prince as being a concrete jungle city (fig. 3.0). The introduction of cement without proper building codes have eventually led to, amongst some other causes, the catastrophic disaster of the earthquake in 2010 and the high number of casualties.

The cement blocks are produced mostly on site where the cement is mixed with sand and water. There are rumours that the cement for a large part has sometimes been replaced with limestone and so decreased the mechanical properties of the cement blocks. CRS of galvanised iron is currently the most used roofing material, although some examples of slate roofs still exist (Crain, 1994).

In the less wealthy, as opposed to the neighbourhood of the Gingerbread houses, and high density urban neighbourhoods of Port-au-Prince, there were two building typologies observed by the author: the cement typology (fig. 5.19) and the CRS typology (fig. 5.20). Within the cement typology there are variants observed between those with a (reinforced) concrete structure and those without. Also, some did have reinforced concrete columns but were lacking a ring beam. Probably due to the fact that population densities are high, the veranda or porch was not observed very often as a climate responsive feature. Almost all houses did have cement ventilation bricks (fig. 5.19). These bricks promote indoor ventilation, but they do disrupt the structure for the distribution of the vertical loads.

The high density of the houses is projected on the space left for the transportation zone. Fig. 5.21 shows two types of streets in the high density neighbourhood of Villa Rosa in Port-au-Prince. The main street picture shows a seamstress working on the street since she either has no space in her house to work or it is too hot inside. So an already narrow street profile will become even narrower due to the inability of the houses to provide in enough floor space for the activities of the inhabitants.

Fig. 5.19: Promotion of ventilation in the cement block houses, Villa Rosa, Port-au-Prince
Source: Author

Fig. 5.20: The CRS house, Villa Rosa, Port-au-Prince
Source: Author

5.4 Vernacular structures and natural hazards

Vernacular structures are non-engineered structures and are the result of 'ancient traditions, improved with time as a response to the requirements of their social and physical environment' (Gutierrez, 2004). In the context of Haiti this also means the ability to cope with natural hazards. Earthquakes and tropical storms have always been present in Haiti. Due to the environmental degradation, also floodings and landslides occur in some areas. To withstand the forces of the earthquakes and tropical storms, the vernacular structures might have specific features.

The Gingerbread houses in Port-au-Prince nearly all survived the earthquake. Only 5% partially or totally collapsed (Katz, 2011). The wooden structure has the ability to withstand the earthquake forces due to the mechanical properties of wood and the structural system (fig. 5.22). Olsen Jean Julien, the former minister of culture, states that "Their (the Gingerbreads) architecture shows us that the people who built them had

Fig. 5.21: Street profiles Villa Rosa, on the left the main street and on the right a secondary street
Source: Author

the memory of hurricanes and the first earthquake in 1770. They respected seismic codes even before they had been written” (Katz, 2011).

The engineered structures elsewhere in the world , such as Japan, have the most inventive features to withstand the forces of earthquakes. For this thesis a solution has to be sought which is affordable. Gutierrez (2004) states that there are six basic principles that have proven desirable for earthquake resistance: proper site selection, lightness, high quality and well protected materials, proper structural layout and proportions, structural integrity and shaking isolation. Low cost base isolation places sand or palm leaves between the supporting soil and construction foundation.

A summary of the history of Haiti’s urban plans, building typologies, climate responses and building materials is shown in fig. 5.24.

Urban form

Communal living in both the urban form and the building typology of the house was the way the Taíno’s lived. Columbus took with him a new form of commu-

Fig. 5.22:Gingerbread house next to a collapsed concrete house
Source: Langenbach, 2010, pp. 40

nal living: a city. The grid was introduced as a tool to structure the city and new building typologies such as buildings for governmental functions made their entry. At the rural areas during the colony period, similarities can be found between the Taíno way of communal living and the plantation. Although the slaves were forced to live this way, the 'common' people were both obliged to pay the cacique or master.
The maroons, runaway slaves, and some scarce Taíno's that survived the horrors started living in the mountains and adopted a different kind of communal living named a Lakou. In a Lakou the families work cooperatively and provide for each other in financial but also in other ways of support.
After the independence the cities grew larger to the present day situation were Port-au-Prince has a population of over one million.

Architectural form

The Taíno's lived with around 10-15 families in one house, which was a circular hut. The cacique was an exception to this architectural form and had a rectangular shaped house.
During the colonization period, urban houses with a second storey can be found on old paintings of Cap-Haitien. The slave huts and plantation houses are two other architectural forms that came with the colonization. The slave huts bare resemblance to the Ajoupas typology found nowadays at the rural areas of Haiti. The building typologies at the rural areas of Haiti are most of the time still built with natural and local materials.

Materialization

The Taíno's used natural and local building materials to built their houses. The colonization brought a new building material: the brick made from clay. Long after the independence, due to a lack of natural and local materials, cement and CRS of galvanised iron became the main building materials. They still are in present day Haiti.

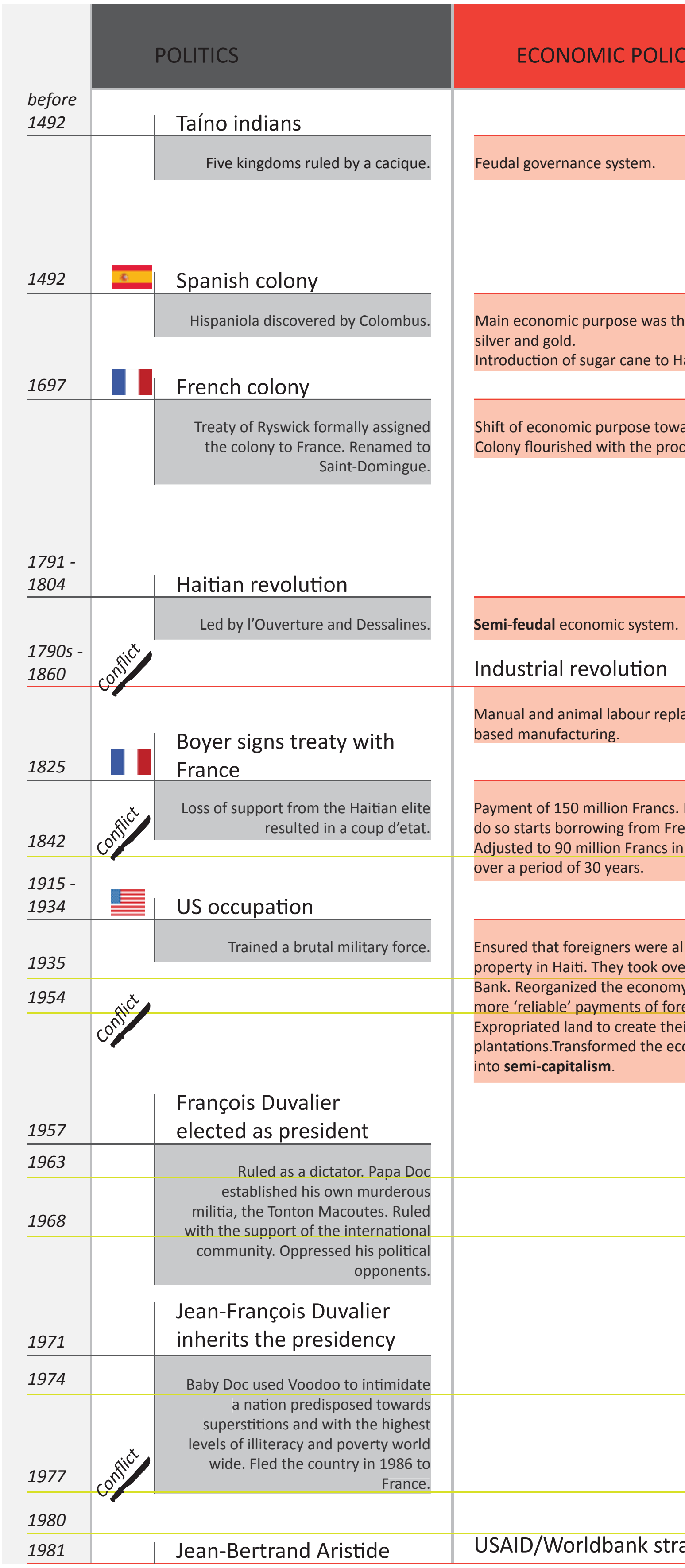
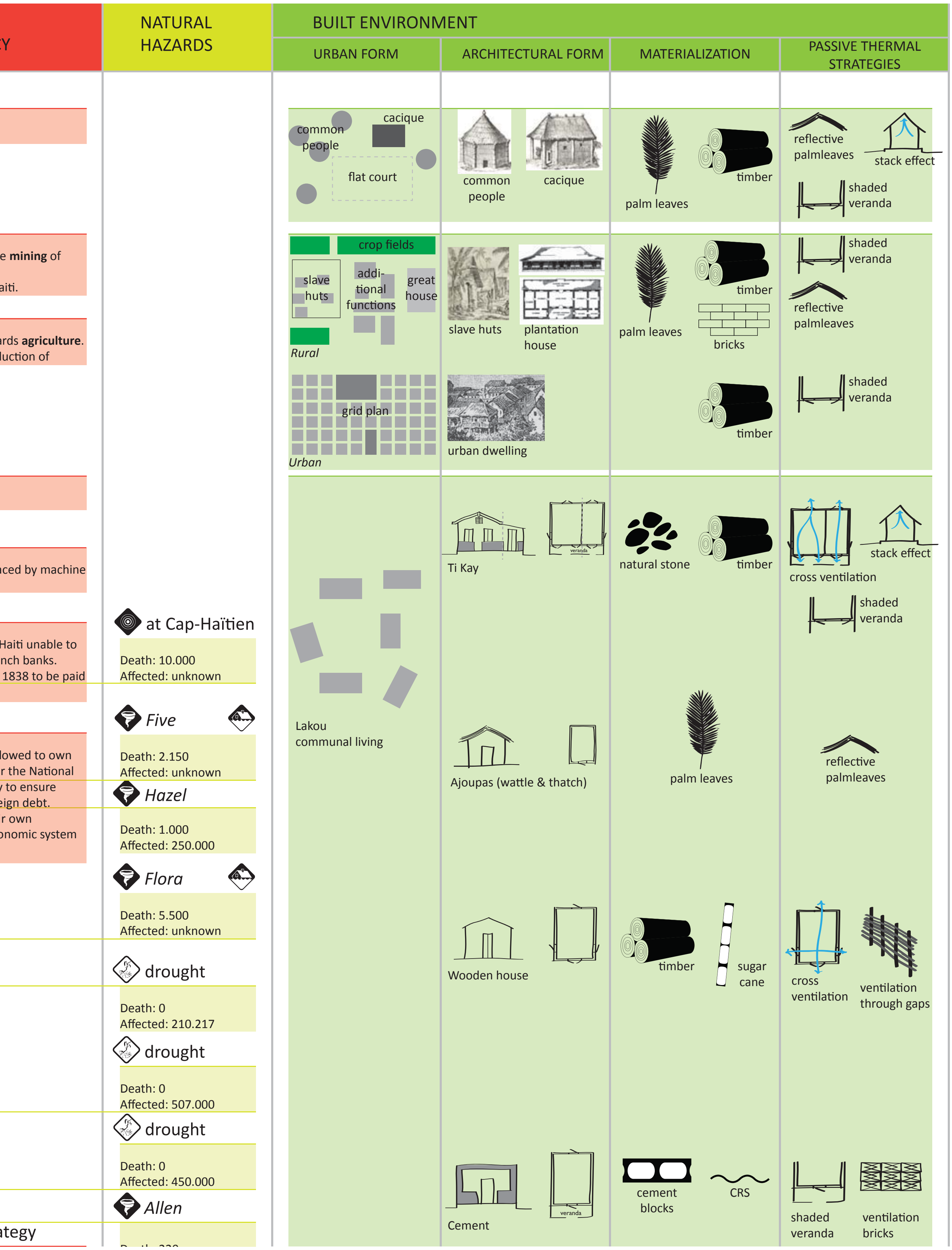


Fig. 5.24: Haiti's history on major events in politics, economy, natural hazards and the building industry from 1492-2011
Source: Author



Y
NATURAL HAZARDS
BUILT ENVIRONMENT
URBAN FORM
ARCHITECTURAL FORM
MATERIALIZATION
PASSIVE THERMAL STRATEGIES
common people
cacique
flat court
common people
cacique
palm leaves
timber
reflective palmleaves
stack effect
shaded veranda
e mining of
aiti.
crop fields
slave huts
addi-tional functions
great house
Rural
slave huts
plantation house
palm leaves
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Death: 10.000
Affected: unknown
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1838 to be paid
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Hazel
Death: 1.000
Affected: 250.000
Ajoupas (wattle & thatch)
palm leaves
reflective palmleaves
Flora
Death: 5.500
Affected: unknown
drought
Death: 0
Affected: 210.217
Wooden house
timber
sugar cane
cross ventilation
ventilation through gaps
drought
Death: 0
Affected: 507.000
drought
Death: 0
Affected: 450.000
Cement
cement blocks
CRS
shaded veranda
ventilation bricks
Allen
ategy

67

Research

Climate responses and passive thermal strategies

The application of the building materials which the Taíno's used, responded to the climate: the roof of a thick pack of palm leaves reflected the solar radiation and the timber acted as a lightweight structure which has a low thermal mass. The veranda is found in the building typology of the house of the cacique.

The urban townhouses at Cap-Haitian have a balcony which runs along the building, a climate responsive feature. These balconies shade the facade and offer a private outdoor space for living.

We can conclude that the shaded veranda has always been a main feature of the building typology as a response to the local climate, even in the urban context. However, in the high density urban neighbourhoods we see that it has disappeared probably due to a lack of availability of space. Other features such as cross ventilation are still observed in todays building typologies, but when problems occur with glare they are closed or blocked.

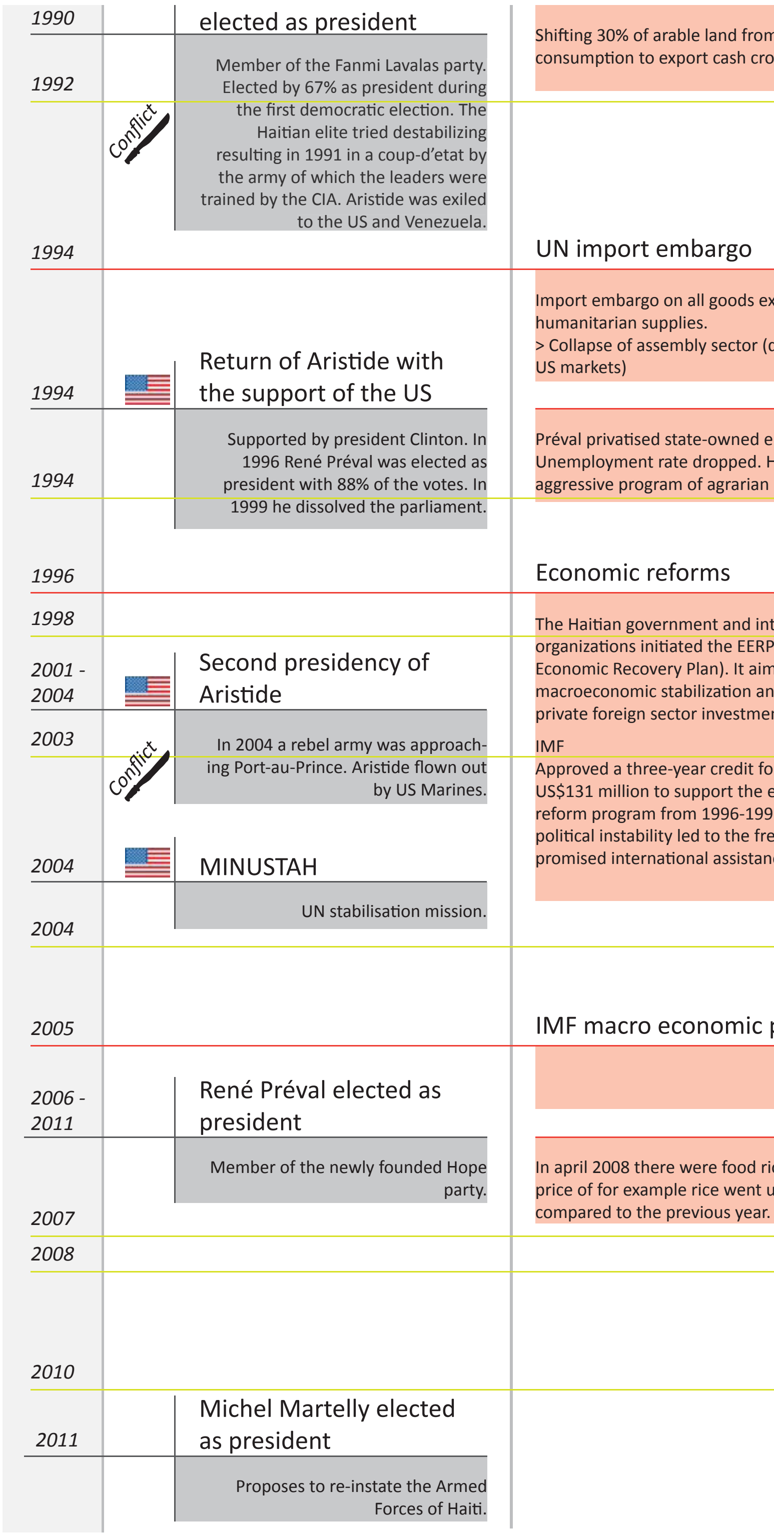

Fig. 5.23: Haiti's history on major events in politics, economy, natural hazards and the building industry from 1492-2011
Source: Author

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Death: 220
Affected: 1.165.000

drought

Death: 0
Affected: 1.000.000

Gordon

Death: 1.122
Affected: 1.587.000

Georges

Death: 190
Affected: 167.000

heavy rainfall

Death: 0
Affected: 150.000

Jeanne

Death: 5.419
Affected: 315.594

Noel and Dean

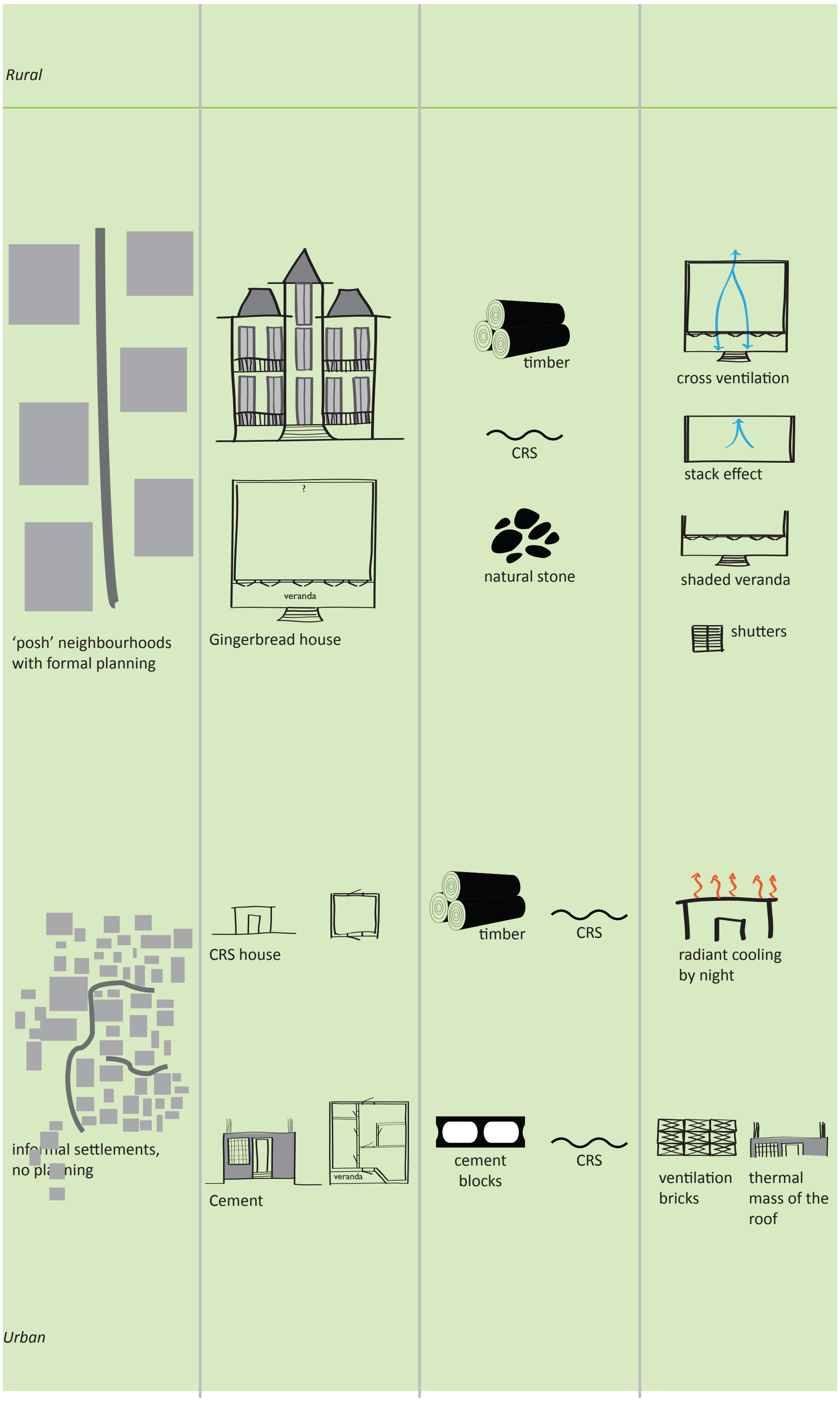
Death: 90
Affected: 108.763

Hanna

Death: 529
Affected: 125.050

at Léogâne

Death: 222.570
Affected: 3.700.000



SUMMARY

From the research on Haitian building typologies, several design features on different scale levels are responses to the hot and humid climate and can be implemented into the design of the research. Together with the research on building typologies in similar climatic zones around the world (chapter 7), this toolbox will be completed.

CLIMATE RESPONSIVE TOOLBOX

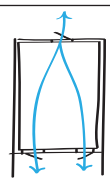
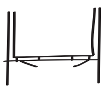
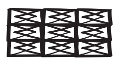
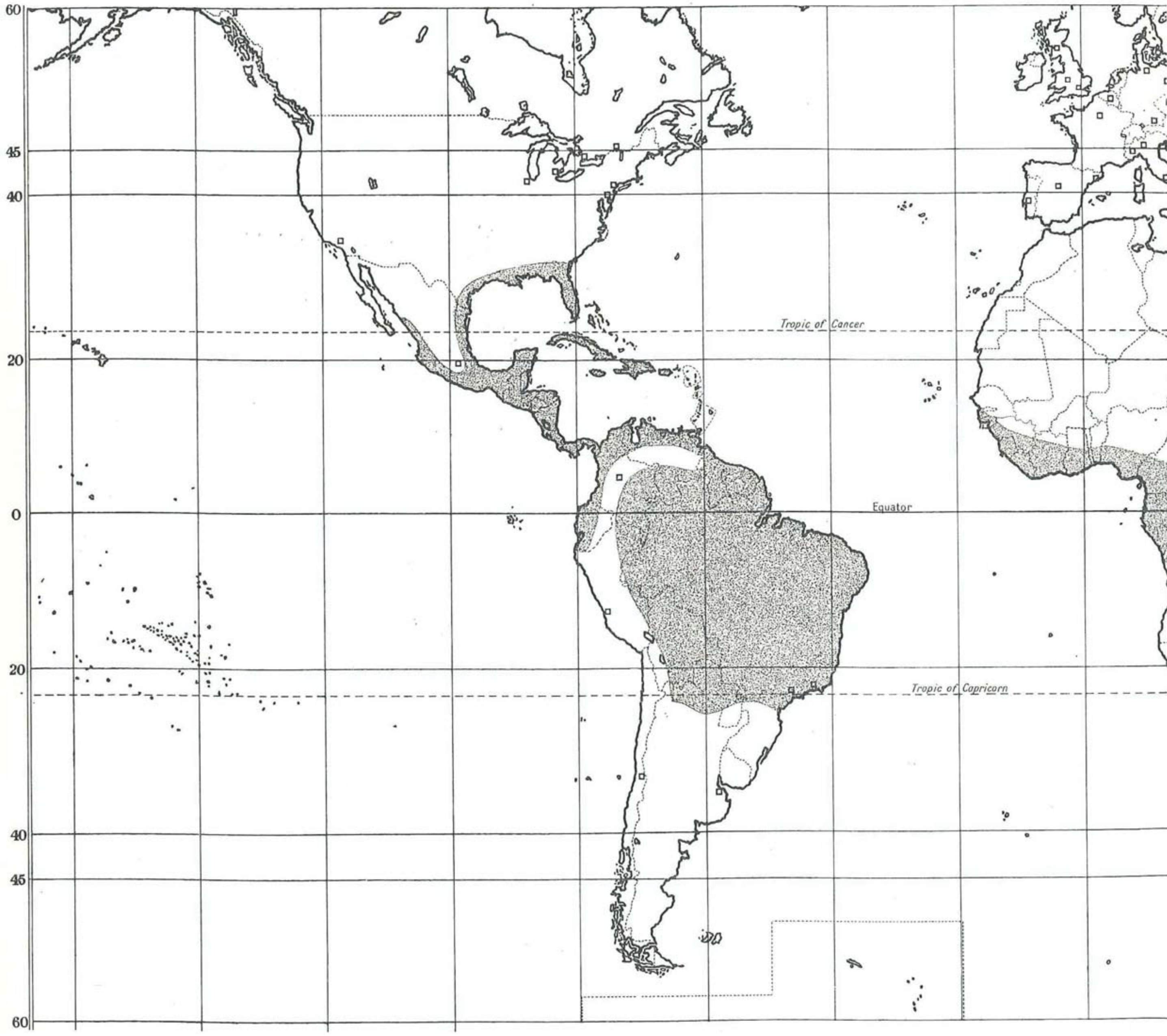
Urban form	• Communal living by family bonds (cultural and contextual)				
Architectural form	• Vodou house layout and detailing (cultural and contextual)				
Passive thermal strateges	• Cross ventilation • Lightweight structure (low thermal mass) + reflective roof material			 cross ventilation	
Climate responsiveness	• Shaded veranda • Shutters • Ventilation bricks • Reflective roof material	 shaded veranda	 shutters	 ventilation bricks	 reflective palm leaves

Fig. 5.24: Voodoo detailing in cement
Source: Author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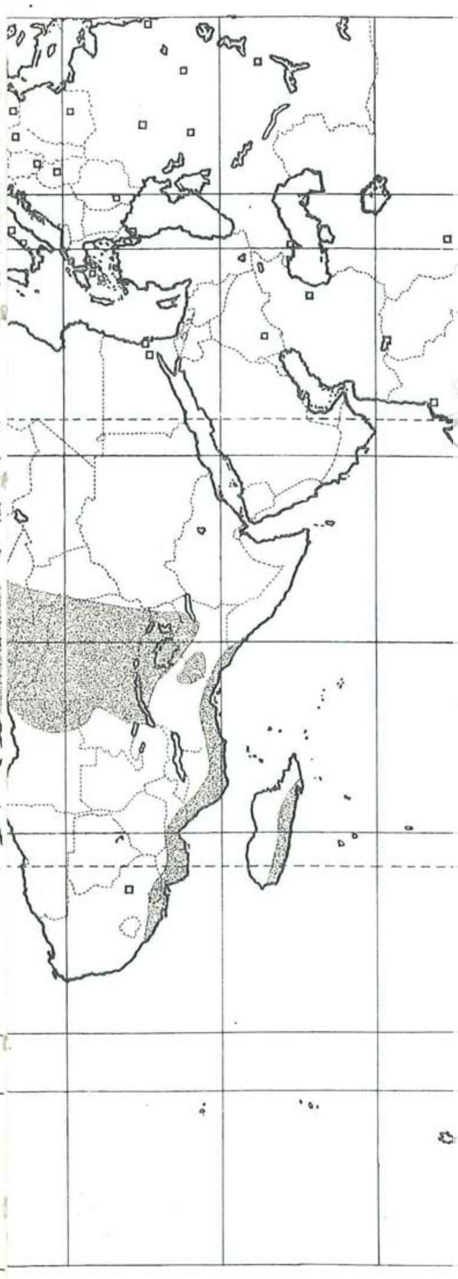
Tropic of Cancer
Equator
Tropic of Capricorn

6. HAITIAN CLIMATE



Content

About

This chapter contains a thorough analysis of the climate of Haiti on three levels: macro, meso and micro. Through this analysis, the parameters of the climate for the location can be evaluated on the appropriate passive thermal strategy to be implemented in the design. The passive thermal strategy should provide in a comfortable indoor climate which is discussed in the next chapter.

6. HAITIAN CLIMATE

"Comfortable conditions in the humid tropics call for currents of moving air which, being supplied by prevailing breezes, demand a suitable orientation of the dwelling and the presence of wall openings to allow the air to pass."
Fry (1982), pp 28

The importance of climate as a determinant in the design process of architecture and town planning was already expressed by Vitruvius in his *Ten Books on Architecture* (Ogunsote, 2002). With modern inventions of air conditioning systems and high-tech materials such as phase changing materials (pcm) and high performance glass, designing with the local climate conditions as a determinant has devaluated. It has led to, amongst others, high energy usage by the air conditioning systems and in sick building syndrome. These western inventions and developments pose a great danger to the tropical zones of our world where the building industry and perception of aesthetically appreciated architecture mimics the western world. The great danger lies in the blind application of the same building materials and techniques within climatic conditions that differ very much from those for which they are intended, the temperate climate. Evans (1980) expresses this trend as that designers are becoming further divorced from the situations for which they are designing.

A profound analysis of the climatic (macro climate, meso climate and micro climate) data leads to an important input for the design process. Together with the desired indoor thermal comfort level they form the two inputs for a climate responsive design. Extensive studies have been made into the thermal comfort levels of the temperate climate zones, they are however not applicable to the Haitian tropical climate.

The adaptive thermal limits approach has to be used to come to the Haitian indoor thermal comfort limits. The climatic conditions, the design and materialization of the building shell (roof and facades) and the indoor activities determine the thermal performance of the house. Goal for the research is to reach an indoor thermal comfort level by passive means. This limits the possibilities to obtain the indoor thermal comfort level due to the Haitian climatic conditions. This will become clear in this chapter.

6.1 Haiti's macro climate

The macro climate is modified by the topography of a location. Haiti's topography consists out of five mountain ranges and the climate is greatly influenced by the northeastern trade winds. Due to the topography with five mountain ranges, Haiti has many distinct climatic zones. There is a macro climate classification for Haiti which is a generalization of the main climatic parameters of humidity, dry bulb temperature, wind, precipitation and solar radiation.

The macro climate is affected by the occurrence of natural hazards. These natural hazards have a tremendous influence on the building design of the house since it can be a case of life and dead as showed by the earthquake of January 12th 2010. However, the return period of a natural hazard may be longer than the life span of the house.

6.1.1 General topography

Haiti is located on one of the northern Caribbean islands, neighbouring Cuba and Jamaica in the west and the Dominican Republic in the east. With the latter it shares the island of Hispaniola. Haiti is located between 18°N and 20°N latitude and 71°W and 75°W longitude, which is between the equator and the tropic of cancer. This determines the seasonal position of the sun and the angle of incidence of the solar radiation.

Fig. 6.1: Topography of Haiti
Source: http://www.worldofmaps.net/en/south-america/map-haiti/relief-map-haiti.htm

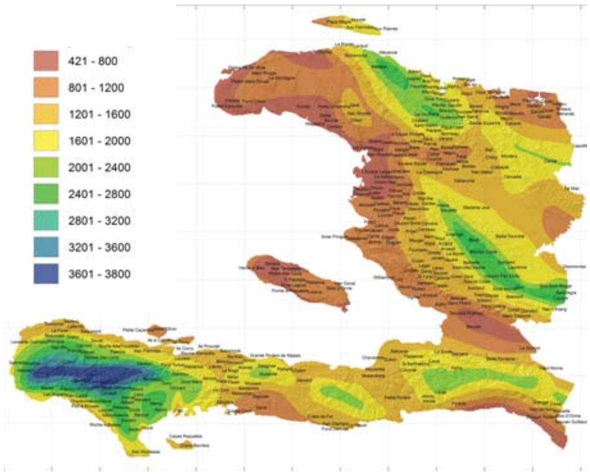


Fig. 6.2: Annual average level of precipitation in Haiti, 1921-1975
Source: Mora, 2010

Haiti is shaped like a horseshoe with a northern and southern peninsula (fig. 6.1). There are five mountain ranges, named from north to south the Massif du Nord, Montagnes Noires, Chaîne des Matheux, Massif de la Selle and Massif de la Hotte. The mountains are mainly limestone, but there are also some volcanic formations to be found (Hadden, 2010).

Haiti is located on the leeward side of Hispaniola where the influence of the Northeast humid trade winds is less then in the Dominican Republic. The humid trade winds bump into the Massif du Nord causing in low precipitation values at the northwest of Haiti (fig. 6.2). This fig. 6.2 also shows that the western tip of the southern peninsula is receiving the highest amount of precipitation. The distribution of the precipitation shows evidently the modifying effect of the topography. Fig. 6.3 shows the type of precipitation found in which area of Haiti. Important aspect from this figure is that the purple parts are not effected by tropical storms.

Haiti has no navigable rivers and the largest lake is the *Etang Saumâtre* which is a saltwater body located in the Cul-de-Sac plain east of Port-au-Prince. The lowlands are vulnerable to floodings but also the most densely populated areas. Port-au-Prince is located on a lowland, the Cul-de-Sac plain.

6.1.2 Macro climate classification

There are several methods to classify a climate; the Köppen system bases its classification on the type of vegetation in a zone. This in turn depends on the amount of rainfall and temperature. Szokolay (1991) relates the climate classification to the human comfort with the parameters temperature, humidity, air velocity and solar radiation. Fry (1982), with a focus on tropical climates, wields an elaborate method including temperature, humidity, rainfall and air movement.Evans (1980) proposes the Atkinson classification where climatic zones can be defined with a minimum of data. Fig 6.3 shows the different climatic zones in Haiti. The zoning is only based precipitation values since this is the only near complete and available weather data.

To study the macro climate and determine those factors important for the building design we need to have extensive climatic data of at least ten years

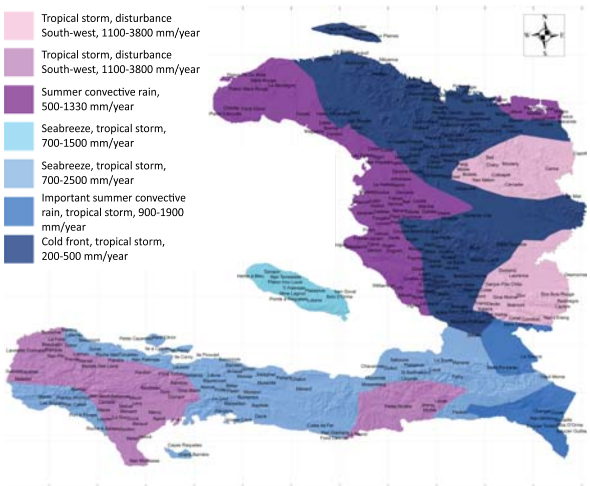


Fig. 6.3: Annual average level of precipitation and type of precipitation in Haiti, 1988-2010
Source: Mora, 2010

(Evans, 1980). Unfortunately, Haiti has not been having a well functioning national meteorological service (NMS) for many years. With only two automatic weather stations, at the airports of Cap-Haïtien and Port-au-Prince, and a pluviometric network of 130 rainfall gauges observed by volunteers, the service lacks the capacity to provide the needed climatic data. The events of hydrometeorological hazards (flooding, tropical storm, droughts) have stressed the need to rebuild this service (Golnaraghi, 2010). The World Meteorological Organization (WMO) has funded a project whose achievements include a network of seven automated weather stations. This project was started after the earthquake. However, the services which were available through a website (www.meteo-haiti.gouv.ht) have been suspended until further notice. From outdated sources it is possible to obtain the climatic data that is needed as input for the building design, but due to climate change and environmental problems Haiti's climate has changed and the data may not be correct any more.

According to Golnaraghi (2010) 3302 km^2 of Haiti's territory is climatically classified as sub-arid, 14.441 km^2 is sub-humid and 17.843 km^2 is arid. Some regions have two rainy seasons: from April-June and August-October, others have only one from May-November. Annual variations of precipitation can cause droughts, widespread crop failure and famine.

The macro climate of Haiti is classified as *island hot and humid* of which the characteristics are given in the appendix (after Fry). The diverse topography shows modification of the precipitation value. The classification can thus be further extended to *wet* or *dry* hot and humid climate.

6.1.3 Natural hazards and environmental problems

Haiti is a country with distinct climatic zones which are affected by natural hazards and secondary effects caused by environmental problems which were discussed in chapter 2. In regard to the building design the primary and secondary effects have to studied and responded to by the design. The UNEP (2010) underlines in a report that 'it is difficult to control natural hazards. It is however, possible to protect ourselves from them.' Protecting from them means making the built environment less vulnerable to them.

DRR strategies start with a risk and vulnerability assessments. Risk assessments investigate in the risk on a disaster caused by a hazard. The risk is determined by multiplying the hazard with the vulnerability, in formula:

$$\text{Risk} = \text{Hazard} * \text{Vulnerability}$$

Hazard maps are a combination of factors, for example the hazard map for landslides is calculated by:

$$H_{landslide} = (L_s * R_r * Hf) * (S_t * R_t)$$

with

L_s = lithological susceptibility
R_r = relative relief
Hf = soil humidity factor
S_t = seismic trigger
R_t = rainfall intensity trigger

There are many possible hazards, both natural and man-made, that could occur. The natural hazards affecting Haiti will now be discussed.

Earthquake (geomorphological)

Haiti is located in a seismic active area near the border of the Caribbean tectonic plate and the North American tectonic plate, who move in opposite directions. This is causing earthquakes during which the accumulated pressure is released. The pathway of a long fault line at the Caribbean plate passes just south of Port-au-Prince. Previous earthquakes destroyed Cap-Haïtien in 1842 and Port-au-Prince in 1751, 1770 and 2010.

A well-known saying is '*earthquakes do not kill people, buildings do'* and this definitely reflects on Haiti's earthquake of 2010. Fig. 6.4 shows the magnitude of the earthquake against the number of casualties. We can conclude that although Haiti's earthquake of 2010 does not belong to the strongest ones, it does have one of the highest number of casualties in history.

The primary effects of an earthquake, in relation to buildings, is ground movement. Important for a building design loaded by seismic forces, is that structurally it can withstand these forces. Secondary effects are a tsunami, landslide, flooding, fault rupture and soil liquefaction.

Seismic building codes should prevent in inappropri-

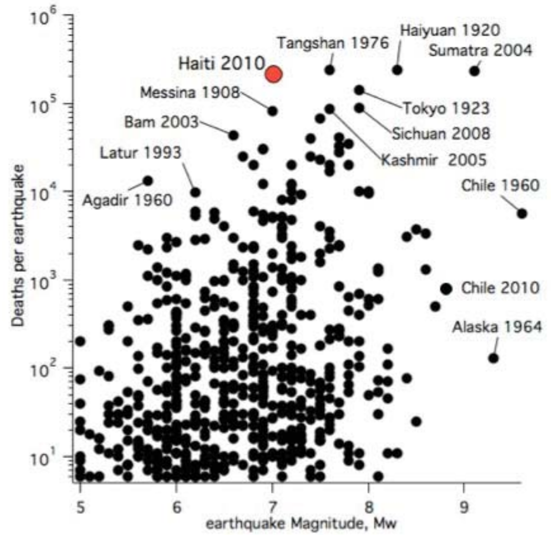


Fig. 6.4: Earthquake magnitude against number of deaths
Source: University of Colorado

ate designs, but unfortunately Haiti did not have an affective building code causing in the grand scale failure of buildings. A seismic hazard risk assessment can provide in a map which gives conclusive answers about safe and unsafe areas for building construction. In general, it is best to avoid heavy structures for the design of buildings for seismic active areas since, according to Newton's second law of motion, F = m*a where the acceleration, a, is produced by the earthquake. A high mass will thus result in a larger force on the structure. This means that the structure of a building should be able to resist these forces.

Tropical storms (hydrometerological)

During the hurricane season, from June-October, Haiti is subjected to severe storms with strong wind gusts and high levels of precipitation. In the documentary Unreported World (2009) they made the characterizing observation that 'all the Caribbean islands get hit by storms, but Haiti always suffers the most damage'. Tropical storms can result in primary effects such as torrential rains and severe wind gusts, but also in secondary effects as extensive flooding and mud slides. The secondary effects are worsened by the environmental degradation. Reasons for why tropical storms in Haiti result in disaster more often than neighbouring countries, lay also in a lack of government infrastructure and rescue services (Hadden, 2010). For the past 50 years, tropical storms have been the most active natural hazard that has severely affected Haiti. From

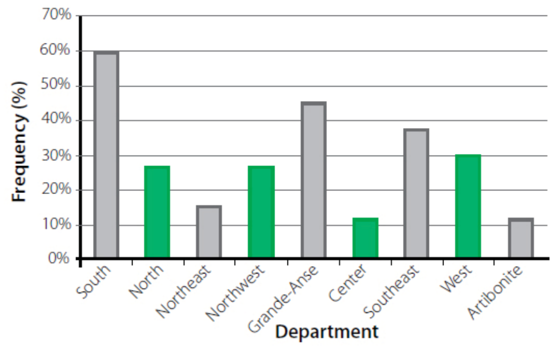


Fig. 6.5: Tropical storm frequency per province, 1954-2001
Source: USAID, 2007

fig. 6.5 we see that the southern peninsula (Grande-Anse, South and Southeast) was the most frequently hit by tropical storms between 1954 and 2001.

The primary effect of wind gusts causes in high and low pressure zones around the building. This can result in roofs or parts of the facades flying of or into buildings. To reduce the vulnerability of the building design to the wind gusts of tropical storms there are guidelines. Heavier structures, especially the roof, tend to fare better than light structures when subjected to wind gusts. This is however in contradiction with seismic design recommendations. Certain slopes of roofs tend to fare better than others. There are more design guidelines, but in general one should keep in mind how to design with the pressure differences.

Environmental problems

In a time span of nearly 90 years, Haiti went from a land surface cover of 60% forest in 1923 to only 1% forest in 2010. Reasons for this major decline are wood logging for charcoal, clearing for agricultural land and timber for the building industry and for export. The absence of trees, and with it also other vegetation and even whole ecosystems, is causing many environmental problems. During the rainy season the soil is unable to absorb and retain the water. Because of Haiti's mountainous topography, the water will flow downhill washing away the few fertile soil that is left and resulting in soil erosion. Downhill, the huge amounts of water can result in flooding if proper drainage is absent. These man made environment problems aggravate some natural hazards and make Haiti more vulnerable to them.

Desertification is defined by the UN as 'land degradation in arid, semi-arid and dry sub-humid areas resulting from various factors, including climatic variations and human activities'. Main cause is the over cultivation of lands when the nutrients within the soul are more rapidly depleted than restored. The climatic zones of Haiti with low precipitation values (fig. 6.2) are vulnerable to this environmental problem. There are ways to restore the balance of nutrients within the soil. A project to re-green the desert in Israel has shown inspiring results (Ecolizer, 2009). The 'extremely salty and flat soil 400 meters below sea level' was turned into 'extremely fertile soil' by a number of steps.

Flooding and droughts (hydrometerological)

Floodings are a natural hazard caused by high precipitation values and improper drainage. The effects in Haiti are aggravated by the deforestation. During the rainy season, water is coming down from the mountain slopes. The inability of the rivers to deal with the amount of water causes in floodings especially when the drainage, if there is one, is clogged by solid waste. Floodings can also occur after an earthquake as a secondary effect. A tsunami that hits the coastal areas, just like in Japan, can flood the hinterland. In coastal areas there can also occur floodings due to wind propulsion (storm surge). Fig. 6.6 shows that the province West, where Port-au-Prince is located, gets flooded most frequently. The topography of the province consists out of two mountain ranges with a lowland in between. This explains the vulnerability to flooding.
Reducing the vulnerability of the built environment to flooding can be in providing adequate drainage. Lifting the buildings from the ground will also reduce the vulnerability.

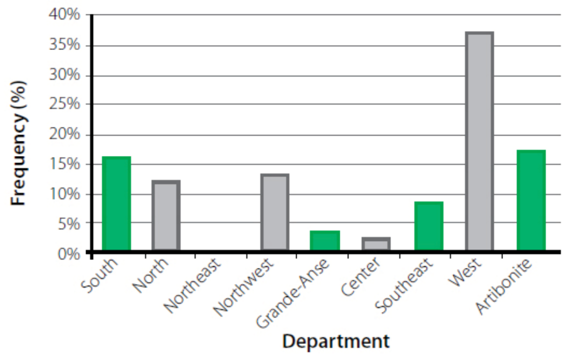


Fig. 6.6: Flood frequency per province, 1968-1997
Source: USAID, 2007

Landslide (geomorphological)

Slope instability is the instigator of landslides which can occur in offshore, coastal and onshore environments. It needs a trigger which can be natural such as an earthquake, heavy rainfall or erosion, or it can be a man made trigger such as deforestation or earth works. The structure of the soil is very important in determining the risk on landslide because when the soil is saturated with water it has reduced abilities to carry vertical and horizontal loads (Arup, 2010). Buildings should not be situated on susceptible slopes or near edges of cliffs. Unfortunately, this is already the situation in large parts of Port-au-Prince. Especially the middle to low income neighbourhoods are vulnerable. Man made terraces build on steep terrain can generate a domino effect downhill when not designed properly.

It is clear that making or obtaining risk maps on natural hazards is necessary when designing for a location prone to natural hazards.

6.2 Meso climate of Port-au-Prince

The location of the design to implement the research findings is Cite Meriken, a neighbourhood in Port-au-Prince. Since weather stations are limited in Haiti, the best option is to use the weather data obtained at the airport of Port-au-Prince.

Extensive weather data is used to perform computer simulations regarding the influences of the climate on the building. Unfortunately, due to the lack of weather data, this can not be done for Haiti. The weather data that will be analysed is divided into five parameters: the dry bulb temperature, precipitation, humidity, wind speed and direction, and the sky conditions (solar radiation and cloud cover).

6.2.1 Five parameters

In the ideal situation the monthly and daily minimum, mean and maximum data is needed plus the hourly data. Moeller (2011) has collected weather data for Port-au-Prince, but is lacking the hourly data. Also some of the data is quite outdated (dating back to even 1863).

The available climatic data offers insight into the meso climate of Port-au-Prince. Per parameter the data will be analysed. The weather data can be found in the appendices.

Dry bulb temperature

The capital of Haiti has little variation in temperature throughout the year, seasons defined by temperature are absent. The absolute annual temperature range is from 15,0 °C ≤ T ≤ 38,0 °C which is small. From this temperature range we can conclude that to obtain the desired indoor thermal comfort there is only a need for cooling.

The annual mean daily average temperature ranges from 24,6 °C ≤ T ≤ 28,0 °C which confirms the lack of seasonal variation in temperature.

Figure 6.7 shows the climograph of Port-au-Prince. This graph is used as a quick view of the climatic parameters of temperature and precipitation for a location and can be used in comparisons with other locations. The monthly maximum, mean and minimum temperatures are plotted with the monthly mean precipitation. The temperature shows little variation throughout the year.

Precipitation

Port-au-Prince has two rainy seasons from April-June and August-October which can be concluded from fig. 6.7. From the data of the daily maximum precipitation we can conclude that the highest daily precipitation values occurred in May and November with around 220 mm precipitation. This results in 220 L per m² which in combination with poor or no drainage and/or a soil that is unable to retain large amounts of water explains in why areas in Haiti flood.

The annual precipitation value ranges from 817,0 mm ≤ x ≤ 1937,7 mm. The ranges of the sum of monthly precipitation values during the rainy season are from 169,7 mm ≤ x ≤ 2354,7 mm.

Water retention has to be dealt with on a large urban scale. On a smaller scale, that of the neighbourhood, proper drainage can be designed. On the scale of the house we can think of water catchment and storage to relieve some of the pressure on the drainage sys-

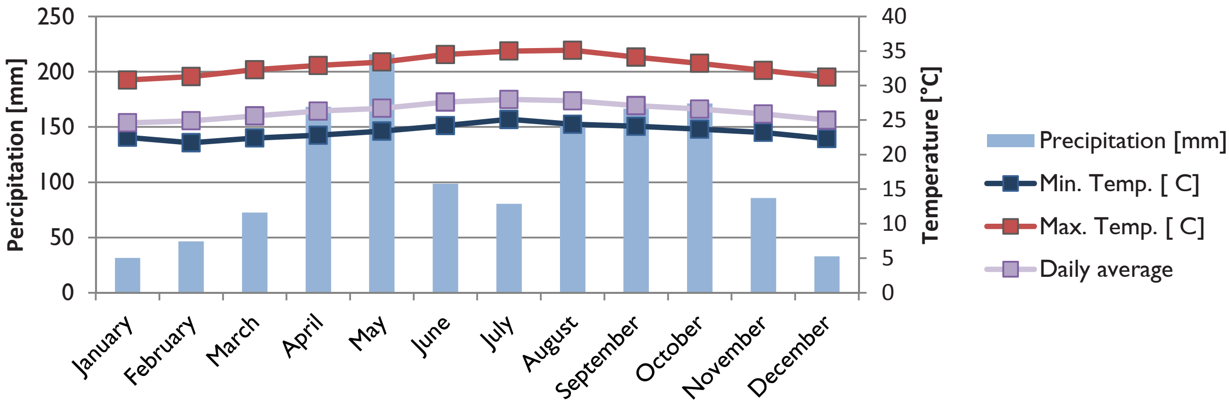


Fig. 6.7: Climograph Port-au-Prince
Source: Moeller, 2011

tem. Drinking water is scarce in Haiti and the precipitation can maybe relief the pressure on the demand for drinking water. Rainwater can be used to wash and clean and some other non-drinking purposes.

SODIS (Solar Disinfection) of drinking water is a low-cost method to disinfect water. To 'achieve microbial inactivation, a solar radiation threshold must be met' (Oates, 2001). This threshold is 3-5h per day of solar radiation above 500 W/m^2. Water in PET-bottles have to undergo a two-day exposure period to complete the microbial inactivation. During this exposure, ultraviolet radiation from the sun, together with an increase in temperature, inactivates the disease-causing organisms in the water. When implemented correctly this low-cost technique can result in drinking water and thus accomplish two important needs: by catching rainwater relieving the pressure on the drainage system and providing in drinking water.

Humidity

The monthly daily mean RH (relative humidity) shows little variation throughout the year with a range of 63% ≤ x ≤ 76%. There are diurnal variations. The mean RH in the morning, at 07:00h just after sunrise, shows a large difference with the mean RH measured around noon, at 13.00h. At 07:00h the annual mean RH has a range from 71% ≤ x ≤ 80% and at 13:00h the range is from 46% ≤ x ≤ 54%.

The higher the humidity of the (indoor) air, the more saturated the air is with water. This affects the indoor thermal comfort in the sense of the possibility of the evaporation of water. Both in the sense of passive cooling strategy (evaporative cooling) and the loss of heat from the human body in the form of sweating. The vapour pressure [hPa] is the parameter that affects the rate of evaporation.

Wind speed and direction

Haiti is affected by the trade winds or tropical easterlies. This is one of the three main global belts of prevailing winds in the hemisphere. The other two main global belts are the mid-latitude westerlies and the polar winds. Wind is caused by the uneven distribution of solar radiation, which causes in high and low atmospheric pressure zones. The hurricane season,

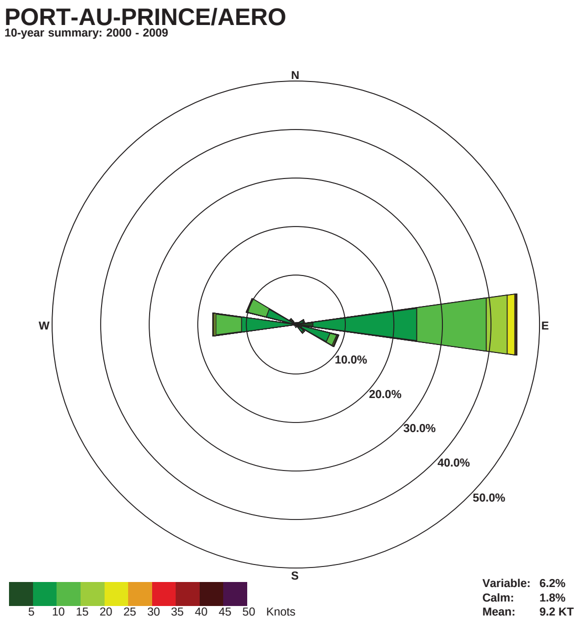


Fig. 6.8: Wind speed and direction from the weather station at the airport of Port-au-Prince. A 10-year summary, 2000-2009.
Source: NCDC (National Climatic Data Centre), 2011

from June-October, can cause in wind gusts and heavy rainfall. However, this does not show in the daily mean wind speeds. It does show in the number of days with storms where there is a great difference between the months November-April, with 0,8-5,5 days of storm, and May-October, with 11,7-19,5 days of storm. The annual number of days with storm is around one third of the total number of days: 106,8.

For a climate responsive design, we need data about the wind speed and direction at the location. Port-au-Prince is located on a lowland in between two mountain ranges, Chaîne des Matheux and the Massif de la Selle. The mountain ranges are oriented west-east and so are the prevailing wind directions (fig. 6.8). East is the main direction and the speed is between 5-25 knots (2,6 - 12,9 m/s) with a mean of 9,2 knots.

From the weather data we find that at 07:00h the mean wind speeds has a range of 1,7 m/s ≤ x ≤ 2,7 m/s. At 13:00h the range is from 3,3 m/s ≤ x ≤ 5,1 m/s.

The wind speed and direction are very important in the building design since from theory it follows that this is probably the only passive way to reach the desired indoor thermal comfort due to the hot and humid climate.

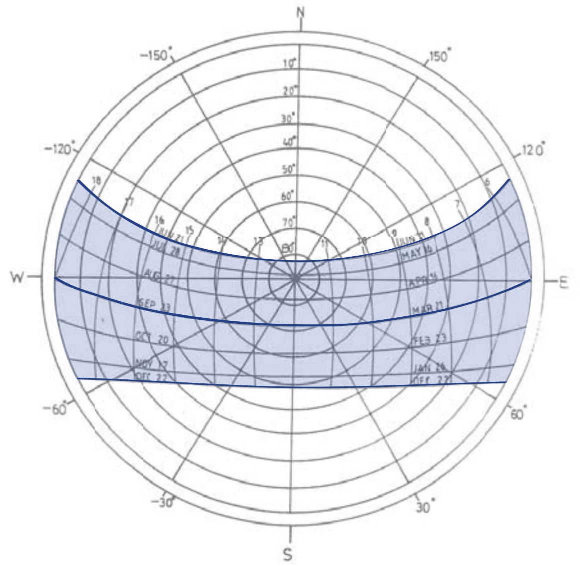


Fig. 6.9: Sunpath diagram
Source: Bansal, 1994

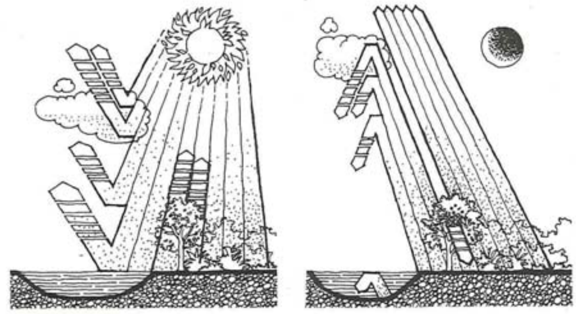


Fig. 6.10: Solar reflection in the hot and humid climate zone, during the day (left), where 40% reaches the ground, and night (right), where 50% radiates back
Source: Konya, 1980 pp. 11

Sky conditions

Haiti (18°N and 20°N) lies between the equator (0°N) and the tropic of cancer (23°N). The annual path of the sun is shown in fig. 6.9. From the sunpath diagram we can conclude that the north side of the house receives some radiation from the 21st of March till the 21st of September, most of it with a high angle of incidence so mostly on the roof. The angles of incidence for the southern side are never below 50°. The eastern and western walls and the roof will receive the most solar radiation.

Throughout the year the daily mean hours of sunshine per day ranges between 7,3 h ≤ x ≤ 9,0 h. In table 6.1 the solar radiation, q in [W/m^2], is determined per month. To do so the insolation [kWh/m^2/day] is divided by the daily mean hours of sunshine [h]. The outcome is multiplied by 1000 to come to q [W/m^2]. This is very important data to calculate the heat flow through the building shell, which will affect the indoor thermal comfort.

From the sky conditions weather data, the annual daily mean percentage of clouds ranges from 27,0% ≤ x ≤ 54,0%. Clouds reflect part of the solar radiation back into the atmosphere so it affects the temperatures on the location (fig. 6.10). However, the data of the number of cloudy days show that this number of days is limited to a range from 1 ≤ x ≤ 5 meaning that there are not many days without any sunshine.

The mean percentage cloudy at 21:00h is important when determining the passive cooling strategies which can be applied to the design. Radiant cooling by the roof surface requires a bright sky during the night (temperature difference, ΔT, between the surface of the roof and the radiating object, the sky, which has the lowest temperature when not cloudy). The annual range of mean percentage cloudy at 21:00h is from 37,0% ≤ x ≤ 74,0% which is large. This could mean that cooling by radiation is insufficient and thus not worth the investment.

Sky conditions	January	February	March	April	May	June	July	August	September	October	November	December
Insolation [kWh/m²/day]	4,17	4,81	5,48	5,82	5,84	6,35	6,29	5,99	5,65	4,98	4,24	3,92
Daily mean hours of sunshine [h]	8,8	9,0	9,0	8,5	8,1	8,1	8,8	8,7	7,8	7,3	8,2	8,2
Solar radiation, q [W/m²]	473,9	534,4	608,9	684,7	721,0	784,0	714,8	688,5	724,4	682,2	517,1	478,0

Table 6.1: Solar radiation analysis, part of the meso climate data for Port-au-Prince.
Source climatic data: Moeller (2011) and New et al. (2002)

Fig. 6.11: The informal settlement Villa Rosa
Source: Author

6.3 Micro climate of Cite Meriken

The location for the design of the research is Cite Meriken, part of the neighbourhood Villa Rosa. Villa Rosa is an informal, high density urban neighbourhood where the residents do not have ownership of the land their houses were/are built on. The neighbourhood is located on the west side of a spur of the Massif de la Selle, with on the other side the neighbourhood of St Maries, a church community. A physical wall separates the two neighbourhoods. According to the meso weather data of wind speed and direction, the west side is most of the time of the year the leeward side (fig. 6.8).

The parameters from the macro and meso climate are strengthened or weakened by the micro climate of the location.

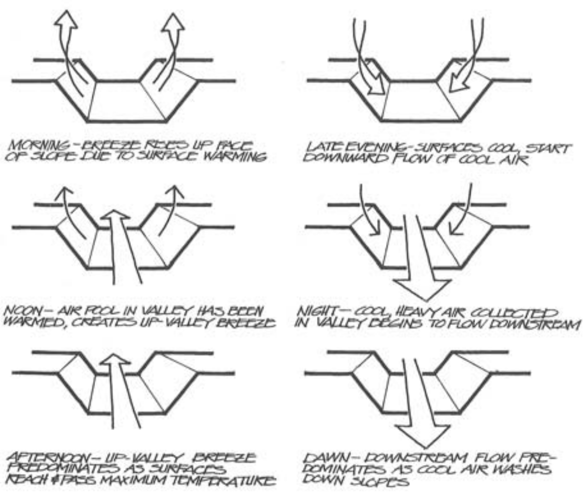


Fig. 6.12: Hill topography and breezes
Source: Watson, 1983 pp. 93

The micro climate is a combination of factors that have to be investigated on site by observations and measurements. According to Bansal (1994) the micro climate is influenced by the factors topography, ground surface and the natural and built environment.

6.3.1 Topography Cite Meriken

As mentioned before, Cite Meriken is located on the slope of a hill which is a spur of the Massif de la Selle. From the contour lines (Mora, 2010) follows that the valley is located at +150 m and the top of the hill is located at +215 m, this is a difference of 65 m.

The hill topography influences air currents (fig. 6.12). From the morning till noon, the air flow is up the hill slope. From the late evening and during the night the airflow is directed down the hill slope. When wanting to catch the prevailing air currents, the design of the openings must be towards the air currents.

Another topographic factor that influences the micro climate, is the proximity to water masses. There are no great water masses present at the location of Cite Meriken.

6.3.2 Ground surface

During the discussion of the weather data of the precipitation, the essential need for proper drainage was mentioned. The absence of drainage or the clogging of it by solid waste, makes it difficult for the rainwater to flow downhill in an organized matter. When an area is not 100% paved, the soil may have the ability to absorb some of the water. Fig 6.13 shows the main street in Cite Meriken, which is unfortunately 100% paved. There is a very small drainage channel next to stairs, but it is probably not effective during heavy rainfall. The fact that the street is 100% paved is also important when determining the heat load on the facade of the building. According to Konya (1980), pavement reflects 40% of the solar radiation and absorbs 50% (fig. 6.14). When the solar radiation strikes grass only 20% is reflected, which is half of the reflection of pavement. Within the climate of Haiti, any solar radiation causing in a heat load on a building is unwanted. Another type of paving for Cite Meriken would thus be very welcome.

6.3.3 Natural and built environment

As we can see on fig. 3.1 the neighbourhood of St Maries contains a lot of vegetation whereas Villa Rosa looks like a concrete jungle. A phenomenon that can occur is the Urban Heat Island (UHI) effect, which increases the outdoor dry bulb temperature. This is caused by the materialization of the buildings which retain heat. An example of such a material is cement of a significant thickness. According to Bansal (1994) the 'high density building clusters can in general create a difference of 2 °C in the average ambient temperature, 6-12 °C in the peak temperature and decrease in the RH by 5-10 %.' From a field survey conducted by the author around 90% of the houses in Cite Meriken are built with cement. So this will create the UHI effect due to the high density of buildings. And this will result in higher ambient air temperatures than the ones provided by the climatic data.

The influence of the reflection coefficient of materials has been discussed for the pavement type, but the same holds for the buildings. Reflection from neighbouring buildings can raise the solar radiation on the facades and roof and increase the heat load.

Site shading by for example vegetation, can diminish the effects caused by direct or indirect solar radiation. A study by Parker (1981) shows that the ambient air under a tree adjacent to a wall is about 2 °C to 2,5 °C cooler than unshaded areas. Different types of vegetation are suitable for various applications. For example, compact trees are able to shade from the low angle sun (just after sunrise and before sunset) whereas tall canopy trees are better to shade the south side with high solar angles. Vegetation can also be used to direct

Fig. 6.13: Main street Cite Mericain with very small drainage channel and 100% paved
Source: Author

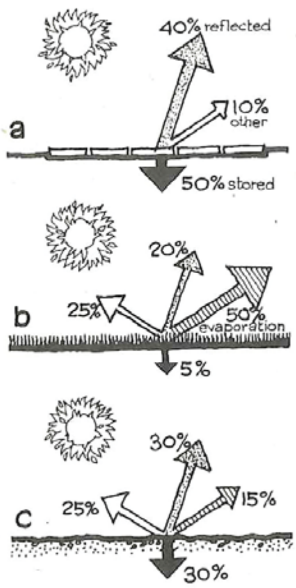


Fig. 6.14: Reaction to solar radiation for paving (a), grass (b) and bare ground (c).
Source: Konya, 1980 pp. 35

airflows. Fry (1982) has composed a list of vegetation species suitable for the hot and humid tropics.
Other factors that contribute to the microclimate are the pedestrian and vehicular circulation. The exhaust of NO_x and CO_2 contributes to the creation of smog, which is both bad for the human health and prevents in reradiation of heat to the atmosphere. Cite Meriken is not accessible by car, accept for the dead end road at the foot of the hill and the road at the top of the hill which goes through St. Maries. The only possible circulation is by foot or moto bike.

6.4 Influences of the climate on the design

The choice of a passive cooling strategy, or a combination of several, for a design in Haiti and other similar climatic regions, always starts with the minimizing of the external and internal heat load. If the external and internal load are as little as possible, the remaining heat that causes for indoor thermal discomfort has to be removed by passive means.

6.4.1 External heat load

The external heat load is caused by solar radiation on the roof and walls of a building, both direct and indirect. There are climate responsive design features, such as verandas and the presence of vegetation which minimize the external heat load caused by direct solar radiation. This will be discussed in the next chapter. Indirect solar radiation coming from neighbouring buildings and ground surface coverage, also needs to be taken into account. The materialization of the building, plays an important role in the amount of heat load that is transferred to the inside.

6.4.2 Internal heat load

The internal heat load is a sum of heat producing objects or people. The internal heat load, ϕ_i, is determined by the sum of:

$$\phi_i = \phi_p + \phi_a + \phi_l \text{ [W]}$$

(people, appliances and lighting)

From the field survey it followed that the residents of Cite Meriken do have some appliances that produce heat. Televisions and music equipment were the main appliances observed and almost always present inside the houses. In some cases there were also fans observed. However, the internal heat load is probably more affected by the heat producing activities. From the field observations conducted by the author the heat producing activities are:

- Cooking
- Working at home (if applicable)

It was observed that cooking took place in an alley next to the house or at the veranda. Cooking indoors was not observed. This is very important for the indoor heat load calculation.

6.4.3 Passive cooling strategies

For cooling there are five different strategies to do so, but a combination might also possible. A building bioclimatic chart shows the meso climatic data and the passive cooling strategies. When such a chart is available, it is very easy to find the appropriate passive cooling strategy. Since there is hourly weather data missing, the five strategies now have to be evaluated by using theory.

According to Evans (1980), the range of dry bulb temperatures (DBT) within which comfortable conditions may be established is approximately between 16 °C to 28 °C: below 16 °C excessive clothing or high activity rates are required, and even this temperature is cool if activity rates are low. Above 30 °C excessive air movement and sweating is required to maintain comfort even at low rates of activity. If we take a look at the meso weather data of Port-au-Prince we see that the mean daily maximum temperature is always above 30 °C. The passive cooling strategy should be able to accommodate air movement and sweating (low humidity).

Direct evaporation

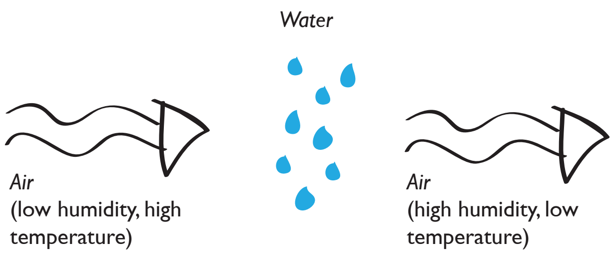
The process of the evaporation of water into the air draws heat from the air. The resulting air is cooled, but also more humid. This is why this technique is mostly used in the hot and arid climatic zones of the world (for example deserts). The principle is explained in fig. 6.15.

The direct evaporation technique is applied in many different forms. In ancient Persian architecture, they used a wind catcher in combination with a qanat (fig. 6.16 and 6.17), which is an underground water stream or interior pond of water, to bring in cool and more humid air. There are variations to this principle, but in general they work the same. The principle has been modified through time and now there are modern versions such as the shower cooling tower and the Arizona tower. On a smaller scale, there is the concept of water-filled porous pots placed in front of windows on the outside of the house and in the path of the passing air.

The potential for evaporative cooling can be calculated by subtracting the wet bulb temperature from the dry bulb temperature, in formula:

$$T_{db} - T_{wb} \text{ [°C]}$$

The data from the meso climate of Port-au-Prince is used to calculate the potential with the use of a psychrometric chart. The difference in temperature is the potential decrease in temperature that can be achieved. The higher the difference, the bigger the potential for evaporative cooling. The potential is calculated for two different situations. For the first situation the data of the relative humidity is taken of 07:00h.



Direct evaporative cooling
The evaporation of a liquid (water) into the surrounding air cools an object or liquid in contact. The latent heat, amount of heat (energy) that is needed to evaporate, is drawn from the air.

DBT - WBT = potential for evaporative cooling

Examples
- Arizona tower
- Windcatcher in combination with qanat (Persian architecture)
- Shower cooling tower

Fig. 6.15: Principle of direct evaporation
Source: Author

Fig. 6.16: Persian windcatcher
Source: Flickr, user dariush1

	Mean daily min. T_{db} [°C]	Mean RH at 07:00 [%]	T_{wb} [°C]	T_{db} - T_{wb} [°C]
January	22,5	74,0	18,7	3,8
February	21,7	74,0	18,5	4,0
March	22,4	73,0	19,0	3,4
April	22,8	74,0	19,5	3,3
May	23,4	76,0	20,2	3,2
June	24,2	73,0	20,5	3,7
July	25,1	71,0	21,0	4,1
August	24,4	75,0	21,0	3,4
September	24,1	79,0	21,3	2,8
October	23,7	80,0	21,1	2,6
November	23,2	78,0	20,3	2,9
December	22,3	75,0	19,1	3,2

Table 6.2: Potential for direct evaporative cooling with min. temperature and RH at 07:00h

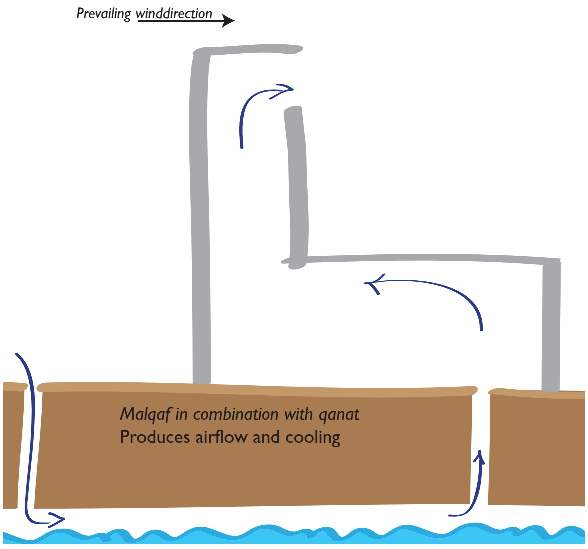


Fig. 6.17: Persian windcatcher with qanat
Source: Author

	Mean daily max. T_{db} [°C]	Mean RH at 13:00 [%]	T_{wb} [°C]	T_{db} - T_{wb} [°C]
January	30,8	46,0	21,7	9,1
February	31,3	46,0	22,0	9,3
March	32,3	47,0	22,9	9,4
April	32,9	50,0	24,3	8,6
May	33,4	52,0	25,0	8,4
June	34,5	48,0	25,2	9,3
July	35,0	46,0	25,0	10,0
August	35,1	50,0	26,1	9,0
September	34,1	52,0	25,5	8,6
October	33,2	54,0	25,3	7,9
November	32,2	52,0	24,0	8,2
December	31,2	48,0	22,6	8,6

Table 6.3: Potential for direct evaporative cooling with max. temperature and RH at 13:00h

This is combined with the mean daily minimum temperature since this occurs during the night, near sunrise. Table 6.2 shows this data with in the third column the determined temperature when the air would be 100% saturated. The fourth column shows the potential drop in temperature that can be achieved when cooling by direct evaporation. This would result in 100% humidity of the air which is not desirable when the only way for the human body to loose heat is transpiration.

In the second situation the data of the relative humidity is taken from 13:00h combined with the mean daily max. temperature. The results are shown in table 6.3. This combination may not be completely valid, since maximum temperatures occur around 14:00h. Also, in warm and humid climates the increase in temperature can cause in afternoon convectional showers. These showers can cause in an increase in humidity just at the time when the minimum humidity is expected (Evans, 1980) and thus influence the measurement.

From the two tables we can conclude that there is a potential to use this passive method for cooling purposes, especially during the warmest period of the day. Within the context of Haiti it might be very troublesome since stationary water attracts flies. Flies infected with malaria are present in Haiti. In 2010 there were 84.153 reported malaria cases (www.globalhealthfacts.org). Other sources say that Haiti reported approximately 30.000 confirmed cases of malaria annually to the Pan American Health Organization (PAHO), although officials say there may be as many as 200.000 cases annually. Nonetheless, the problem is significant and a just consideration should be made wether it is wise to apply this passive cooling technique. Especially since the temperature drops may not be that great.

Indirect evaporation

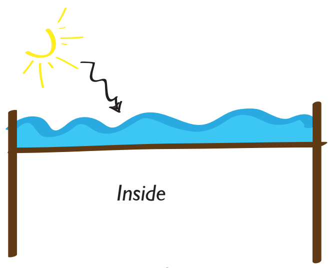
During the process of direct evaporative cooling, the humidity of the indoor air rises. This can be unwanted since the heat loss of the human body by evaporation is less effective with a high humidity. Therefore, there are indirect evaporation principles where the process of heat exchange between surfaces is used (fig. 6.18). In the case of a roof pond (fig. 6.19), the water absorbs the heat from the striking solar radiation during the day. At night it acts as a radiant cooler and cools down by heat radiation towards the sky. There are roof ponds which are ventilated, have floating insulation panels (shading from direct solar radiation and during the day they keep the temperature of the water low) or are pebble-filled. The roof pond keeps the indoor ceiling temperature low and cools the indoor space by radiation and convection. Since warm air rises this will result in effective cooling. The concept works in the same way for walls.

A Roof ponds has some practical limitations:

- It needs a proper structure to support the loads.
- It only cools the spaces that are in contact with it
- The waterproofing of the roof may cause problems
- Again, the flies are attracted by stationary water (for example, the fly that causes the dengue virus lays its eggs in stationary water)

Another way to apply indirect evaporation is the spraying of water on roofs and/or walls. Fig. 6.20 shows an example of a roof that is sprayed with water. This concept of indirect evaporation acquires the input of energy (electricity).

A roof pond causes too many problems regarding the structure, earthquake proof building (the mass of the roof pond will cause too much forces), costs and the attracting of flies by the stationary water. However, an application of water in a closed system as a wall is a promising possibility. The water catchment storage barrel can be used simultaneously as an indirect evaporative cooling wall.



Indirect evaporative cooling

The roof is designed as a shallow water tank where the water acts as an insulator. The water makes sure the T_s of the roofing material is not raised by solar radiation. Water spraying of materials follows the same mechanism.

Fig. 6.18: Principle of indirect evaporation
Source: Author

Fig. 6.19: Roof pond
Source: archinspire.com

Examples
- (shaded) Roof pond (heat sink)
- Wetting impermeable walls by water
- Water sprayed roof/wall

Fig. 6.20: Sprinkled roof
Source: Carnegie Institute for Global Ecology

Airflow

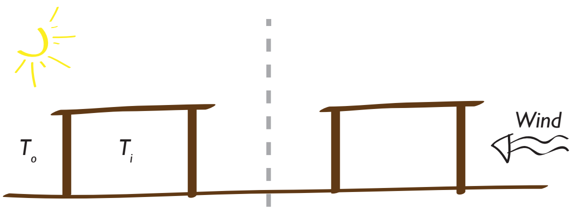
Airflow is an effect of pressure differences. Warmer air is less dense, low air pressure, than cool air, high pressure, and this creates a natural airflow caused by the pressure differences. The creation of air flow can be on a large scale and small scale (house design). Examples of creating airflow by temperature differences are solar chimneys which implement the stack effect. This is a small scale creation of air flow. An example of a modern solar chimneys is given in fig. 6.22. According to Evans (1980) the ventilation created due to the stack effect will usually be small compared to the ventilation created by wind pressure.

The movement of air by temperature difference is most of the time insufficient to provide air movement in hot zones to provide indoor thermal comfort (Konya, 1980).

The hill topography of Cite Meriken provides in air movement up and down the slope, because of a difference in temperature between the top of the hill and the valley.

The airflow created by wind, large scale airflow, is capable of providing the necessary air velocities to cool indoors. Fig. 6.8 shows the wind direction and speed for a ten-year period in Port-au-Prince. This chart shows that the prevailing wind directions are east and to a lesser extent the west. The weather station at the airport is most definitely located at a bare environment. There will be no obstacles which will block the wind. In an environment with a high density of buildings, the term wind should be changed into turbulence. Also, the wind speed measured at the weather station is much greater than the turbulence speed at the micro climate level of Cite Meriken. The turbulence can still be catched by a wind catcher and diverted into the house to create ventilation. A windcatcher (fig. 6.23) is used when air movement at the ground level is low. There are different ways to use this concept, such as one opening at the windward side (high pressure in the tower), two openings and one opening at the leeward side (low pressure in the tower), but the general idea is the same. The prevailing wind direction determines the orientation of the windcatcher. When there is no wind available windcatchers can be used as solar chimneys since a temperature difference inside is created.

When wind strikes a building it creates high and low pressure zones and a windward and leeward side. The pressure difference will cause air to flow through the structure when in- and outlets are provided. To reach



Airflow
Air velocity occurs when temperature differences appear. These temperature differences are caused by solar radiation. Air flow in a building can be created by a temperature difference between the inside and outside and by wind near windows or air inlets. There is comfort (daytime) ventilation and nocturnal ventilative cooling.

Fig. 6.21: Principle of cooling by airflow
Source: Author

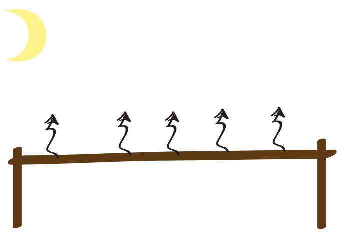
Examples
Temperature difference:
- Solar chimney
- Stack ventilation

Windflow:
- Cross ventilation
- Windcatcher
- Airwell, Venturi effect

Fig. 6.22: Solar radiation heats up the solar chimney and ducts
Source: http://greenbuildings-in-the-world.blogspot.com/2009/10/green-buildings-zero-energy-structure.html

Fig. 6.23: Wind catch towers
Source: buildinggreen.com

the optimum amount of airflow the in- and outlet should be positioned opposite each other, with one on the windward side. This type of ventilation is named cross-ventilation. To increase the air velocity inside the inlet must be smaller than the outlet. The desired indoor airflow is according to Evans (1980) between 0,1 m/s < x < 1 m/s.



Radiative cooling
The emission of long wave (thermal) radiation of a surface towards the sky during the night. This cooling effect will be transfered to the inside of the building.

Fig. 6.24: Principle of radiative cooling
Source: Author

Radiative cooling

During the day the solar radiation heats up surfaces. Solar radiation becomes more intense with an increase in altitude, since the solar radiation is passing through a thinner layer of the atmosphere. This is also explaining the airflow patterns in fig. 6.14. When a surface is exposed to a clear sky without clouds during the night, it loses heat through long wave, thermal, radiation (fig. 6.24). The cooling effect is the difference in temperature between the atmosphere and the surface temperature of the roof. The roof sheets must be in direct contact with the indoor space to transfer the cooling by conduction and convection. This radiative cooling is most effective under a clear sky (fig. 6.10). From the weather data of the meso climate of Port-au-Prince, it followed that the annual daily mean percentage of clouds ranges from 27,0% ≤ x ≤ 54,0%. At 21:00 this range is from 37,0% ≤ x ≤ 74,0% which is very large and thus radiant cooling looses effectivity.

Fig. 6.25: Radiative roof, palm leaves
Source: blogspot.com

Examples
• Highly conductive roof with operable, external insulation (such as concrete)
• Metallic specialized radiators (air space underneath metallic roof)
• Radiative roof with operable, internal insulation

Fig. 6.27: Radiative roof, metal sheets
Source: blogspot.com

Metal roofing sheets with a high emissivity property perform best as radiant coolers. But during the day, they radiate the heat from the direct solar radiation to the indoor space causing in a rise of indoor temperature.

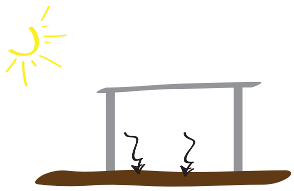
Radiant cooling by the roof is only effective for rooms in direct contact. In a multistory house other passive cooling techniques have to be implemented.

Mass

The fifth passive cooling technique is thermal mass. This principle can be used both in cold and warm climates. The principle is based on the heat storing capacity of a material with a significant thickness (fig. 6.28). The material can be any that has the right thermal properties of a high heat storing capacity.

Earth sheltering is used in colder climates to prevent the loss of heat through the building shell (fig. 6.29). In temperate and also hot and arid climatic zones the direct solar radiation is stored by the thermal mass during the day and radiated during the night when temperatures drop. An example of this are adobe houses in New Mexico (fig. 6.30).

Application of this passive cooling technique in Haiti is limited since temperatures do not decrease that much during the night in the meso climate of Port-au-Prince. The material which stores the heat during the day, will radiate this when temperatures start decreasing. This would mean that the indoor temperature stays high during the night and this is unwanted. A connection with the earth by the ground floor may be the only possible application of this technique.



Mass
Heat from solar radiation is stored in a significant amount of material (for example earth or cement). This heat will be radiated when temperatures decrease (during the night).

Fig. 6.28: Principle of cooling by mass
Source: Author

Fig. 6.29: Thermal mass by earth sheltering
Source: http://coolfunclub.blogspot.com/2011/07/unique-houses-around-world.html

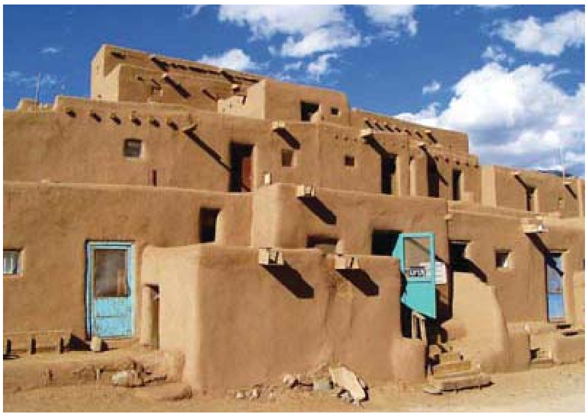


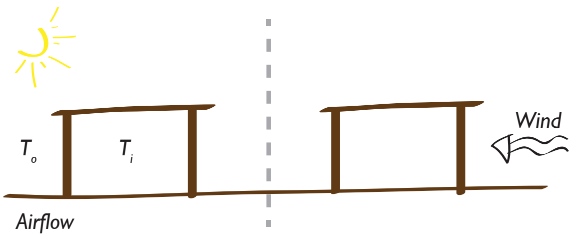
Fig. 6.30: Adobe used as thermal mass
Source: http://clarkrichardson.wordpress.com/2011/11/12/the-natural-vernacular/

Examples
- Earth
- Thermal mass on the inside
- Phase changing materials

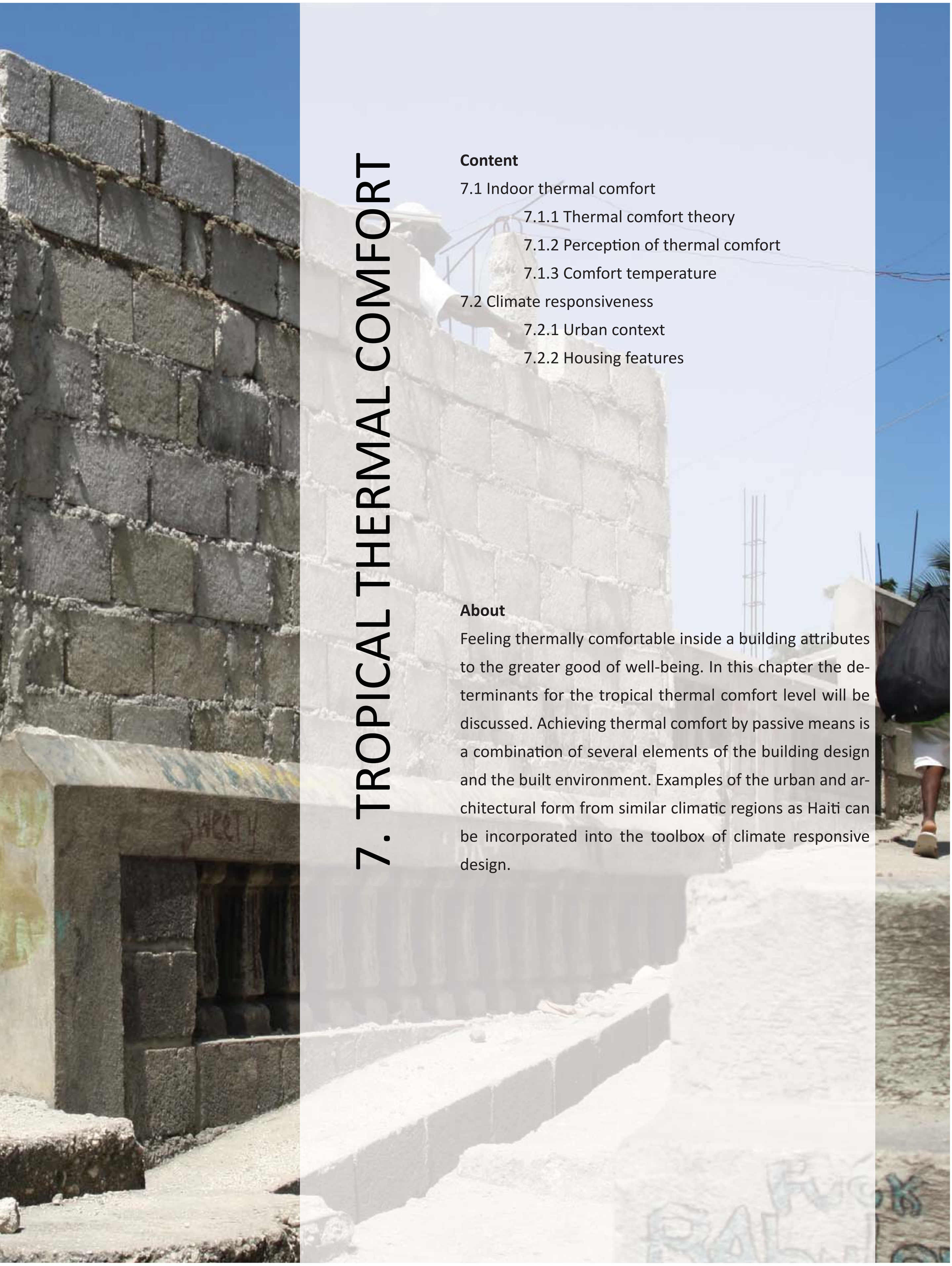
SUMMARY

The climate of Port-au-Prince is classified as hot and humid. The temperature and humidity show no seasonal variation. There are small diurnal variations visible. The climatic parameters in combination with contextual aspects rule out four of the five passive cooling strategies: for direct evaporation the relative humidity of the air is too high, indirect evaporation by a water surface is impossible due to the danger of attracting mosquitos with a possibility of malaria, radiative cooling seems promising but there is a high percentage of cloudiness during the night thus this strategy looses its effectiveness and the last one of thermal mass does not suit the hot and humid climate due to the small diurnal temperature differences. The only possible passive cooling strategy is cooling by airflow.

PASSIVE COOLING STRATEGY FOR DESIGN: AIRFLOW




Produits Alimentaires
En gros
Sauce tomate
Lait
Savon



7. TROPICAL THERMAL COMFORT

Content

About

Feeling thermally comfortable inside a building attributes to the greater good of well-being. In this chapter the determinants for the tropical thermal comfort level will be discussed. Achieving thermal comfort by passive means is a combination of several elements of the building design and the built environment. Examples of the urban and architectural form from similar climatic regions as Haiti can be incorporated into the toolbox of climate responsive design.

7. TROPICAL THERMAL COMFORT

Maybe the first question we have to ask ourselves is why indoor thermal comfort is important. To stress the importance, lets start with the basics. The UN measures poverty by the basic needs which try to define the absolute minimum resources necessary for long-term physical well-being. The basic needs are food, shelter, clothing, sanitation, education and health care. A shelter offers cover or protection from the weather. A shelter or house must guarantee an acceptable thermal comfort level for the inhabitants, regardless of the outdoor conditions.

7.1 Indoor thermal comfort

Givoni (1998) and Evans (1980) state that thermal comfort during nighttime is more important than during the day because of the need to recuperate from heat stress incurred during daytime. This means that the thermal comfort level at night should be stricter than during the day. We have already established that according to the meso weather data of Port-au-Prince, the thermal conditions are requiring a need for cooling.

The human body looses heat to its environment in four ways: radiation (towards the air), conduction (towards the ground), convection (by airflow) and evaporation (by perspiration). Because of the hot and humid climate of Haiti, the first two do not offer the human body enough opportunity to dissolve the heat. Convection and evaporation will be the two ways in which the human body can obtain thermal comfort.

7.1.1 Thermal comfort theory

Thermal comfort is a subset of the broad definition of comfort and it focuses on human and environmental factors. The main determinants affecting thermal comfort are:

- Air temperature
- Mean radiant air temperature
- Air velocity and air movement
- Humidity

The indoor thermal comfort is influenced by the outdoor weather conditions, the built environment, the thermal properties of the building materials of the building shell, the passive (or active) thermal strategy and the indoor environment. The desired indoor thermal comfort can be obtained by additional heating, cooling or no conditioning. For hot and humid climatic zones, such as Haiti, only cooling is needed to achieve the desired indoor thermal comfort.

The indoor thermal comfort level is, for the western world with mainly temperate climates, put down in requirements set by national or international building codes. The ASHRAE's codes are an example of such a code which sets limits for the indoor thermal comfort range, with minimum and maximum indoor temperature and humidity. These standards are not suitable for the tropical hot and humid climatic zones where outside temperatures most of the time exceed these limits, especially during the day. Research into indoor thermal comfort requirements for tropical areas is intensified during the last decade. The perception of thermal comfort of people living in the tropical climatic zones is an important input for the development of the indoor thermal comfort requirements for the tropics.

7.1.2 Perception of thermal comfort

The way people perceive the indoor climatic conditions has to do with the metabolic rate (the activity) they produce and the clothing they are wearing. The perception of thermal comfort of people living in tropical areas differ from our western standards. Both Givoni (1998) and Nicol (2004) state that the people living in tropical climates prefer higher temperatures since they are acclimatized or adapted to the heat. This improved heat tolerance is achieved by a higher sweat rate (evaporative cooling), a lower inner body temperature and a lower heart rate (Givoni, 1998). A method to determine the appropriate indoor thermal comfort level for tropical regions, is to make use of the adaptive method. This method has been developed as a more sustainable approach for the calculations of the sizing of the climate installation used in buildings. It is based on field surveys and it demonstrates that people are more tolerant to temperature changes than some standards suggest (Nicol and Humphreys, 2002).

A field survey amongst the Haitians at the location, Cite Meriken, brought insight into the perception of the indoor thermal comfort in their houses. This field survey is conducted by the author. First, the seven-point numerical scale was used to rate their thermal sensation at the time of the survey. The points are:

Hot | Warm | Slightly warm | Neutral | Slightly cool | Cool | Cold

After this rating they were asked if they were comfortable or uncomfortable with the indoor climatic conditions. During the questionnaire the ambient air temperature, the relative humidity and the air velocity were measured for both indoor and outdoor. For some houses the radiant temperatures of the roof was measured. The house was analysed on the presence of appliances that modify the indoor climate such as fans or sun shading. The materialization and plan of the house was also documented.

Findings from the field survey are that more than 90% perceived it to be hot or warm at the time of questioning. From this 90% almost 60% thought it was comfortable. The measured indoor temperatures were very widespread and showed no difference in range which would explain the difference in perception of comfortable or uncomfortable. Other relationships between the parameters of climate were sought, but none were found that fit the hypothesis of showing a clear difference between comfortable and uncomfortable (fig. 7.1). The only recommendation for defining the indoor thermal comfort range is to provide in an indoor air velocity that is at least 0,1 m/s, which is also recommended by Evans (1980).

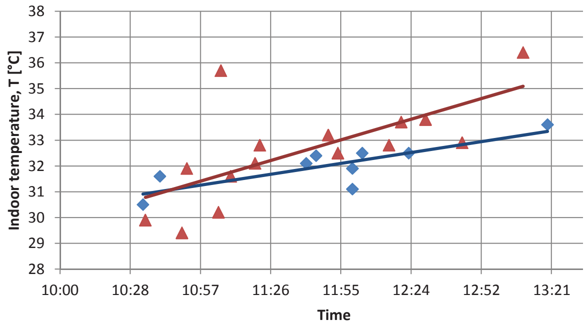


Fig. 7.1: Graph of measured indoor temperature against the time for the perception of comfortable and uncomfortable
Source: Author

In five houses the radiant temperature of the roof was measured to see if the perception of comfort has a relation with this determinant. All the surveyed perceived the indoor climate conditions as *hot*. One of the roofs was materialized with cement, the others were CRS of galvanised iron. Table 7.1 shows the radiant and indoor temperatures that were measured near the ceiling surface. Also, it was observed if there was any climate control present at the house. From the measurements and questionnaire we can

Roof materialization	Radiant temperature [°C]	Indoor temperature [°C]	Climate control
CRS	37,5	33,8	-
Cement	33,9	32,9	Air conditioning unit
CRS	31,5	31,9	Fan
CRS	34,9	33,6	Shutters
CRS	37,5	36,4	Ventilation bricks
CRS	35	32,8	Ventilation bricks

Table 7.1: Radiant temperatures of the roof

not define a clear relation between the perception of uncomfortable (type of materialization in table 7.1 in red) and the radiant temperature of the roof. We can conclude that without an active climate control, the radiant temperature is high.

7.1.3 Comfort temperature

For free-running buildings, which is without active heating or cooling, Humphreys developed a linear relationship between the mean outdoor temperature and the indoor thermal comfort temperature (Nicol, 2004). This comfort temperature is calculated with the formula:

Tc = 0,534*To + 12,9

with:

Tc = comfort temperature [°C]

To = mean outdoor temperature [°C]

	T_o [°C]	T_c [°C]	x_{min}	x_{max}
January	24,6	26,0	24,0	28,0
February	24,9	26,2	24,2	28,2
March	25,6	26,6	24,6	28,6
April	26,3	26,9	24,9	28,9
May	26,7	27,2	25,2	29,2
June	27,6	27,6	25,6	29,6
July	28,0	27,9	25,9	29,9
August	27,8	27,8	25,8	29,8
September	27,1	27,4	25,4	29,4
October	26,6	27,1	25,1	29,1
November	25,9	26,7	24,7	28,7
December	25,0	26,3	24,3	28,3

Table 7.2: Temperature comfort zone Port-au-Prince

For the weather data of Port-au-Prince this results in a comfort temperature:

There is a comfort zone range with a minimum of $x_{min} = T_c-2$ and a maximum of $x_{max} = T_c+2$ is acceptable. In this formula the humidity and air velocity do not play a role. However, research shows that an increased air velocity can increase the acceptable comfort temperature about 2 °C. Fig. 7.2 shows the relationship between the air velocity and comfort temperature.

Humidity is a factor of which the effect on thermal comfort is more difficult to describe. Humidity is related to the temperature of the air and the level of

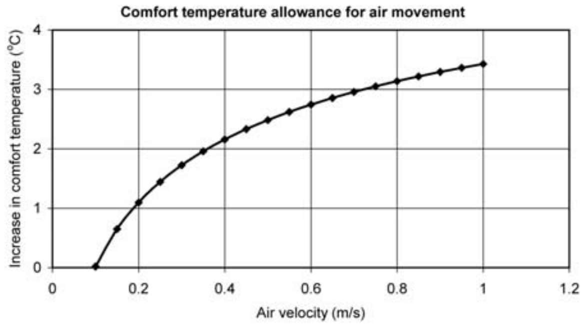


Fig. 7.2: Increase in comfort temperature for different air velocities
Source: Nicol, 2004

saturation of water. When unable by other means of loosing heat, the human body tries to loose heat by producing sweat. Through evaporation this sweat (water) is absorbed by the air. Under high relative humidity conditions the air is almost saturated. The air velocity has to be increased to absorb the sweat by creating a larger volume of air passing by the human body. The main effect of the humidity will reduce the width of the comfort zone and lower the comfort temperature with about 1 °C.

Research into thermal comfort standards for the hot humid/dry regions is pioneering. The equation of the comfort temperature Tc should be complemented by 'the conduct of local field survey to fully reflect local climate and culture' (Nicol, 2004). The remark most research concludes with, is that air velocity or ventilation is the key to thermal comfort in the hot and humid tropics.

7.2 Climate responsiveness

The building typologies of Haiti have been discussed previously. In similar climatic zones, there may be climate responsive features in building typologies which are not found in Haiti. If so, they may be applicable into the design.

The climate of Haiti is generally classified as hot and humid and thus the search will focus on similar climatic regions.

7.2.1 Urban context

Since the design of the thesis will be located in a high density urban neighbourhood, it is necessary to research the urban context of hot and humid climatic regions. From cities dealing with similar problems of massive urbanization and a similar climate, such as Rio de Janeiro (fig. 3.8) and Caracas (fig. 3.9), there was no passive thermal strategy found which responds to the local climate and would be applicable to the Haitian context.

Fig. 7.3 shows two different strategies for the urban context to deal with the climatic conditions: a group of buildings shading an inner courtyard and the closely packed buildings resulting in a high thermal mass. The first strategy can be applied to Haiti. The second strategy acts on the thermal mass which retains heat during the day and releases this at night to the indoor spaces. This is wanted in hot and arid climates where the night time temperature is much lower than the day temperature. Heat storage by the building elements during the day is needed to provide in thermal comfort during the night.

When the Spanish colonists started building their new cities they took with them a building typology which can be traced back to the Arabic influences of Northern-Africa. The climate of North-Africa is a hot and arid and urban plans were designed similar to the (now) old part of Tripoli (fig. 7.4). The dense urban plan with almost no open space provided in thermal mass. This is needed to cope with the heat during the day by offering shade and trapping colder air from the night in the inner courtyard. During the night, with low temperatures, the stored heat is radiated towards the indoor space. Many elements of the Arabic house can be found in the Spanish colonial buildings of Latin America, as well as the traditional buildings of Spain (Evans, 1980).

This is not applicable, and even unwanted, to Port-au-Prince where there is a hot and humid climate. The neighbouring Caribbean Islands do not provide in passive thermal strategies for the urban context.

7.2.2 Housing features

The neighbouring Caribbean islands do show climate responsive features within the design of the house.

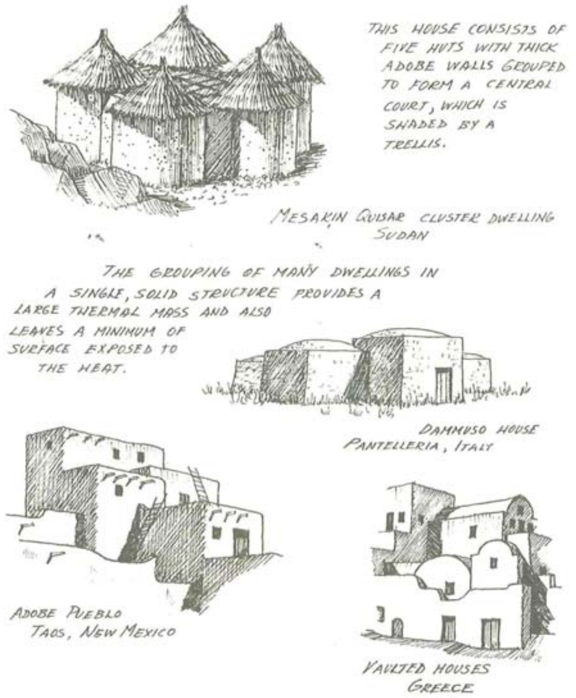


Fig. 7.3: Grouping of housing for a large thermal mass
Source: Taylor, 1997, pp. 64

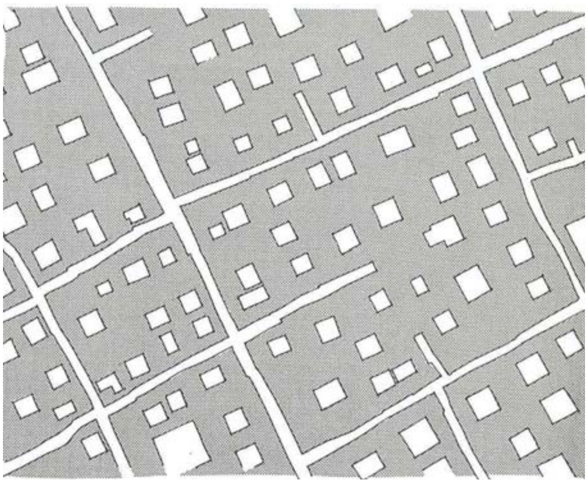


Fig. 7.4: Urban plan of the old town of Tripoli, Libya
Source: Evans, 1980, pp. 155

Veranda or balcony

Fig. 7.5 shows an urban house in Barbados with a shaded balcony. This also shades part of the facade. The one on the left has a balcony with floor to ceiling shutters just as the Jacaranda residence in the Bahamas (fig. 7.6). The floor to ceiling shutters promote ventilation, offer the residents the possibility to adjust the amount of light that enters the space behind it and offer privacy when wanted.

Fig. 7.5: Townhouses with unique Barbadian urban characteristics, Barbados
Source: Crain, 1994, pp. 79

Fig. 7.6: Jacaranda residence with floor height shutters at the balcony, Bahamas
Source: Crain, 1994, pp. 110

The climate responsive feature of the shaded veranda and/or balcony is also found in other parts of the world. Fig. 7.7 shows other countries with a warm climate that have their own architectural expression but share the same goal: catching the cooling breeze, protecting from precipitation and shading facades from direct solar radiation. The balcony is used as an additional living space, sometimes housing all the daytime activities.

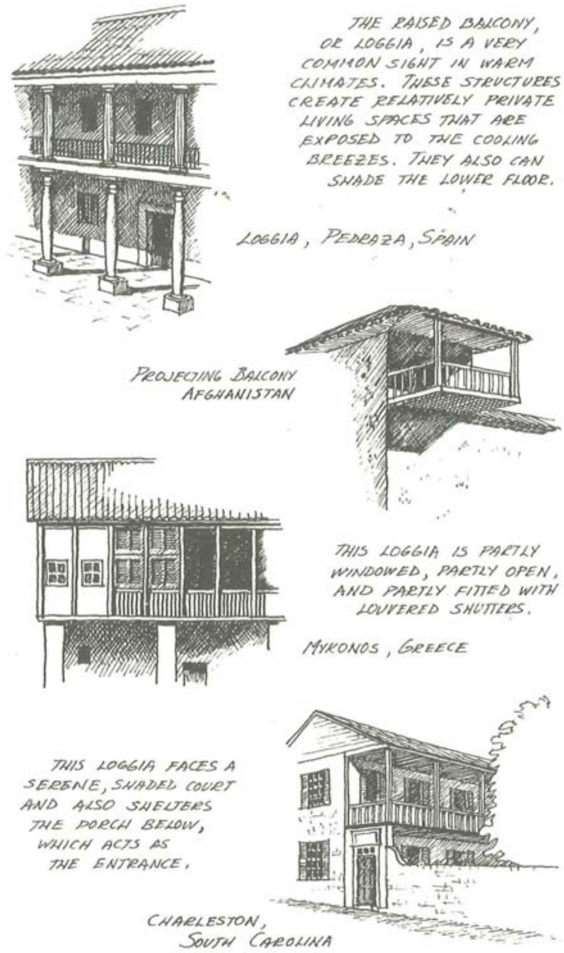


Fig. 7.7: Shaded balconies in warm climates
Source: Taylor, 1997, pp. 52

Airflow

Catching the breeze is the main goal of other climate responsive features found in warm climatic zones. Shutters have been mentioned before in relation to the balcony, but they are also applied as windows, doors or in front of glass surfaces. Shutters are a stacking of smalls trips of wood with a gap in between when they are open. They can also be used to adjust the amount of light that enters an indoor space. Fig 7.8 shows a small house in Trinidad which has shutter windows and a shutter front door.

Another climatic responsive feature of this house is the fact that it is lifted from the ground. This will promote air flow underneath the ground floor. When night temperatures are low this will cool down the house quicker than when the house is directly on the ground. Fig. 7.9 shows more examples of raised ground floors in other parts of the world. There is an example of a house which is lifted from the ground sig-

Fig. 7.8: Small house with shutters and lifted from the ground, Trinidad
Source: Crain, 1994, pp. 65

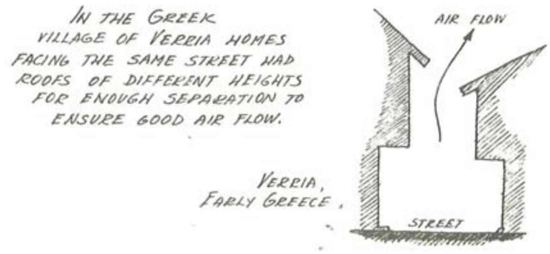


Fig. 7.10: Section of a street to promote airflow, Greece
Source: Taylor, 1997, pp. 57

nificantly to catch the prevailing breeze (tree house, New Guinea). In the hot an humid tropics, ventilation should be promoted to achieve thermal comfort. An example in fig. 7.9 shows the urban plan of a village in Sudan where the houses are spaced from each other to promote ventilation. This example is seen more often in literature, but examples of how to implement the strategy of optimizing air flow for the urban planning of the high density neighbourhood, is rarely seen if not at all.

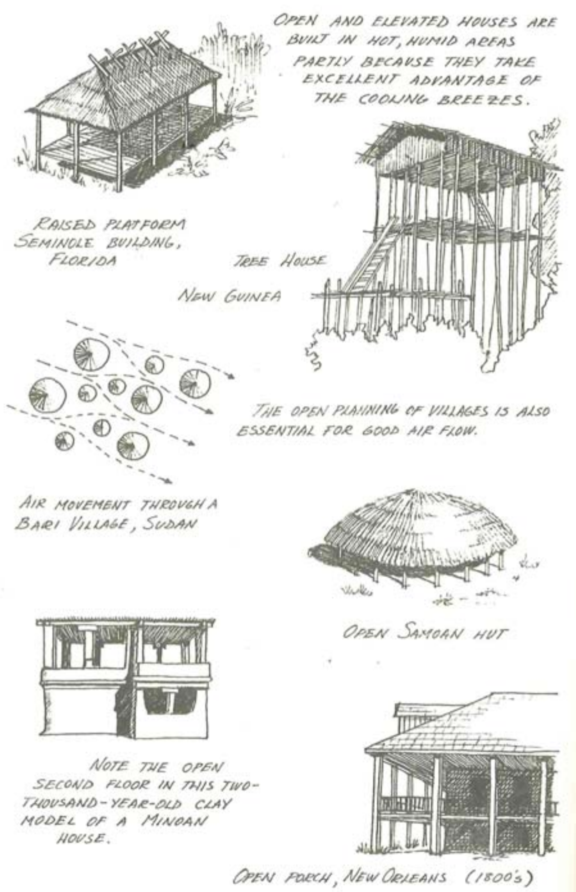


Fig. 7.9: Promoting ventilation
Source: Taylor, 1997, pp. 56

A building typology of a dwelling in Greece has a completely open floor (fig. 7.9). This space can be used for day time activities and even for sleeping during the night. In the context of Haiti one has to bare in mind that flies (and thus possibly malaria) are a spoil-sport when it comes to sleeping in the open air.
Another feature coming from Greece is the section of a street (fig. 7.10). This section shows different heights of pitched roofs which promotes air flow due to temperature differences. The temperature difference determines the amount of airflow.

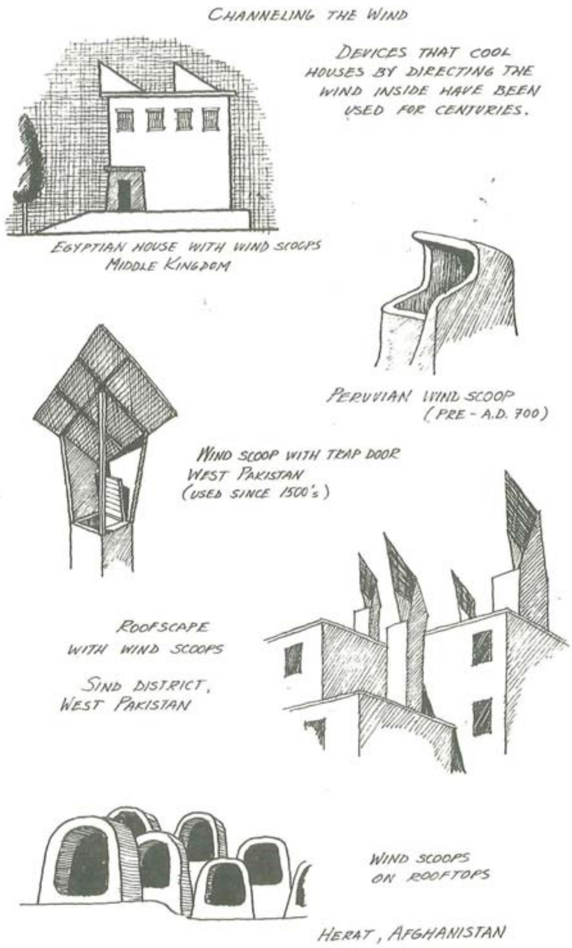


Fig. 7.11: Different ways to catch the wind
Source: Taylor, 1997, pp. 62

A way to direct the airflow into the building are wind catchers (fig. 7.11). With a standard wind catcher the cooling effect will be because of airflow passing by the human body. When the wind is first directed over a pond before entering the indoor space, which lowers the temperature by evaporation, the cooling effect will be because of a temperature difference between the human body and the ambient air temperature. The last version of the wind catcher is mainly found in the hot and arid climatic zones.

Vegetation

In the warm climatic zones, vegetation is used as a climate responsive feature to cool down the air (by evaporation), direct the air flow or offer shading. Fig 7.12 shows an internal courtyard of a house in Cuba. The courtyard has vegetation to cool down the air and offer shading. Vegetation can also be applied to shade a facade or roof of a building. Fig 7.13 shows a house in Louisiana (US) which uses vines on an iron grillwork to shade the outdoor facade.

Shade

Not only vegetation is used to offer shading to the residents and their houses. Shading is necessary in areas where the direct solar radiation is very intense. Haiti has very high solar radiation values since it is located close to the equator. Also, indirect or reflected solar radiation is unwanted. The reflection property of the pavement type and the materialization of the outdoor facade type of neighbouring buildings, determines the amount of indirect solar radiation causing in a heat load.

Fig. 7.12: Internal courtyard with balconies at the house of the Arabs, Cuba
Source: Crain, 1994, pp. 86

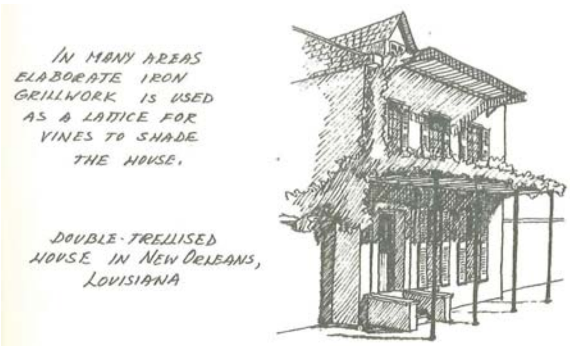


Fig. 7.13: Vines applied to shade the outdoor facades
Source: Taylor, 1997, pp. 49

Spanish colonial houses have adapted the Spanish architectural body to respond to the climate by preserving the courtyard (fig. 7.14), but adjusting the proportions of the house. The proportions have changed from a tightly enclosed space to an east-west orientation which maximizes the north and south facades (Evans, 1980).

Fig. 7.14: Spanish colonial house in the warma nd humid climate
Source: Evans, 1980, pp. 155

In Spain, fabrics are applied to shade the public space (fig. 7.15). A feature which was also observed by the author in a warm climatic zone of China. Wooden louvres between opposite buildings facing a street can also shade a public space, in fact a lot of different materials or building products can.

Angled shutters are applied by Ken Yeang in his 'roof-roof' design for a house (fig. 7.16). He designed an extra roof to shade the actual roof. He hereby created a shaded outdoor space on top of the actual roof. This

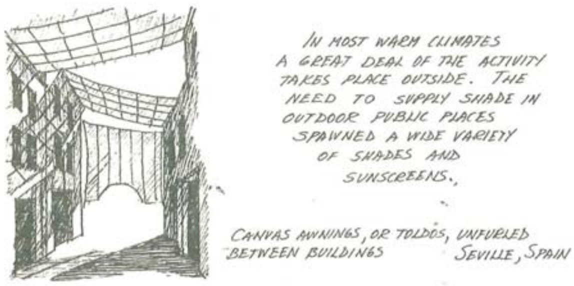


Fig. 7.15: Shading of the public space in Spain
Source: Taylor, 1997, pp. 50

Fig. 7.16: A double roof: a shaded parasol of angled shutters. By Ken Yeang
Source: Hyde, 2000, pp. 152

design shows similarities with the house design by the ancient Greeks (fig. 7.9). This climate responsive feature of a roof just to shade the underlying structure was also applied by the Yokut Indians of Southern California (fig. 7.17). They built an entire separated structure to shade their huts.

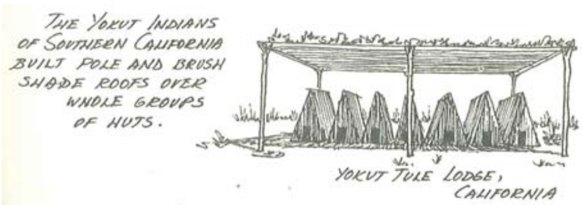


Fig. 7.17: A double roof to shade a group of huts, California
Source: Taylor, 1997, pp. 47

SUMMARY

It was not possible to determine the temperature, humidity or wind speed range for the indoor thermal comfort level in which the inhabitants of Villa Rosa would feel comfortable. The only recommendation which can be made is to promote ventilation of the indoor space to the fullest, because when both the temperature and the humidity are high the only way for the human body to loose heat is through evaporation. The potential of evaporation is dependent on the amount of airflow.
The toolbox which was started in chapter 5, can now be supplemented with climate responsiveness of similar climatic zones, hot and humid, around the world.

CLIMATE RESPONSIVE TOOLBOX

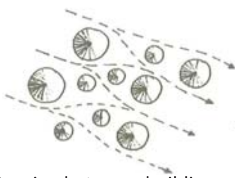
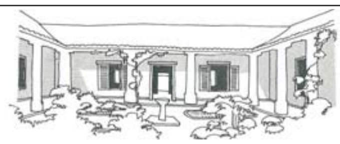
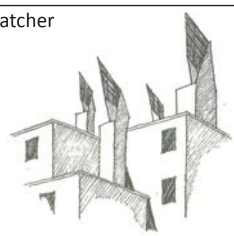
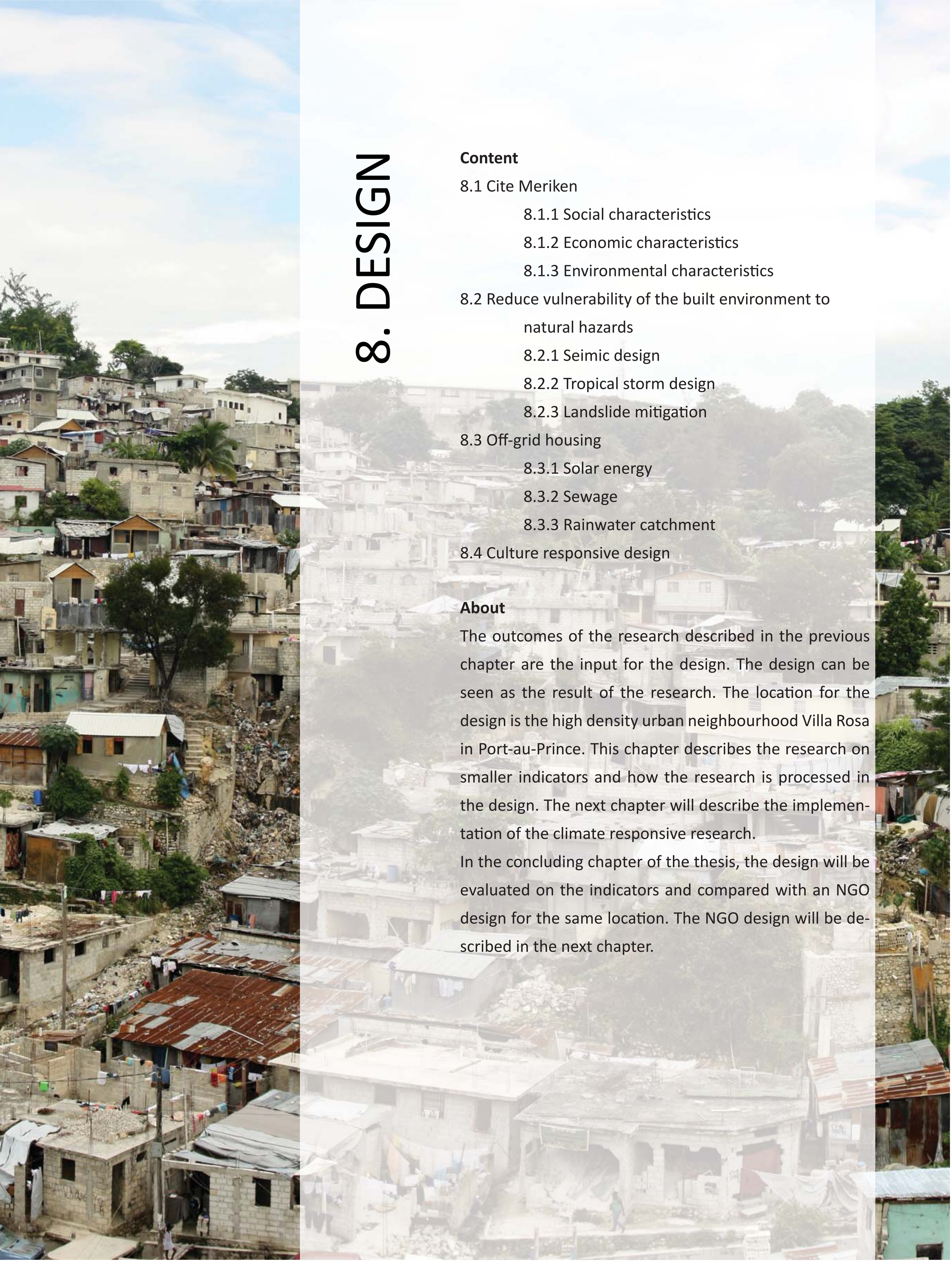
Urban form	• Shading of an inner courtyard • Spacing between buildings to promote airflow  Spacing between buildings to promote airflow  Shading of an inner courtyard
Architectural form	• Adjusting of facade surface according to solar angles  Adjusting facade surface to solar angle
Passive thermal strateges	• Elevated house to utilize airflow to the fullest • Windcatcher Windcatcher   Elevated house
Climate responsiveness	• Shaded balcony • Shutters • Shading of the surrounding built environment  Shading of the surroundings  Shaded balcony

Fig. 7.18: Conducting the fieldwork questionnaire of the perception of thermal comfort
Source: Author

Fig. 8.0: View on Villa Rosa
Source: Author



8. DESIGN

Content

About

The outcomes of the research described in the previous chapter are the input for the design. The design can be seen as the result of the research. The location for the design is the high density urban neighbourhood Villa Rosa in Port-au-Prince. This chapter describes the research on smaller indicators and how the research is processed in the design. The next chapter will describe the implementation of the climate responsive research.

In the concluding chapter of the thesis, the design will be evaluated on the indicators and compared with an NGO design for the same location. The NGO design will be described in the next chapter.

8. DESIGN

The research has up till now focussed on the climate responsiveness of the buildings and the use of locally produced, sustainable building products. These two subjects are the main focus of the research, but there are also small research topics whose outcomes are implemented into the design and decrease the vulnerability to future hazards. These topics were already introduced in chapter 3 as indicators of the delineation of the theory. These smaller research topics will now be discussed and the implementation into the design will be shown.

8.1 Cite Meriken

The location to implement the research findings into a design is an area within the high density urban neighbourhood Villa Rosa in Port-au-Prince. A new design, with the research findings, of the built environment for this neighbourhood, will act as an example case study for similar neighbourhood. If the design will be implemented on a large scale, this will stimulate the development towards a higher level of resilience to disasters.

One of the four smaller neighbourhoods within Villa Rosa is Cite Meriken. A series of concrete staircases that branch of the main road down in the valley and go up the hill of Villa Rosa (fig. 8.1), are used as physical landmarks to demarcate the boundaries of the four neighbourhoods (Cordaid, 2011). A small area of Cite Meriken is marked as the initial phase of the Integrated Approach (fig. 8.2). This is an approach developed by Cordaid and partner agencies which 'builds on the existing urban fabric and community's ability to organise themselves towards a common goal' (Cordaid, 2011). The aim of this approach is to build capacity including

Fig. 8.1: One of the main streets in Villa Rosa
Source: Author

livelihood opportunities for long-term improvements. The overall objective includes to 'improve their living conditions and environments'. This initial phase area is divided into ten sub areas. Zone number seven is chosen as the exact design location.

8.1.1 Social characteristics

Since the devastating earthquake, Cordaid (2011) has been carrying out assessments in Villa Rosa to investigate the neighbourhood characteristics. According to the assessment, there is a total of 1.474 households

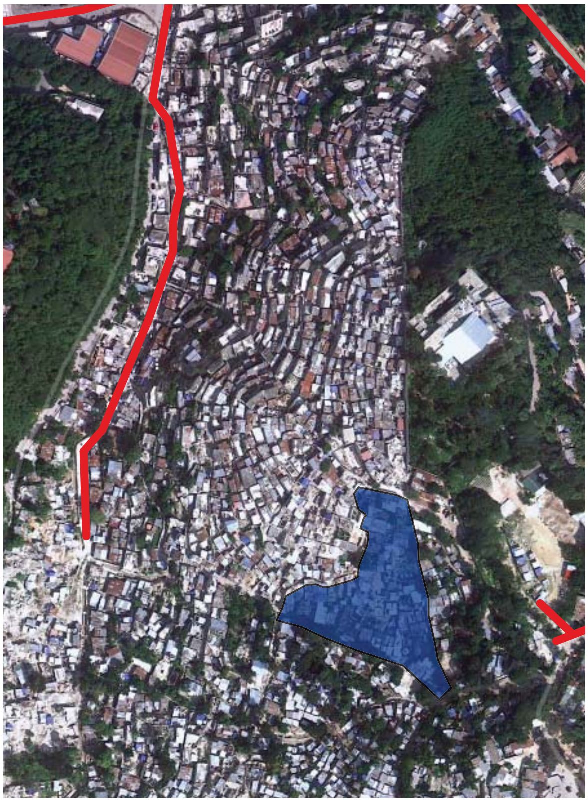


Fig. 8.2: Villa Rosa with the initial phase indicated in blue and car accessibility indicated in red
Source: Google earth and author

in Villa Rosa. With a total population for Villa Rosa of 8.168, the average household size is 5,5 members.
In Cite Meriken there are 568 households of which 215 are headed by a female, 38% of the total number of households. 199 persons are 65 years or older, which makes up for 35% of the population.
There is no health center in Villa Rosa, people go to St. Marie or Bourdon for medical care. There are three primary schools in Villa Rosa which is sufficient to cover the total number of school age children.

8.1.2 Economic characteristics

According to the assessment of Cordaid, 53% of the household heads in Cite Meriken are without income. This is above the national unemployment rate of 41% (CIA Factbook, 2010). Of the 538 households assessed in Cite Meriken, the labour force consisted out of 48 masons, 6 carpenters, 4 electricians, 14 plumbers, 6 painters/artists, 324 students, 235 commerce and 31 drivers. This shows a potential for economic activities for the commercial sector. The building industry is also well represented and can benefit from these numbers.

Villa Rosa is labelled as a slum since it is an informal, high density urban neighbourhood. Jane Jacobs (1961) addressed the problem of the downward spiral of slums in her book on American cities. The key link in such a 'perpetual slum is that too many people move out if it too fast- and in the meantime dream of getting out. If this link is broken, a slum spontaneously unslums.' This means that a so-called slum must try and keep those inhabitants attached to the neighbourhood that 'find it both desirable and practical to make and carry out their own plans right there. For the design, this implies that conditions must be created where businesses can carry out their activities.

8.1.3 Environmental characteristics

There has been none or very limited planning during the construction of Villa Rosa. The buildings are constructed on a sloped terrain 'without taking land stabilisation measures' (Cordaid, 2011). The informal neighbourhood has densified over the years, resulting in very small plots of sometimes only 10 m^2. There is irregular circulation often over 'private' land (Cordaid, 2011). A survey carried out by Cordaid shows that 90% of the people living in Villa Rosa do not have legal ownership over the land their house is built on. This has impeded the rebuilding process after the earthquake.
The neighbourhood is not accessible by car. There are only two vehicular accessible roads connecting to Villa Rosa. One down in the valley and one at the top of the hill which runs through St. Marie (fig. 8.2). Circulation inside the neighbourhood is on foot or by motobike. The main street connecting the valley with the top of the hill, is shown in fig. 8.1. Here, we see a special lawn in the middle of street for wheeled traffic.
Drinking water was supplied to Villa Rosa before the earthquake by a piping system, but the system was severely damaged and is currently not in service. The majority of the households have a pit latrine next to their houses. Very few have a flushing toilet with a sceptic tank. There is now solid waste collection with a disposal system present in Villa Rosa (Cordaid, 2011).
Due to the cutting of trees on the steep slope and the lack of proper surface water drainage, there is a high risk on soil erosion and landslides.

8.2 Reduce vulnerability of the built environment to natural hazards

Causes as to why the earthquake of January 2010 resulted in a disaster with so many casualties can be found in the vulnerability of the built environment to the natural hazard of an earthquake. No effective seismic building code was provided by the government, a lack of knowledge of the building industry about building materials and their response to seismic loading and perhaps also a lack of purchasing power of the inhabitants, these are all factors which contribute to the vulnerability.

A goal which absolutely has to be met in this research, is a resilient built environment to natural hazards. These hazards are to a certain extend predictable and thus the design can act on it. First we must know which natural hazards affect Haiti. From chapter 2 and 6 we know that the natural hazards are: earthquake, tropical storm, flooding, drought and landslide. A risk map shows the gradient of a risk to a specific natural hazard for an area. From the risk maps made by Mora (2010) we can conclude that in Villa Rosa only earthquakes, tropical storms and landslides are a risk.

8.2.1 Seismic design

During an earthquake the seismic forces that act on a building generate internal forces called the inertial force, Finertial (Whole Building Design Guide, 2010). Newton's second law of motion implies that this forces is calculated by:

$$F_{inertial} = M * a$$

Where M = mass
a = acceleration

The greater the mass, the greater the inertial force. The soil composition is of great importance when determining the risk. Soft soil generally has a tendency to increase shaking as much as 2 to 6 times as compared to rock (Whole Building Design Guide, 2010). The soil composition is part of the formula which calculates the risk gradient of the risk map.

The hazard of earthquakes at the design location is shown in fig. 8.4. The height lines are shown to give an indication of the location. Zone 7, the design location, is shown in white. The risk on a disaster caused by an earthquake in Villa Rosa is graded as *medium.*

The materialization of the structural components influences the choice of seismic design strategy. The choice is based on the mechanical properties of the materials and determines the way of detailing the joints. Seismic design strategies can be a rigid box with a moment resisting frame, base isolation (building has to be designed as a rigid box), floors and roof designed as diaphragms or shear walls/braced frames (Whole Building Design Guide, 2010).

Implementation in design

Wood was chosen as the material for the structural frame. This has a good energy absorption, is light weight but the connections or the joints are critical (Whole Building Design Guide, 2010).

The grid of the design is 1600 x 1600 [mm] which creates spans of only 3200 [mm]. This is very appropriate and common for seismic design. The design is three storeys high and therefor a seismic design is chosen

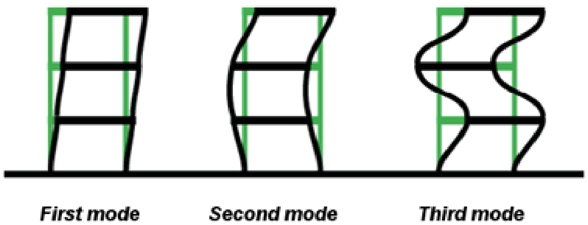


Fig. 8.3: Seismic modes of vibration
Source: Whole Building Design Guide, 2010

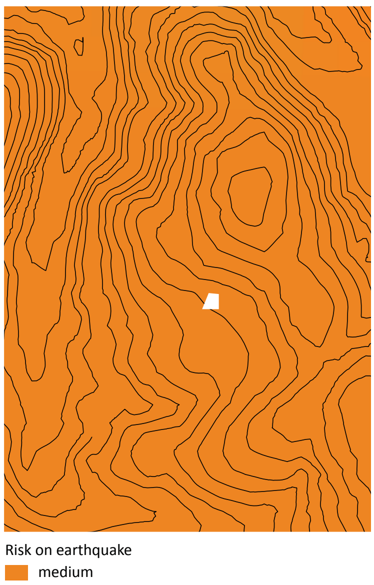


Fig. 8.4: Hazard of earthquake for Zone 7, Cite Meriken
Source: After Mora, 2010

where the stepped row blocks are designed as one entity with braced corners to increase the stiffness and prevent in deflection. Base isolation, which separates the foundation and the upper structure, is not needed. It will even increase the sizes of the structural components since a rigid structural frame is than demanded. The materialization of the floor is important to determine whether the floor needs additional bracing. The floor is part of the seismic design which has to withstand the seismic loading. The floor has to be stiff. When wooden planks are chosen, than braces between the beams should be applied to ensure the stiffness of the floors. If another material for the structure is chosen, than the design strategy should be adjusted. The seismic design is a braced wooden frame which does not have moment resisting joints between the columns and beams.

8.2.2 Tropical storm design

The wind gusts during tropical storms create high and low pressure zones in and around buildings. Therefore, care has to be taken in the designing of the buildings to reduce the vulnerability. First of all, the building should be appropriately attached to the foundation. Than the vulnerable elements of the design have to be indicated. These are the elements mounted to the structure. The roof is such an element and so are facade panels. When a roofing sheet gets blown of the roof, it poses a great danger to the environment.

There are design guidelines for the fixation of the vulnerable elements to the structure that should decrease the vulnerability. Fig. 8.5 and 8.6 show some of those design guidelines for the roof.

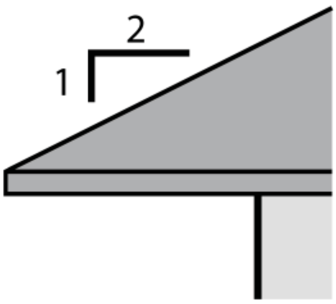


Fig. 8.5: Ideal roof slope to minimize the effect of fatal pressure cause by tropical storms.
Source: Architecture for Humanity, 2010, pp. 18

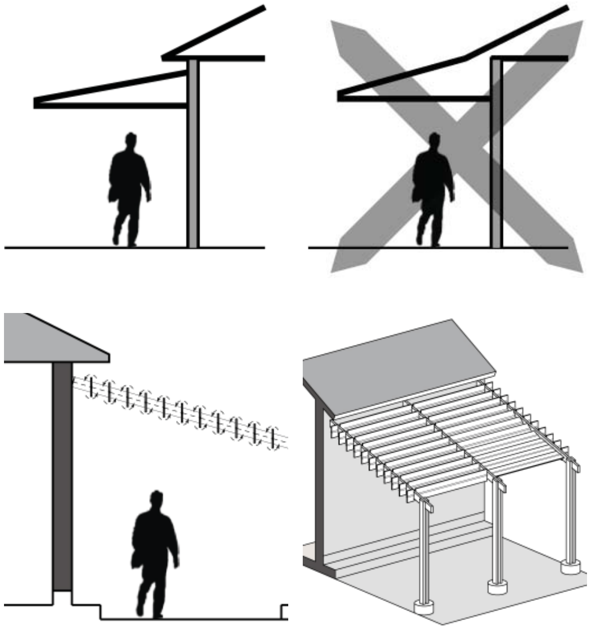


Fig. 8.6: Guiding principles for the design of a roofs and eaves subjected to a tropical storm.
Source: Architecture for Humanity, 2010, pp. 22

Implementation in design

The roof design of the top floor is sloped to catch the rain and guide it towards the drain and the storage tank. The slope of the roof is according to the design guidelines of Architecture for Humanity (2010), of the ideal slope degree 1:2.

The closed facade parts are not vulnerable to tropical storms. The shutters are vulnerable and should be well fastened. All openable facade parts (doors, shutters and windows), should open outward to prevent them from becoming interior projectiles during a storm.

Tropical storms are events that can be predicted and therefore security measures can be taken before a storm hits to diminish the damage. The balconies can be protected by closing them off with solid shutters.

8.2.3 Landslide mitigation

There are numerous causes for landslides to occur, the ones for Haiti are heavy rainfall and earthquakes. Heavy rainfall adds moisture and weight to the soil. Deforestation increases the susceptibility since less heavy rain is needed to trigger a landslide. Earthquakes cause shocks and vibration, which can create stresses that weaken slopes.

The hazard map of the occurrence of landslides in Villa Rosa is shown in fig. 8.7. The design location, zone 7

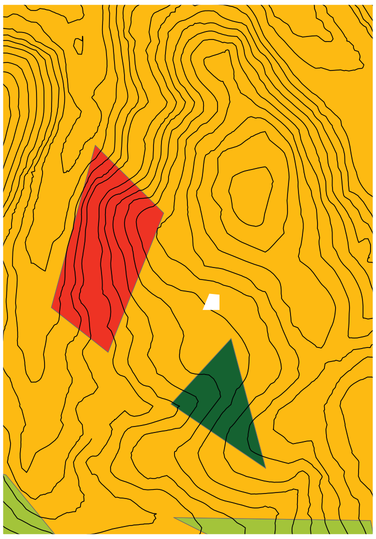


Fig. 8.7: Hazard of landslide for Zone 7, Cite Meriken
Source: After Mora, 2010

indicated in white, has a occurrence level of 4 which is high. The design should anticipate to this risk.

The number one measure to prevent in human loss by landslides is to stop building on steep slopes. But there are also some less dramatic measurements which can be taken to decrease the risk on disaster caused by landslide. To prevent for disaster, slopes must be stabilized. There are three ways to stabilize a slope: the geometric method (changing the geometry of the hill), the hydrogeological method (lowering the groundwater level to reduce the water content of the soil) and chemical and mechanical methods (increasing the shear strength of the mass or introducing external forces to contrast the destabilizing forces).

Implementation in design

The heavy rainfall and the inability of the soil to absorb the water due to deforestation is the most prevailing cause of landslides in Haiti. Measures that can be taken are the planting of vegetation, the control water run-off by proper drainage canals and not watering the slopes. In the courtyard of the design some small vegetation will be planted. At the street some bigger trees can be planted to decrease the vulnerability of the built environment to landslides. The water run-off will be controlled by proper drainage canals and semi-permeable bricks.

8.3 Off-grid housing

A way to achieve a higher level of resilience is by being less depended on the infrastructure of electricity, sewage and drinking water. The energy crisis, which some say will increase when developing countries are also becoming mass consumers, has underlined the need for the implementation of renewable energy. When a disaster, like an energy crisis, happens to an off-grid building, they are more resilient than buildings connected to the grid. The off-grid buildings are able to return to a reference state much quicker or are even not affected at all.

8.3.1 Solar energy

The potential for using the sun as the resource for energy is big in Haiti. It was observed that PV cells have already made there entrance to Haiti, both at the rural and urban areas (fig. 8.9). Due to high insolation values and an increased efficiency of PV cells, it is worth researching the potential for the design. PV panels tend to be very expensive due to the multiple layers of cells that are specified to create electricity out of a certain range of light. PV panels with only one layer of cells are less efficient, but also less expensive. These one layer PV panels may be within the purchasing power of the inhabitants of Cite Meriken. The use of solar energy can serve several purposes, for the design of Cite Meriken it can be used to provide in hot water and electricity.

A thermosyphon system (fig. 8.8) passively produces hot water by the heat exchange based on natural convection, which is convection based on a difference in

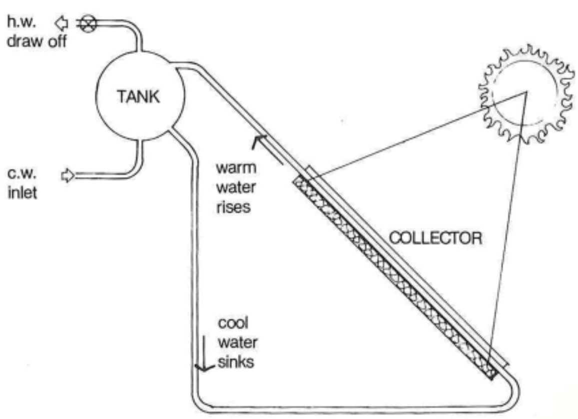


Fig. 8.8: Thermosyphon system.
Source: Fry, 1982, pp 235

Fig. 8.9: PV cells to generate electricity in Villa Rosa (top) and Septieme Gerard (bottom).
Source: Author

pressure. This pressure difference between warm and cold water will circulate the water. The solar radiation will warm up the water running inside the tubes in the collector. This warm water can be used for washing or cooking.
A Haitian company, Enersa, is manufacturing solar panels and solar appliances. In Haitian culture, music and mobile phones are indispensable. Lighting, music appliances and mobile phones are therefore the three main product groups where Enersa focuses on (Enersa, 2012).

Implementation in design
A thermosyphon system will be implemented to provide in warm water for the whole housing block. The system will be placed at the roof of the toilet units in the courtyard. The system will provide in hot water for

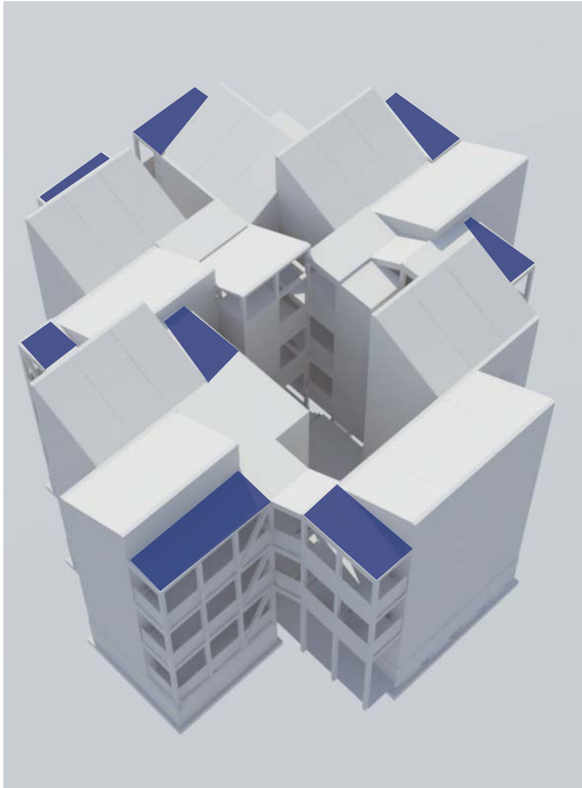


Fig. 8.10: Roofs selected for PV usage
Source: Author

washing purposes and cooking.
The individual houses will have a Solar Home System of Enersa, which consists out of 3 lights, a radio and a mobile phone charger, to provide in the needed electricity. The solar panel to provide the electricity will be placed on top of the balcony roof (fig. 6.18).

8.3.2 Sewage
Improper sanitation and sewage can cause in diseases and epidemic outbreaks when the waste is not treated or disposed properly. Off-grid solutions to sewage include EcoSan (ecological sanitation). This is an integrated sanitation strategy developed through traditional knowledge and biological science in which natural processes are utilized to transform human wastes (poop and pee) into fertile soil (Kramer, 2011). It is based on three principles: the prevention of pollution, the sanitation of urine and poop and using the 'waste' products to enhance agricultural production (Kramer, 2011). It creates livelihood opportunities for the community, since the compost and urine are valuable fertilizers. This system separates the wastes and stores them until it is transported to the composting site. The wastes are not in direct contact with fresh water and

will pose no danger in causing in improper sanitation. SOIL (Sustainable Organic Integrated Livelihoods) has the mission to transform wastes into resources in Haiti (Kramer, 2011). It is advised to separate the urine and the poop to reduce the volume that requires sanitation and transportation. In the urban context, off-site composting is necessary. SOIL uses a so-called poop-mobile to collect the drums filled with poop or urine and transport them to the composting site outside the city.

Implementation in design

In Cite Meriken there is no sewage infrastructure present. Pit latrines are the most prominent way of sanitation in Cite Meriken, accounting for 87% of the sanitation (Cordaid, 2011). A pit latrine is nothing more than a very deep pit with above it a toilet (fig. 8.11). When the pit is full, a new one has to be dug. A pit latrine neglects the economic potential of the human feces and there is still the risk on polluting water sources causing in improper sanitation. Also, flies are given the opportunity to breed in the sludge due to the larger amount of urine compared with poop. Poor ventilation causes in terrible odours and it increases the soil instability (Kramer, 2011).

In the design 9 UD (urine diverting) toilets (fig. 8.12) are implemented, 3 toilets per storey (fig. 8.13). The UD toilets have drums where the poop and carbon material, which is needed to remove odours, is collected. The drums will be transported to composting sites by the poop mobile. Effective management of the toilets is necessary for a successful project (Kramer, 2011).

Fig. 8.11: Digging a pit for a latrine
Source: Author

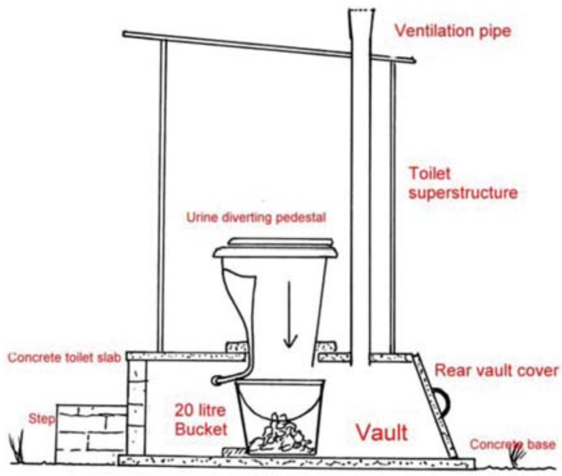


Fig. 8.12: Side section of urine diversion toilet.
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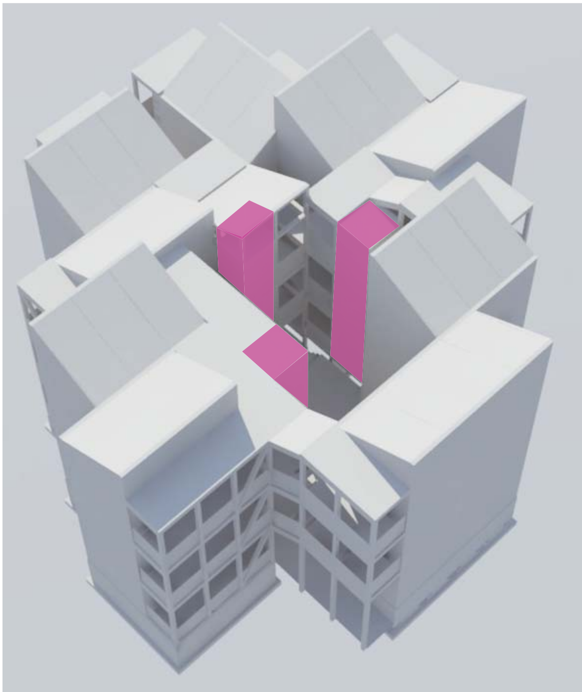


Fig. 8.13: UD toilets in courtyard
Source: Author

8.3.3 Rainwater catchment

Contaminated water and food are the main reasons which have caused in the epidemic cholera outbreak in Haiti. Fresh water can be provided for by an infrastructural system. This infrastructure for drinking water is lacking in Cite Meriken. Though there is a huge potential of drinking water which is not implemented at this moment: rainwater catchment and purification. It is stressed by a report by US aid agencies that the harvested rainwater does not typically contain essential minerals. So care should be taken in modifying intake diets (Project Concern International, 2010).

With an annual mean precipitation of 1321,7 mm (Moeller, 2001) in Port-au-Prince, a rainwater harvesting system is a huge potential. But this rainwater first has to be treated before it is drinkable. SODIS (solar water disinfection) is a water purification method using the solar radiation for a minimum of 6 hours at a high solar insolation. The ultraviolet wavelengths in the solar radiation kill the viruses, bacteria and parasites. The method is filling PET bottles with water and leaving them on the roof for at least one day. It does not remove chemicals or salt and thus using rainwater is the safest.
Haiti is subjected to annual tropical storms which can cause in heavy rainfall. During these heavy rainfalls, slow infiltration into the ground of the water can cause in floodings and/or landslides. The rate of infiltration is determined by the gravity, capillary action and soil porosity. The soil porosity is controlled by its texture, structure and organic content. Measurements have to be taken to mitigate the risk on flooding and landslide. Vertical drainage can bring the excessive water deep into the soil to the groundwater level.

Implementation in design
The sloped roofs of the houses will catch rainwater (fig. 8.14) which is stored in a tank per two houses. An appendix shows the calculation of the capacity of the rainwater storage tanks. A total of five tanks, made out of recycled plastic with a pump, pressure tank and tap, are implemented in the design below groundlevel. The rainwater potential for harvesting is unfortunately not sufficient to provide in the amount of 15 L/day required per person (The Sphere Project, 2011). The deficit has to be supplemented with water that is bought. Non-potable water costs approximately US$5 per m^3 delivered in Port-au-Prince (Project Concern International, 2010).
If 5,5 person is living per house than 16 persons share 14 m^2 of rainwater harvesting potential. This results in 1156,48 L rainwater per person per year. The demand for water is 5475 L per year. This leaves a deficit of 4318,52 L per year. The costs for this water will be $21,6 per year per person.
The pavement type at Cite Meriken at this moment is cement. This material does not allow for water to be absorbed by the soil. The very few drainage channels (fig. 8.15) present in Villa Rosa, direct the water towards the open sea if the channels are not clogged with solid waste. The application of permeable bricks (fig. 8.16) will increase the amount of water absorbed by the soil and decrease the pressure on the drainage canals. It also reduces the reflection of solar radiation significantly from 40% for pavement and only 20% for grass (fig. 6.14). During heavy rainfall the absorption

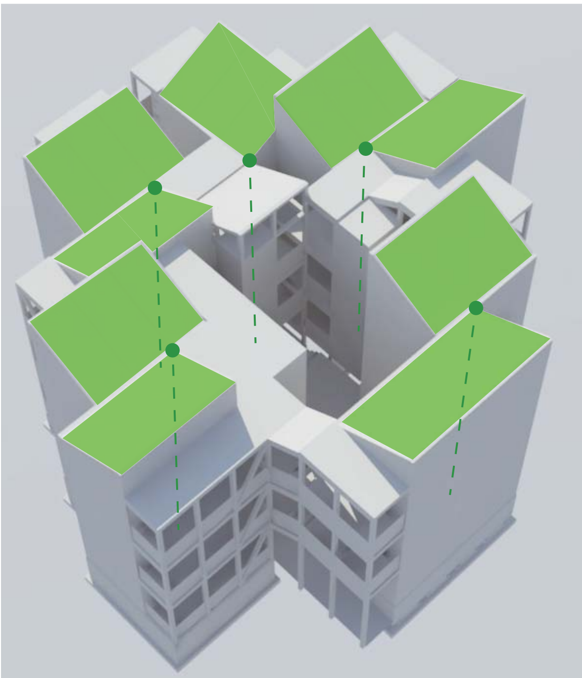


Fig. 8.14: Rainwater catchment roof surfaces and vertical drainage
Source: Author

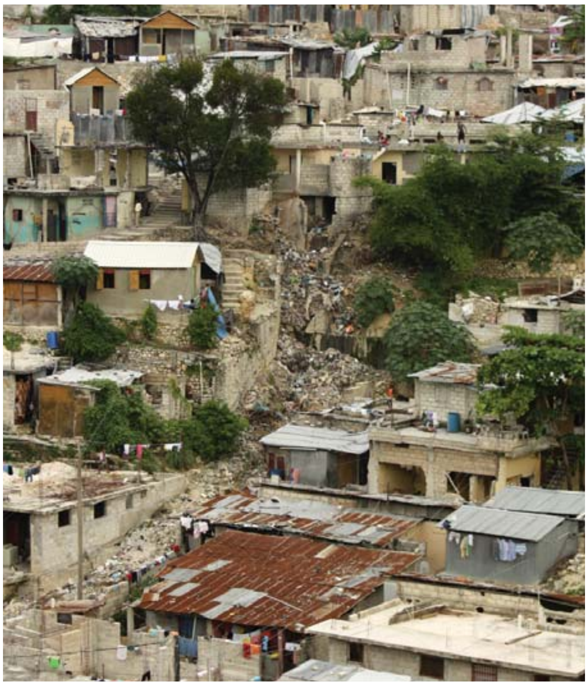


Fig. 8.15: Drainage channel Villa Rosa clogged with solid waste.
Source: Author

Fig. 8.16: Permeable pavers
Source: http://lateameffort.blogspot.com/2010/04/road-less-traveled-pervious-pavement.html

of water by the soil will not be fast enough to deal with the water. Other measures such as proper drainage and vertical drains at the bottom of the hill have to be provided.

8.4 Culture responsive design

There are factors from a cultural and contextual point of view which influence the design. These factors do not increase or decrease the resilience, but are important for the cultural relevance of the design.

House and household size

From an assessment by Cordaid it was found that the average household size in Cite Meriken is 5,5 persons. The average amount of floorspace of a household is only 15 m^2. It is not specified wether these square meters include an outdoor space if there is one.

The design provides per household unit in 14 m^2 of indoor living space and an additional 5 m^2 of veranda or balcony where cooking activities take place.

Flexibility

Purchasing power and affordability are two very important factors within the context of Haiti and the design. The building process in Haiti of a house has several phases during which an extra floor and walls will be added when sufficient funding is present. This poses a threat to the structural safety of the house. Therfore and for seismic design purposes, in the design the whole structure, including the roof and floors, is built during the first phase. To provide in flexibility for the people it is possible within the design to link two houses by an interior door creating. This will double the living space.

Constructing the roof already in the first phase will offer, according to Van Lengen (2007), the advantage that walls for the second phase can be made with 'lighter and less costly materials' and that the space on the ground floor, which is still unbuilt can be used as 'a rest area, a dining room or workshop'.

Population growth

It was found that the Lakou system of communal living, described in chapter 5, still finds its occurrence in the urban context. Families want to live in each others proximity. When a family expands with children extra floor space is needed and ideally this is found in the same housing block. This is the first reason why there is extra floor space in the design.

The second reason is that it is predicted that the urban population will grow with 3,9% annually. For these people housing is needed. Since transportation means are low, people want to live in the proximity of their economical activity. The already dense neighbourhoods such as Villa Rosa, will densify in the coming years. Providing already in extra floorspace will at least make sure that the structural safety is guaranteed.

The extra floor space added to the design, has resulted in a three floor design.

Stimulate local entrepreneurship

A goal of this research is to stimulate the economic growth of Haiti. To do so, jobs have to be created to reduce the high unemployment rate and to increase the purchasing power of the people.

For the new design of Cite Meriken, extra floor space is added to stimulate the establishment of local businesses.

Fig 8.17 shows a map of the initial phase area in Cite Meriken with the local businesses and services. There are three primary schools, water points, solid waste collection points and cultural and medical facilities. Zone 7 houses a barber shop, a water point and a solid waste disposal ground. The road bordering the zone on the left is a main road in connecting the valley with the top. This place has potential for starting up local businesses.

The created courtyard in the design can also be used for business purposes. An example of a business which can be started is the small-scale production of sustainable building products. For example permeable bricks from rubble which serve as paving. Or the weaving of bamboo mats which will later be pressed into corrugated roofing sheets.

Voodoo

Prominent in Haitian culture, especially at the rural areas, is Voodoo. Opinions differ about wether it is a religion, a culture or a lifestyle. It is expressed in the house design in the detailing, colouring and decorations (fig. 5.14). But also in for instance in the number of doors in the Ti Kay typology, described in chapter 5. There is no set of rules as to how design a house in line with voodoo believes. In the new design for Cite Meriken the people can add woodcarving or colours to express their believes.

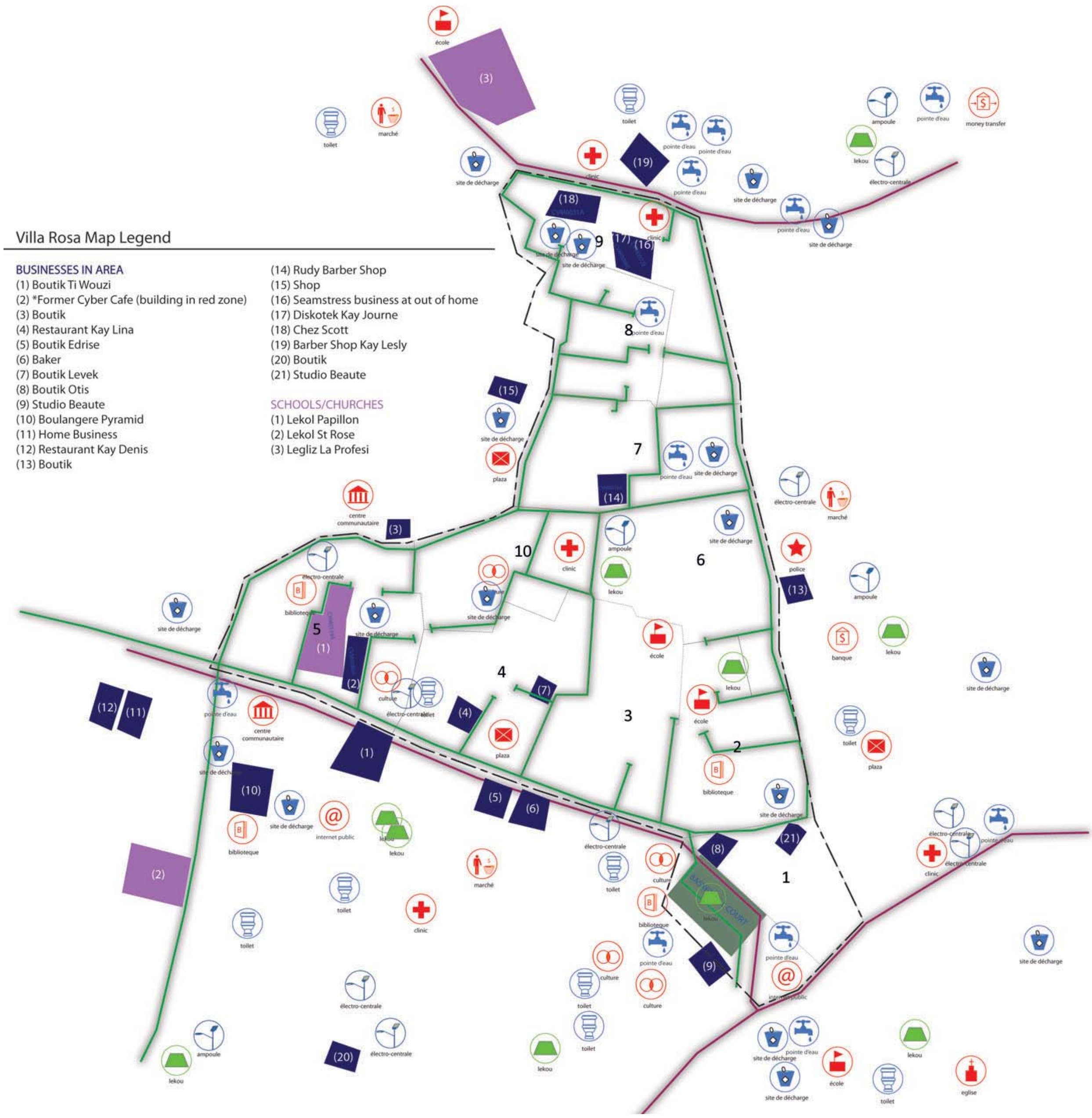


Fig. 8.17: Services within the initial phase area of Cite Meriken
Source: Architecture for Humanity

SUMMARY

The location for the design is the informal, high density urban neighbourhood Villa Rosa in Port-au-Prince The neighbourhood is located on a steep slope and was hard hit during the earthquake. This neighbourhood is the typical concrete jungle which is seen all over Port-au-Prince.

The natural hazard of the earthquake does not pose the greatest risk on disaster in Villa Rosa, landslides do. The third natural hazard which poses a risk are tropical storms. The outcomes of the research on how to mitigate the risk have been implemented into the design.

Man made hazards can also result in a disaster. Mitigating the risk is difficult since these hazards are difficult to predict. What can be done is to be as independent as possible. Therefore, the design is not connected to the infrastructure of electricity, sewage and water. Electricity is gained by PV panels, a sewage is not necessary since all toilets are dry toilets and rainwater is stored to diminish the daily demand for water.

Cultural or contextual responsiveness is necessary for the design to be accepted by the future user. Several cultural aspects have been implemented in the design. Flexibility of the construction process and the housing sizes, extra space for population growth, local entrepreneurship is stimulate by extra floor space for economic purposes and there is a possibility for the user to express cultural believes by painting the house or decorating with woodcarving.

RESILIENCE TO NATURAL AND MAN MADE HAZARDS AND CULTURE RESPONSIVENESS

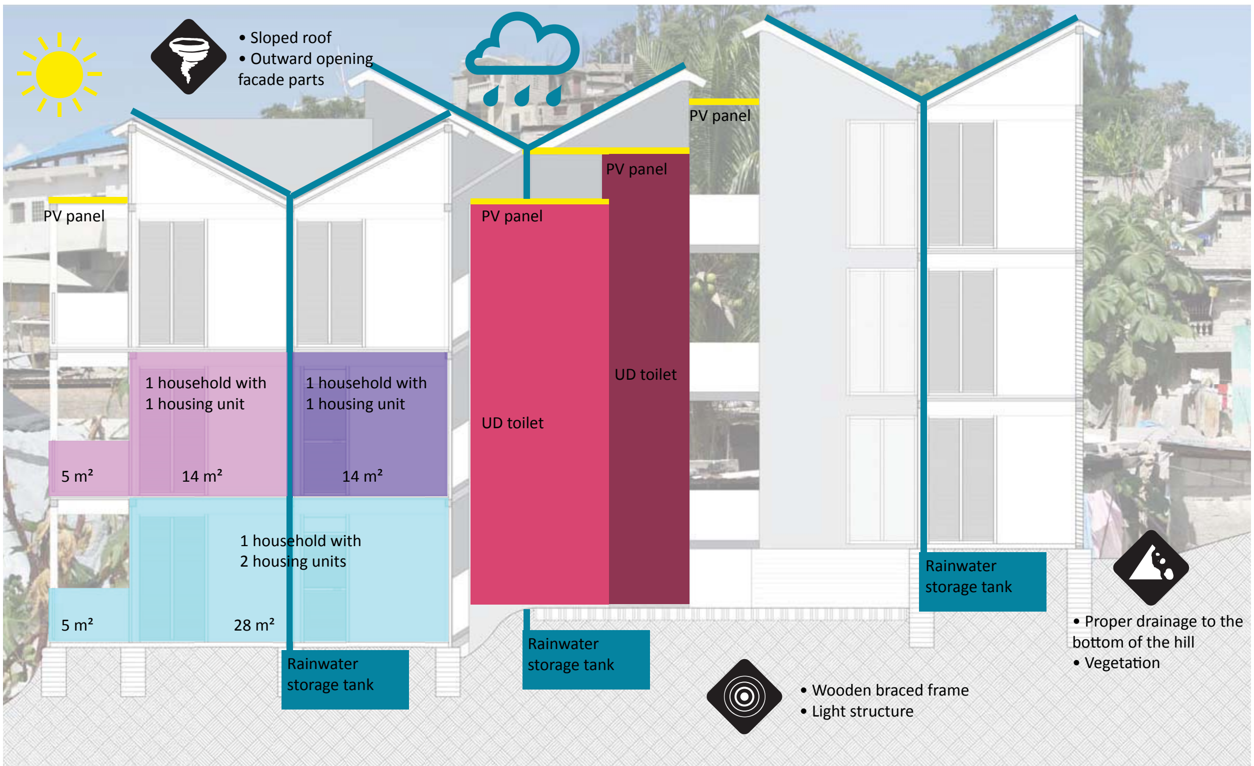
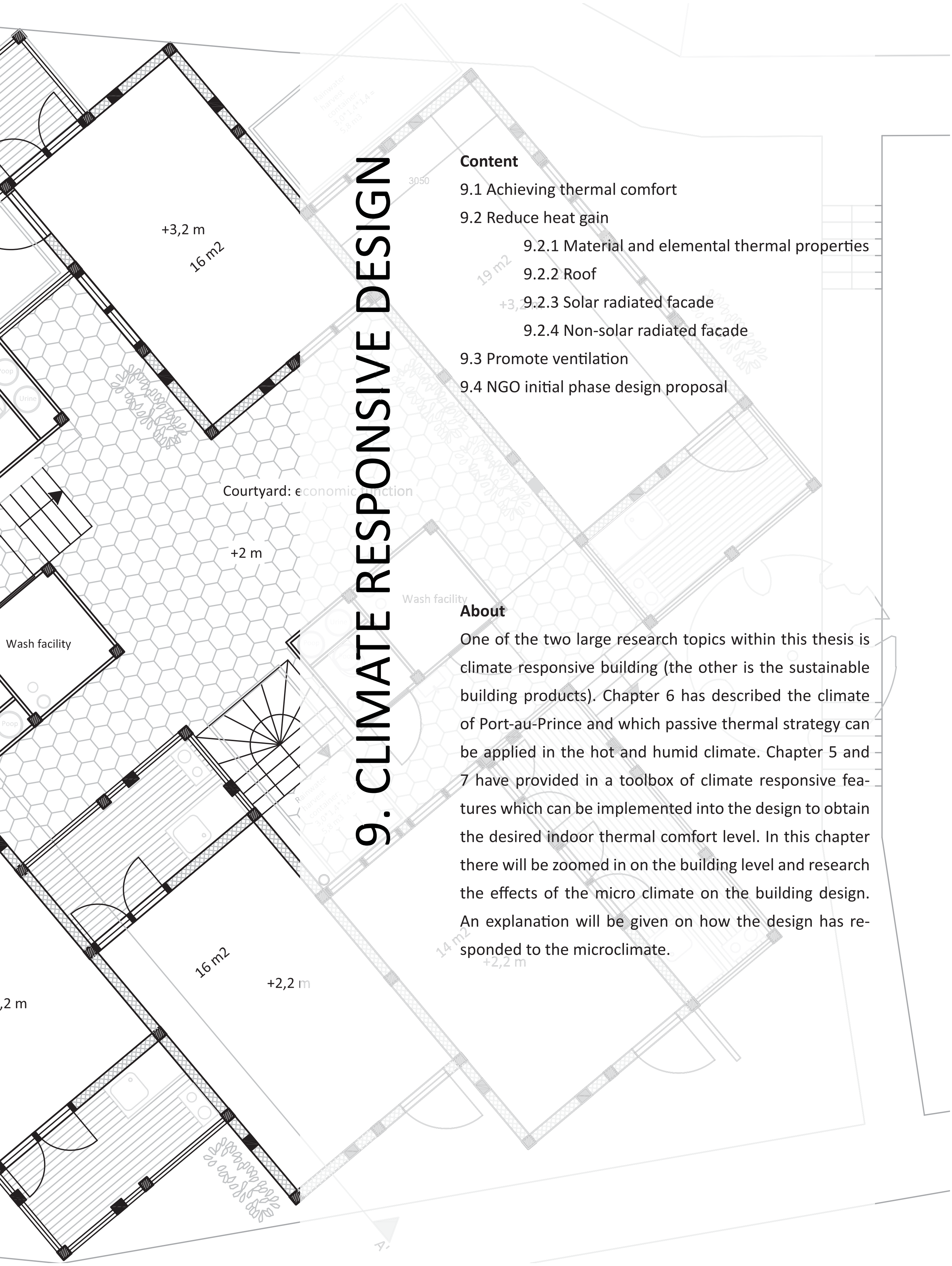


Fig. 9.0: Groundfloor redesign Cite Meriken



9. CLIMATE RESPONSIVE DESIGN

Content

About

One of the two large research topics within this thesis is climate responsive building (the other is the sustainable building products). Chapter 6 has described the climate of Port-au-Prince and which passive thermal strategy can be applied in the hot and humid climate. Chapter 5 and 7 have provided in a toolbox of climate responsive features which can be implemented into the design to obtain the desired indoor thermal comfort level. In this chapter there will be zoomed in on the building level and research the effects of the micro climate on the building design. An explanation will be given on how the design has responded to the microclimate.

9. CLIMATE RESPONSIVE DESIGN

The form, layout, orientation and scale of dwelling-groups should be controlled in relation to the needs of the climatic zone. For both indoor and outdoor (surroundings) especially in hot climates where activities most of time are taking place outdoors (Evans, 1980).

To reduce the risk on disaster by hazards, communities must become more resilient. Achieving a higher level of resilience is accomplished by reducing the vulnerability on social, environmental and economical aspects of the community. The design of the built environment is a tool to achieve this goal since it creates the conditions for sustainable development towards a higher level of resilience. The research described in previous chapters has given input for the design.

A climate responsive design is the starting point to achieve this goal of a higher level of resilience. The form of the buildings can be adjusted to reduce the impact of unfavourable aspects of the climate (Evans, 1980). For the context of Haiti this entails designing with a response to reduce the heat gain by direct and indirect solar radiation on facades and roof and the promotion of ventilation to achieve thermal comfort. Important in how to achieve thermal comfort is not only the design of the buildings, but the whole built environment around the buildings. Especially in hot and humid climates as Haiti's where outdoor spaces function as indoor spaces. These spaces harbour activities such as cooking and in some cases employment.

9.1 Achieving thermal comfort

Resilience can be increased by improving the health conditions within a community. In chapter 7 it was discussed that feeling thermally comfortable inside a house improves the ability to cope with heat stress incurred during the day. It was also discussed that obtaining indoor thermal comfort in the hot and humid climate is passively only possible through promoting ventilation by air flow. But first, heat gain due to solar radiation on the exterior surfaces of the building should be minimized as much as possible. Conflicts may occur between a demand of daylight for indoor activities, the minimizing of heat gain and the tedious effect of glare.

9.2 Reduce heat gain

In the warm and humid climate with small diurnal temperature differences, the indoor and outdoor heat gain should be minimized as much as possible. Outdoor heat gain is caused by solar radiation on the facades and roof and by indoor heat gain by heat producing activities. It was observed by the author that cooking, the main heat producing activity, is taking place outdoors in Haiti. In the design, a space to cook is reserved at the outdoor space of the veranda or balcony.

The heat gain coming from solar radiation can be divided in direct solar radiation and indirect radiation. The direct solar radiation will be most intense on the roof, west facade and east facade, in this specific order. The east facade receives slightly less heat load, since morning temperatures are lower, humidity higher and skies may be more cloudy (Evans, 1980). The direct solar radiation is short wave radiation and the indirect radiation, or thermal radiation which is emitted by elements from the built environment, is longwave radiation.

To reduce the heat load on the building shell of the design we must first know what different thermal conditions there are for the elements of the building and which thermal properties of the materials are related to those conditions.

9.2.1 Material and elemental thermal properties

There is a difference between material thermal properties and elemental thermal properties. In a layered facade or a layered roof the material properties can be used to determine the elemental properties. The elemental properties are needed to determine the heat gain by or heat flow through the element. Different values for thermal properties may be leading during the decision making process of the materialization.

The important thermal material properties are:

• Absorptivity, a [%]

Proportion of solar radiation which will be absorbed by the material. This property is colour depended. The reflectivity of a material is: r = 1- a

• Conductivity, λ [W/m*K]

Rate at which heat will be transmitted by the material.

• Thermal capacity, C [J/K]

Amount of heat required to raise the temperature of the material by one degree.

The elemental important thermal properties are:

• Overall heat transfer coefficient, U [W/m²K]

Rate at which heat is transmitted from one side of the element to the other side.

• Solar heat gain factor

Determined by q/I, where q [W/m²] is the rate of heat transfer through a construction and I [W/m²] is the intensity of the solar radiation.

• Time lag or delay, Φ [h]

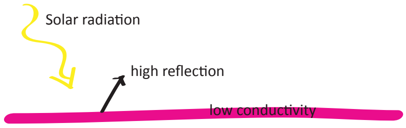
Difference in time between the change in outdoor temperature and the indoor temperature response.

• Admittance, a [W/m²*°C]

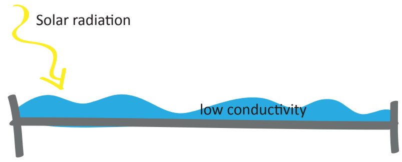
Rate at which heat is absorbed or emitted when there is a difference between air temperature and surface temperature. High admittance is achieved by using heavy materials such as brick and concrete (Evans, 1980).

9.2.2 Roof

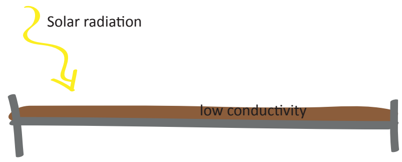
The roof will receive the most direct solar radiation due to the proximity to the equator with high solar angles (fig. 6.9). Fry (1982) stresses the fact that in warm and humid climates, even under overcast conditions, the solar radiation is high. Another important function



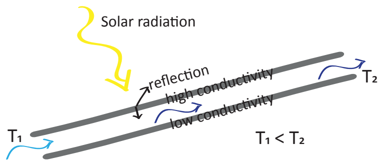
Ideal roof
One material that has a low absorptivity and a low conductivity.



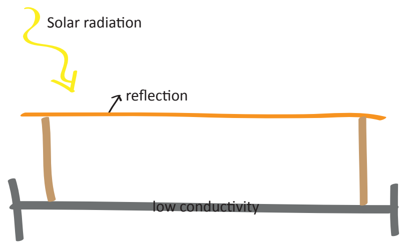
Roof pond
High specific heat capacity of water makes it a good insulator. Technical complex, extra structural requirements, attracts flies.



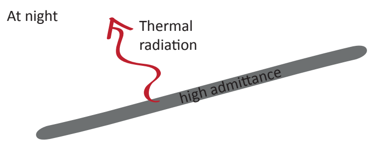
Earth roof
The layer of earth acts as an insulator. Technical complex and extra structural requirements. Positive aspects within the conext: space to grow food.



Double solid roof
Two layers with an air cavity in between. The air cavity is ventilated and hereby removes unwanted heat.

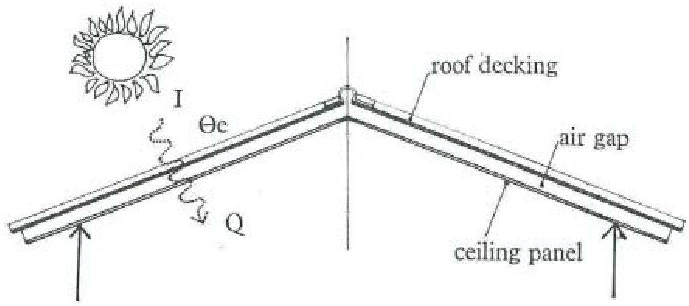


Shaded roof
The roof surface is shaded by another surface (for example by fabric) which reflects the solar radiation. The roof's material need to have a low conductivity to prevent heat gain by thermal radiation.



Radiative roof
At night the roof looses heat by radiating towards the sky. Highest heat loss when there is a clear sky. The roof material needs to have a high admittance.

Fig. 9.1: Roof typologies and thermal properties.
Source: Author



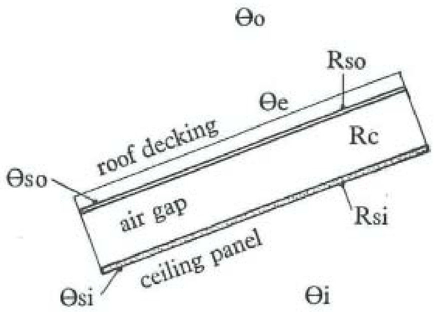


Fig. 9.2: Heat flow through a standard roof and corresponding thermal properties.
Source: Koenigsberger, 1965, pp20

of the roof which we must not forget in this context, is that it is offering protection from the rain and storm. According to Koenigsberger (1965), a roof must absorb as little radiant heat as possible and offer almost complete resistance to heat flow which is from the outside to the inside. This results for the design in a roof material with absorptivity, a, as low as possible (or a high reflectivity, r) and a conductivity, λ, as low as possible. In the ideal situation there would be one material that posses these thermal properties (fig. 9.1).

Thermal insulators, such as polystyrene and glass-wool, have a low conductivity due to the low density of the material. The thermal property of absorptivity is depended on the colour of the material. White reflects the most solar radiation and black absorbs the most. The property of absorptivity changes for some materials with aging. For instance, new corrugated roofing sheets of iron start of with a high reflectivity, but due to corrosion this decreases. Dust, fungus and algae can also discolour the surface and change the thermal property (Koenigsberger, 1965).

An ideal roof based solely on the thermal properties would be a white painted insulator. However, this ideal roof which main goal is reducing the heatflow by selecting the materials on the thermal properties, may not be the ideal roof within the total picture. Other factors such as the resistance to storm and precipitation, seismic performance, durability and costs are important. They have to be taken into account when making a decision on the roof design and the materialization.

Heat flow through a roof

Before choosing a roof typology with a materialization, we have to analyse the heat flow through a roof. Fig. 9.2 shows the section of a standard roof, a double solid roof, with the heat flow and corresponding thermal properties of the element and materials. Thermal radiation by the reflection of the neighbouring built environment will not be taken into account when determining the heat flow through the roof. Because this thermal radiation is negligible small in comparison to the direct solar radiation.

So the goal of the roof design is to minimize the heat flow and keep the ceiling temperature as low as possible. The temperature of the ceiling should be kept as low possible to prevent radiation. According to Koenigsberger (1965) an increase of the ceiling temperature of around 5 °C above the ambient air temperature is acceptable.

The heat transfer through the roof, or heat flow, is calculated by:

$$Q = U * (\theta_e - \theta_i)$$

Where U = thermal transmittance
θ_e = outdoor temperature
θ_i = indoor air temperature

The outdoor temperature, θ_e, is not the dry bulb temperature of the outdoor air which is derived from the climatic data. The calculation of the heat flow through the roof and the ceiling temperature are provided in the appendix. The calculations can only be made when the materialization of the roof is known.

Roof design

The design and materialization determine the indoor heat gain through the roof. Fig. 9.1 shows several roof designs which can be divided into three principles. The first is a thick roof package with a low conductivity (roof pond and earth roof). The second is a layered roof which is ventilated (double solid roof and shaded roof). And the third is a radiative roof which is 'active' during the night and has to be insulated during the day.

A decision for one of the three principles should be based not only on the thermal properties, but also on the other factors which were described earlier. Table 9.1 shows the decision making model for the roof design. The possibility to catch the water is important to increase the resilience by off-grid housing. According to Van Lengen (2007), steep slopes of roofs in the hot and humid climate are desired for the drainage of rainwater. Because a steep roof is less affected by solar radiation and a steep roof creates an air buffer underneath.

	Roof principle 1	Roof principle 2	Roof principle 3
Thermal performance	Good	Good	Cools during the night, if insulated the performance during the day is acceptable
Resistance to storm and precipitation	Good during a storm, difficult to deal with the precipitation	When sloped, good performance to storms and water catchment	Vulnerable to storms, good water catchment possibilities
Seimic performance	Bad (heavy)	Good (light)	Good (light)
Durability	Depended on materialization	Depended on materialization	Depended on materialization
Costs	Due to heavy weight, extra costs for the supporting structure	Depended on materialization	Depended on materialization

Table 9.1: Decision model for the roof

A layered roof which is ventilated, is the best option for the roof design, since with relatively affordable measurements it can be made resilient to storms. To catch the rain the roof has to be pitched, improving also the ventilation of the roof. The materialization will be discussed in the next chapter.

9.2.3 Solar radiated facade

Indoor heat gain can also be caused by direct solar radiation on the facades. As opposed to the roof, these facades can be designed in a way to receive the least solar radiation by shading them. From chapter 5 and 7 we saw that balconies are applied to the design to shade the facade and to provide in an outdoor private space. Balconies, verandas and overhanging eaves are all design features which block the direct solar radiation on the facade, thus not causing in indoor heat gain.

Shading can also be provided by vegetation. An ivy kind of vegetation, will shade the facade. Larger vegetation such as trees can also direct the airflow, cool the air and offer a thermally comfortable outdoor space underneath the tree.

Since the facades will have to deal with thermal radiation, other thermal properties are determining the heat flow through the element. Thermal radiation is emitted by surfaces when the surface temperature rises above the ambient outdoor air temperature. The material property related to this is admittance. When the surface temperature is below the ambient outdoor temperature, the surface will absorb heat from the ambient outdoor air temperature coming to a state of equilibrium. If heat is absorbed, it is stored in the element. This is highly unwanted since this will cause in radiation of the heat to the indoor space at night when the temperatures are low.

For the direct solar radiated facades, ways to shade have to applied first. When this is impossible, materials or elements need to have a low conductivity and/or a low thermal mass.

9.2.4 Non-solar radiated facade

The direct solar radiation on facades can be blocked by design features such as verandas, balconies and vegetation. This should be applied in the design to those facades receiving the most solar radiation (west orientated facades). A solar study of the design is shown in fig. 9.3. In the design for zone 7, it is not always possible to apply the veranda or shaded balcony at the west facade, due to the form of the plot and the morphology of the housing blocks which will be explained later. When a facade is shaded the materialization can be different than those which receive direct solar radiation. The thermal properties of the material is of lesser importance. The need for the promotion of ventilation determines the design of these facades. If there may be heat gain despite of a good design, the walls must have a high conductivity and a low thermal mass to loose this heat when temperatures drop during the night.

9.3 Promote ventilation

If the outdoor and indoor heat gain are as low as possible, the last step to provide in thermal comfort is to promote ventilation. To provide in a thermally comfortable indoor situation, air movement is essential in the hot and humid climate (Evans, 1980). Catching the wind or turbulence is the passive way to ventilate a building.

Wind or air movement is caused by a pressure differences in the atmosphere. The goal of the wind is to come back to a state of equilibrium which is never reached due to the creation of new pressure zones by the sun. Wind will flow along the path of the least resistance. In high density urban zones, with a lot of resistance because of buildings, the path of the wind is unpredictable. It is no longer named wind, but turbulence. Since the morphology of urban areas changes constantly it is difficult to design for catching the wind. Urban climatic studies produces a GIS-based UCMap (Urban Climatic Map) which can be used by urban planners when making 'strategic planning decisions' (Chao, 2009). Such a study includes information about the building volumes, topography, green spaces, ground coverage, natural landscape and proximity to openness. Just like Port-au-Prince, Hong Kong has a hot and humid climate, a hilly topography and a very high building density. The government of Hong Kong commissioned in 2006 studies towards producing a UCMap since the general public got fed up with the 'Wall Buildings' build by developers which blocked the wind promoting ventilation of the city (Chao, 2009). From the draft of the UCMap of Hong Kong a major negative factor to decrease air ventilation is ground coverage (ground occupied by buildings). Positive effects that increase air movement are natural landscape and the proximity to openness (Chao, 2009).

Composing a UCMap for Port-au-Prince falls outside the scope of this thesis research, but assumptions based on the findings from the Hong Kong map can still be made.

Morphology of the design

The prevailing wind direction in Port-au-Prince is east (fig. 6.8). From fig. 9.4 and fig. 9.5 we can see that this wind is blocked by the hill. Villa Rosa is located on the leeward side and St. Marie on the windward side. Luckily, another type of air movement is caused by the temperature difference between the valley and the top of the hill. In the morning the top of the hill

Fig. 9.4: The initial phase and zone 7 (red) with height lines
Source: Google earth and author

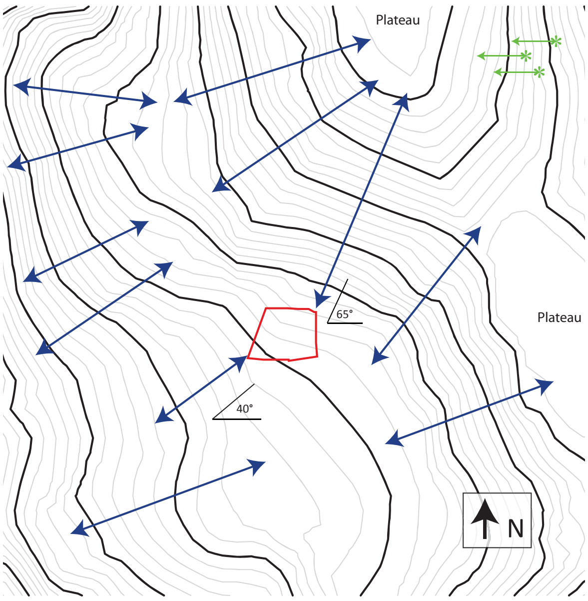


Fig. 9.5: Zone 7 (red) with height lines and air movement directions
Source: Google earth and author

heats up faster than the valley, creating an air movement from the valley to the top. This air movement is due to the fact that cool air is more dense than warm air. In the late evening and at night, the path of the air movement is reversed (fig. 6.12) due to the higher intensity of radiation towards the sky at the top of the hill. This air movement is regardless of the prevailing wind direction and can thus ventilate the buildings. The path of this air movement follows the slope of the hill and thus the angle of the path will be 40° for the bottom left corner of zone seven (fig. 9.5) and 65° for the upper right corner.

In the ideal situation, when designing solely to promote ventilation in buildings, the facades should face the direction of the air movement. With openings for ventilation in the facing and the opposing facade of the building, cross ventilation will be created. The section of a building in the hot and humid climate, which

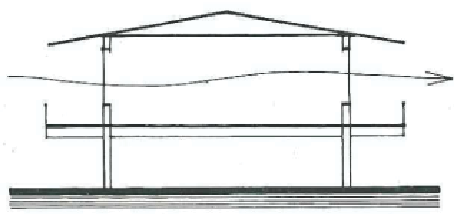


Fig. 9.6: Single-banked rooms should be used when low heat capacity and cross ventilation are required.
Source: Evans, 1980, pp. 60

is ventilated by air movement from outside, should be single-banked (fig. 9.6). In such a section cross ventilation will be most effective (highest air velocities).

In the context of the design location, the wind and solar radiation on the facades come from approximately the same direction (west). This poses a struggle since heat gain needs to be minimized and ventilation promoted. To minimize the heat gain the surfaces of the east and west facing facades should be as small as possible. A solution to this struggle is provided by Evans (1980 in fig. 9.7. By not designing the houses in one row but step-wise, high and low pressure zones are created which promote cross ventilation. At the end of the stepped row extra measures have to be taken to guarantee the continuation of the pressure zones. The stepped row houses have to be single-banked in order to promote cross ventilation.

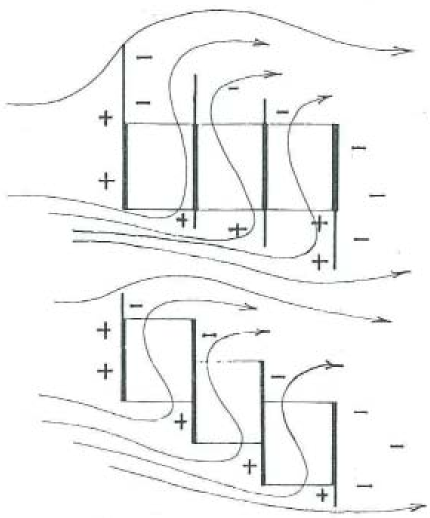


Fig. 9.7: Solution to the problem created when sun and wind come from the same direction in hot climates where cross ventilation is required for comfort.
Source: Evans, 1980, pp. 63

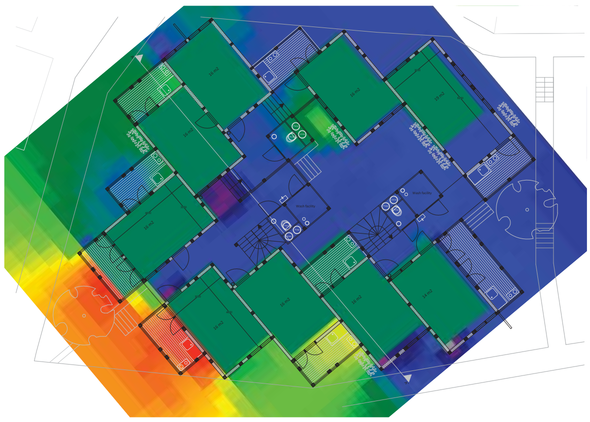


Fig. 9.8: Air movement is creating high and low pressure zones within the design which promotes cross ventilation.
Source: Author

A CFD (Computational Fluid Dynamics) model can be used to analyse the design on the occurrence of high and low pressure zones. Fig. 9.8 shows a 2d CFD analysis for the design with the stepped row houses. It has to be stated that the only thing we can conclude from this figure and analysis is the location of the high and low pressure zones. A lot of factors that do influence the air movement path has not been taken into account as we know from the project in Hong Kong discussed earlier. For example, the surrounding buildings, the ground coverage and the topography (hill).

Spacing between the buildings stimulates the air movement since the wind encounters less resistance. In high density urban neighbourhoods such as Villa Rosa, this is very hard to achieve without decreasing the densities resulting in disrupted communities. According to Evans (1980) wide spacing between buildings is required to achieve air movement. He suggests that a spacing of approximately 5 times the height of the building should be provided. This would mean that the spacing between the three storey buildings of the design, which is around 9 meter high, need a spacing of 45 meters. It is clear that this requirement is not suitable for the urban context since this can never be achieved within a high density such as that of Villa Rosa. Draft results from the UCMap research for Hong Kong showed similar recommendations as those of Evans. Proximity to openness and natural landscape increase the air movement.

In the design of zone 7 a courtyard is added to maximize the spacing between the stepped rowhouses (fig. 9.10). Vegetation will be present in this courtyard to serve four purposes: shading, cooling the air, filtering the air from dust and direct airflows. It is a necessity that this courtyard will remain an open space. Knowing that policies of the government are have not been effective other measures have to be taken to prevent the courtyard from becoming built in. Social capital is a sociological concept which refers to the value of social relations and the role of cooperation and confidence to get collective or economic results. The courtyard is a collective space which can become social capital by providing in an economic activity which benefits the residents. Examples of possible economic activities in the courtyard have been discussed in the previous chapter.

Design of the openings

Ventilation is needed to reach an indoor thermal comfort level which is acceptable for the inhabitant. The air flow will increase the capacity of the body to loose heat by evaporation. The cooling effect is due to the velocity of the air which is one of the three reasons to ventilate (Evans, 1980). Other reasons are to replace the indoor used air with fresh outdoor air and heating or cooling by ventilation (significant difference between outdoor and indoor temperature is necessary). The air inlets and outlets to promote ventilation differentiate in size and design. This is due to different reasons to ventilate. In the hot and humid climate of Haiti, with only a very short dry season, the emphasis of the design of the openings should be on large openings rather than the difference in height between inlet and outlet to direct the airflow (Evans, 1980). The inlet and outlet should be on opposite sides of the indoor space and should be at least 20% of the wall area (Evans, 1980).

So to promote air movement, the openings in the design should be maximized. However, due to the intense solar radiation this can cause in problems. Daylight needs to be provided to the interior for the few daytime activities that will take place indoors. Glare problems occur when there is a high contrast in light levels. The entrance of direct day lighting should be avoided to diminish heat gain. Day lighting can be provided by the reflection from surfaces in the built environment or by an overcast sky which provides in diffuse day lighting. Excessive lighting should still be avoided so the usage of adjustable shutters is recommended since they can regulate the indoor light levels. Flies need to be banned from the indoor spaces. In Haiti malaria is a medical problem. The design provides in screens behind the openings. Unfortunately, these screens lower the air velocity of the wind entering the indoor space and will reduce the thermal comfort at night. Preventing in heat gain during the day becomes thus even more important since are a must.

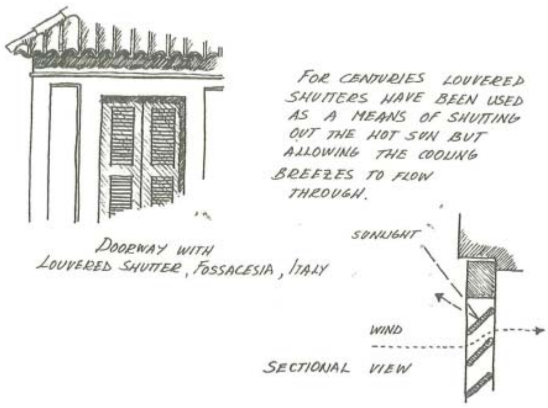


Fig. 9.9: Purpose of shutters
Source: Taylor, 1997, pp. 54

Fig. 9.10: Plan ground floor, 1:100
Source: Author

9.4 NGO initial phase design proposal

The selection of the location for the design is based on the fact that NGO's have indicated zone 7 as the initial phase of the integrated approach. Together they are preparing a design to implement as an example project for the remaining initial phase which consists out of ten zones. Their design is shown in fig. 9.11 and 9.12 and more drawings can be found in the appendix. They are applying confined masonry as a seismic design strategy with a materialization for the whole building of cement. Shutters are applied with a height of around one third of the floor to ceiling height. They are placed directly under the ceiling which means that ventilation will only be present at the top of the indoor space.

The design with the input from the research described in this thesis, will in the last chapter be compared with the design of the NGO's for zone 7. An comparison between the two designs will be made on the indicators described in chapter 3.

Fig. 9.12: Plan of the design for Zone 7
Source: Architecture for Humanity

Fig. 9.11: View from the west on Zone 7
Source: Architecture for Humanity

SUMMARY

The first step to achieve thermal comfort is to diminish the heat gain as much as possible. Removing the heat producing activities from the indoor space to the outdoor space will diminish the indoor heat gain. Therefore, the activity of cooking is provided for in a space at the veranda or balcony. A correct design and materialization of the building shell (facades and roof), according to the amount of solar radiation received, will reduce the outdoor heat gain.

Because of the proximity of Haiti to the equator, solar angles are high and the roof will receive most solar radiation. The chosen roof typology for the design is a double solid roof with an air cavity. The correct materialization based on thermal properties will determine the eventual thermal performance of the roof.

Since airflow should be catched as much as possible, so that ventilation will be maximized, the facades which do not receive direct solar radiation are materialized as shutters. Those facades that do receive direct solar radiation should have a low conductivity and a low thermal mass to prevent in the accumulation of heat during the day.

Airflow is the only passive cooling strategy which can make an indoor space thermally comfortable in the hot an humid climate. The design location is at the leeward side of a hill which makes the potential for an acceptable indoor air velocity for ventilation difficult to obtain. Another type of airflow is present at the location due to the topography of the hill. The building is designed to catch this airflow by a stepped-row housing block. The morphology of the stepped row will create high and low pressure zones and by placing the facade openings at the correct place, cross ventilation is promoted. The indoor spaces have to be single banked to ensure the cross ventilation. The design of the facade openings should focus on maximizing the ventilation and thus a choice is made for floor to ceiling high shutters.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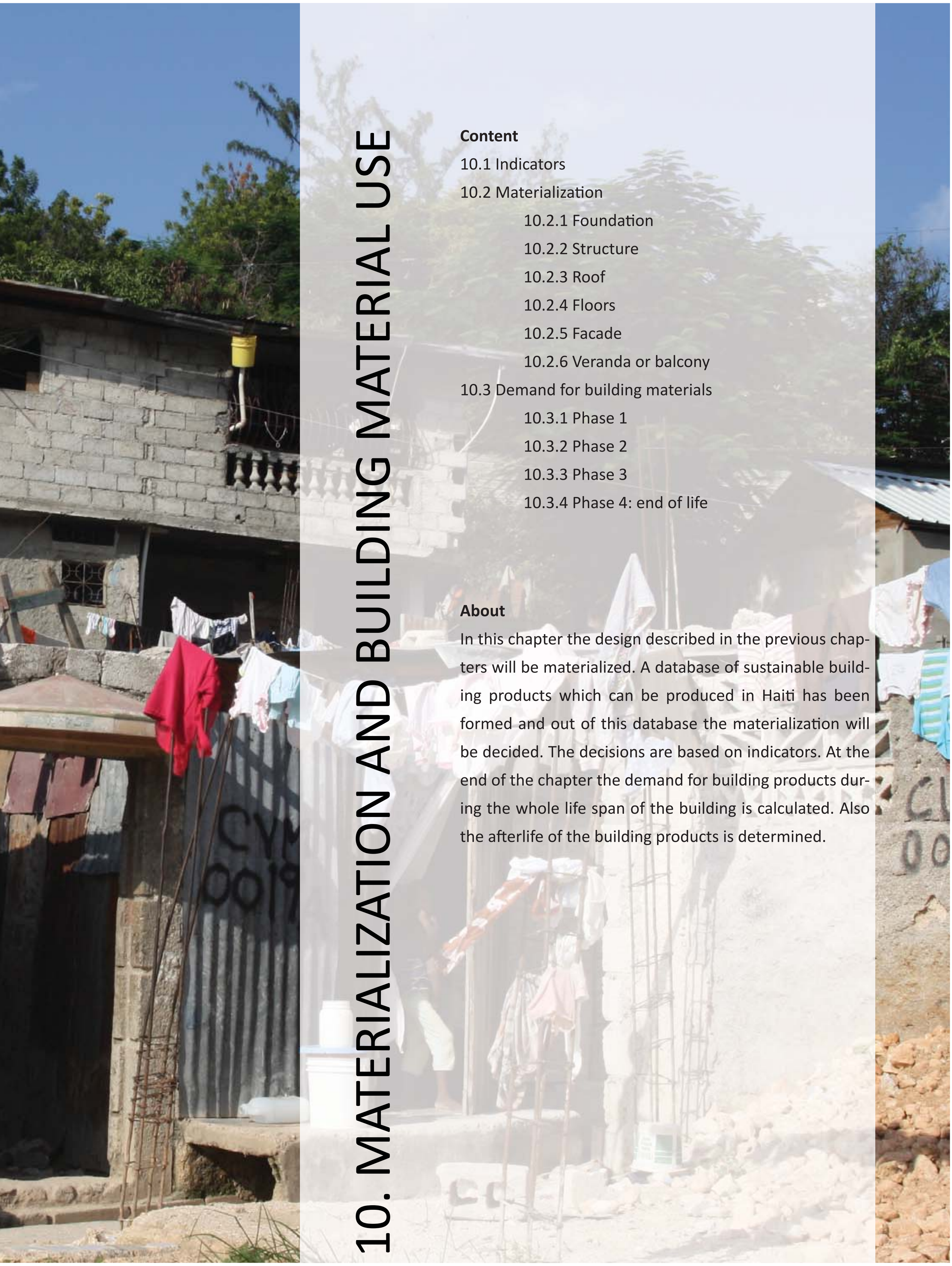


10. MATERIALIZATION AND BUILDING MATERIAL USE

Content

About

In this chapter the design described in the previous chapters will be materialized. A database of sustainable building products which can be produced in Haiti has been formed and out of this database the materialization will be decided. The decisions are based on indicators. At the end of the chapter the demand for building products during the whole life span of the building is calculated. Also the afterlife of the building products is determined.

10. MATERIALIZATION AND BUILDING MATERIAL USE

“The Earth and its Resources are not a gift from our parents but a loan from our children.”
Kenyan proverb

An essential part of this research is the materialization of the climate responsive design. The materialization determines the demand for the production of building materials. It has already been discussed that within this thesis research, the building industry with the production of sustainable building products will be used to ignite the economic development of Haiti in a sustainable way. By producing building materials for the local building industry with local resources the transportation distances between the phases of the life cycle of a building product will be diminished. Limiting the transportation distances will reduce the CO_2 emissions. By a sustainable resource management of the natural capital of Haiti, the natural capital will be restored or even improved (forest regeneration and ecosystem restoration). During all the phases of the life cycle of a building product jobs are created.

The first step of the compilation of a building product database for Haiti is to lists all possible sustainable local raw material resources. This list is provided in fig. 10.1. The second step is researching which building products can be produced with these raw materials. A criteria for a product to be enlisted in the sustainable building products database is that it has to be produced already somewhere in the world, since we want a database which is ready to be used. This also offers the advantaged that material properties, production processes and sustainability labels are known. Unfortunately, the amount of building products in the database was very low and thus the field of research was expanded to products which are in a testing phase, but have already promising results.

With the database, which is evidently never complete, the process of the materialization of the elements of the design can be started. When having to make a decisions for a specific building product, there is a need for indicators to compare and evaluate the products with each other. Indicators which are formulated by the sustainability theory and the context of Haiti will be used. There are many indicators to pick, but these are chosen to meet the goals of the research which were discussed in chapter 3.

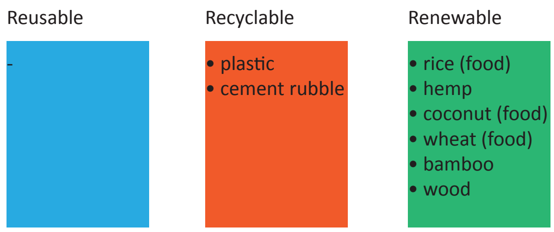


Fig. 10.1: Possible raw materials for building material production in Haiti
Source: Author

10.1 Indicators

The selected indicators for the decision making process, prioritized in the following sequence are:

- Toxicity of the building product
- Affordability within the Haitian context
- Afterlife of the building product after the end of life of the building
- Embodied CO_2 of the building product
- Embodied water of the building product
- Embodied energy of the building product
- Availability of the raw material resource
- Durability of the building product

Element specific indicators:

- Thermal performance (depending on application within the design)
- Mechanical performance (depending on application within the design)

Another important aspect of the research is to improve the resilience of Haiti and stimulate development. Indicators which evaluate the building product on these aspects are:

- Job creation (labour intensity)
- Educational value
- Decreasing food insecurity (building material of agricultural waste)
- Contribute to the protection and expansion of Haiti's natural capital

All the indicators should be taken into account when deciding on the type of materialization of the design. The indicators will first be described and explained on the way of evaluation.

The scores for the indicators are determined by information provided for by companies producing the building products or by a material database. For this research CES Edupack 2011 is used as a material database. Some indicator scores are determined by sub-indicators and some of the scores are set by the understanding of the author of the Haitian context. There is no theory which has set the score values.

Indicator 1: Toxicity of the building product

During the production process of a building product, toxic chemicals might be added to the product to increase the durability or to glue parts together (fibreboards). In the fourth chapter these possible toxic chemicals were discussed (fasteners, adhesives, finishes) and in the appendices there is a black list of certain product components.

During the product use phase, these toxics can affect the indoor air quality. For example, VOCs (Vollatile Organic Compounds) contribute to unhealthy indoor air quality and is found in low level emissions in paints and in formaldehydes.

When a building product has reached its end of life it might be burned as biomass and thus release these toxic components into the air. It is therefore best to select products without toxic chemicals.

Indicator scores toxicity

1 = high (persistent (not biodegradable) and bioaccumulative (stockpiling of the substance in organisms))
2 = medium
3 = low

Indicator 2: Affordability within the Haitian context

The scores for this indicator is very much related to the context. For instance, the perception of affordability in the Netherlands is different compared with Haiti's perception. It has been stated before in this thesis that low-cost products are most likely to be within the purchasing power of most of the Haitians. Off course, subsidy by the government and/or NGOs of certain building products could benefit the production, but this should not be the goal. The costs of a building product is the sum of raw material costs, labour costs, machinery costs, transportation costs and profit. The costs of the building products in the database are contextualized in the western societies and will thus probably be higher than when the product would be produced in Haiti. This is an important indicator, but also an indicator which is difficult to evaluate since the production is not yet in Haiti.

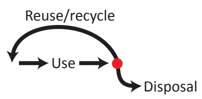
Indicator scores affordability

1 = high costs (>5 €/kg)
2 = medium costs (1-5 €/kg)
3 = low costs (<1 €/kg)

Indicator 3: Afterlife of the building product

The technical life span of a building product/material is independent of the life cycle of a building. So it is possible that at the end of life of the building, the product may still be appropriate for further use. Options for a 'new life' are reuse or recycle. If this is not possible biodegradation or the landfill are the other options. Obviously, the option of the landfill is worst regarding from the sustainability point of view and it is a loss of resources. Instead of biodegradation, the products could also be burned to obtain energy from it (biomass). One could note that the burning will produce CO_2 emissions, but this is also the case with the biodegradation process. The use of renewable resources is preferred above the other options since it can be regenerated by nature.

Indicator scores afterlife



1 = landfill

2 = recycle

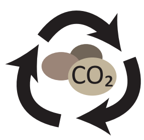
3 = reuse

4 = renewable (biodegradable)

Indicator 4: Embodied CO_2 of the building product

One of the gas emissions during the production and transportation of the building product is CO_2. The gas is of immediate concern due to its effects on climate change. This gas is emitted to the air when burning fossil fuels. Renewable resources such as wood and bamboo use CO_2 during their growing process and transform it into O_2 through photosynthesis. This process transforms the carbon into a carbohydrate. Some manufacturers of building products who use renewable raw materials claim to have a negative embodied CO_2. When not giving full disclosure about the production process it is difficult to say wether this means that they do not produce any CO_2 or that it is less than the amount absorbed by the growing of renewable raw materials.

Indicator scores embodied CO_2



1 = high (>8 kg/kg)

2 = medium (1-8 kg/kg)

3 = low (<1 kg/kg)

Indicator 5: Embodied water of the building product

The fresh water [L] required to make 1 kg of the material is expressed by the embodied water of a building product (CES Edupack, 2011). The water usage is divided into commercial water usage and total water usage. The difference is that the total water usage includes the non-irrigation water to grow trees and plants and the commercial water usage does not. The provided data from CES Edupack takes into account the commercial water usage. Salt-water usage is ignored (CES Edupack, 2011). There are production processes where there is a closed loop of water usage and only one time water has to be added.

Indicator scores embodied water

1 = high (>1000 L/kg)

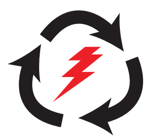
2 = medium (100-1000 L/kg)

3 = low (<100 L/kg)

Indicator 6: Embodied energy of the building product

According to CES Edupack (2011) the embodied energy is the energy, other than from biofuels, required to make 1 kg of the material from its ores or feedstock, calculated for the primary production from cradle to gate. The term cradle to gate indicates that the primary energy will be measured from the raw material extraction to the point of leaving the factory towards the building site. It does not say anything about whether the energy is from a renewable (for example solar or wind energy) or non-renewable (such as oil) resource. The scores are determined according to the data of known examples to the author of high and low embodied energy material production.

Indicator scores embodied energy



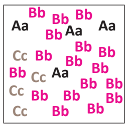
1 = high (>150 MJ/kg)

2 = medium (50-150 MJ/kg)

3 = low (<50 MJ/kg)

Indicator 7: Availability of the raw material resource

This indicator is strongly related to the context. If a raw material is available in abundance, production processes could hypothetically start tomorrow. For some renewable materials, such as wood and bamboo, the raw material has to grow for several years before being suitable for production purposes. The availability would thus be low. Unfortunately, for the Haitian context only rubble and plastic are available in abundance at this moment. Indicator scores have so been adjusted to the context and reflect on the future.



Indicator scores availability

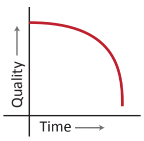
1 = not available or only after more than 10 years

2 = not available yet, but within ten years

3 = already available or within two years

Indicator 8: Durability of the building product

A number of sub-indicators determine the score for the durability. The sub-indicators are the total life span (years) of the product (low = <10 years, medium = 10-40 years or high = >40 years), the moisture resistance (unacceptable, acceptable or excellent), the termite resistance (bad or good), the UV resistance (bad or good) and the flammability (high, medium or low) of a building product. In general, this indicator determines the life span of the product and how well it performs in the contextual climate. In the hot and humid zones like Haiti, high humidity levels in conjunction with the constant heat represent a major problem for building materials. In the case of organic materials these conditions lead to swelling, and in the case of metals, to increased corrosion that can take the form of rust or oxidation. The high humidity level also creates problems for organic building materials, such as fungus, microbes and insects, termites, and other pests.



Indicator scores durability

1 = low

2 = medium

3 = high

Optional indicators

Indicator 9: Thermal performance

To minimize the indoor heat gain by the roof and facade of the design, specific thermal properties are the indicators for the decision making process of the materialization. For the different elements, depending on the amount of direct solar radiation and thermal radiation received, different thermal properties play a role. The thermal conductivity, λ [W/m°C], specific thermal conductivity, U [W/m².°C], and the reflection coefficient, r [%], are the properties which determine the score for the indicator. This indicator is element specific and the score will be explained for each element indpendently.

Indicator 10: Mechanical performance

Another indicator which is element specific is the mechanical performance of the building products. The decision making process for the materialization of the structural elements uses indicators which can be divided into the seismic performance and the transportation of the dead and life loads to the ground. Both the seismic performance and the transportation of the life and dead loads are strongly dependent on the chosen structural system. The materialization is also dependent on the choice of structural system.

The sub-indicators of the seismic performance are ductility of material (ability to deform under tensile stress) and the stiffness of the structural system (amount of bending or deformation). The indicator score for the dead and life loads is element specific and will thus be explained at the relevant elements.

Indicator scores mechanical performance (seismic)

1 = high (not affected)

2 = medium (affected but no failure)

3 = low (failure)

10.2 Materialization

At the time of starting with the materialization of the design, the database consisted out of the building products listed in table 10.1. The now following step is evaluating per element which building product should be applied to materialize the design.

10.2.1 Foundation

Before the materialization of the foundation can be decided, we first have to choose a foundation typology (on poles, deep foundation, shallow foundation). The soil type is an important determinant for the decision of the foundation typology. The soil type of Cite Meriken is most probably rock or at least a firm material. There was no data found about the exact soil type, but from observations by the author and a structural design of the foundation for a house by Build Change for the exact same location (Guy Nordenson and Associates, 2011), this could be concluded. The foundation of the Build Change house is a shallow foundation.

There are different types of shallow foundations: a mat-slab foundation, a slab-on-grade foundation, a rubble trench foundation and an earthbag foundation (fig. 10.2). The last two examples are the most sustainable since instead of using (Portland) cement as the main material, local raw materials such as earth and rubble from the earthquake are used.

Tropical storms and earthquakes are two natural hazards that pose loading on the foundation. The foundation typology has to be able to withstand these forces and maintain structural stability.

Conventional foundation materials are concrete, steel and/or timber. The materialization of a foundation in Haiti is bounded to the following criteria:

• Able to transfer vertical loads to the ground (mechanical properties and structural frame)

• Able to maintain structural integrity when under seismic loading (mechanical properties and structural frame)

• Able to withstand cyclonic (tropical storm) forces

• Moisture resistance (durability) > affects the structural safety

• Termite resistance (durability) > affects the structural safety

The scores on the indicators should appoint to the best choice. However, the general criteria, in particular the moisture and termite resistance, rule out timber. This leaves the choice between concrete, steel and the less conventional earthbags. Steel is an alloy composed from mostly iron and some carbon. The raw materials are not a part of the natural capital of Haiti and should thus be imported.

Although becoming more mainstream, earthbag foundations are still unique and thus knowledge about the seismic performance is low. The Earthbag Building

Renewables	**Product**	**Application**
Rice	3 types of rice straw board	Facade, roof
Hemp	Hempbrick	Facade
	Hemp fibre insulation	Insulation
	Hemp plaster	Facade
Coconut	Binderless fibreboard	Facade, roof
	Coconut husk insulation	Insulation
Wheat	3 types of wheat straw board	Facade, structural
Bamboo	2 types of structural bamboo	Structural
	Corrugated sheets of bamboo mats	Roof
	Bamboo flooring	Floor
Wood	Haitian pine wood	Structural

Recyclables	**Product**	**Application**
Plastic	Plastic roof tiles	roof
Rubble	Plaster (mixed with natural fibres and cement)	facade

Table 10.1: Building products included in the database
Source: Author

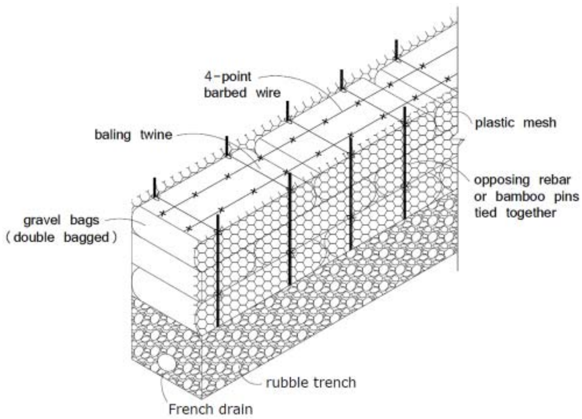


Fig. 10.2: Seismic resistant gravel bag foundation
Source: Earthbag Building Blog, 2008

Building product	Stainless steel	Fly ash concrete/lime-pozzolana cement	Earthbag (polypropylene bags)
Availability	**1** (imported)	**2** (cement production is an option in Haiti, other components, sand, imported)	**3** (rubble can also be used instead of gravel)
Toxicity	**3**	**3**	**3**
Affordability	**1** (6,26-6,89 €/kg) *Source: CES Edupack 2011*	**3** (0,03-0,12 €/kg) *Source: CES Edupack 2011*	**3**
Embodied energy	**2** (77,2-85,3 MJ/kg) *Source: CES Edupack 2011*	**3** (1-1,3 MJ/kg for concrete) (5,4-6 MJ/kg for cement) *Source: CES Edupack 2011*	(unknown)
Embodied water	**2** (112-337 L/kg) *Source: CES Edupack 2011*	**3** (1,7-5,1 L/kg) (10,8-32,5 L/kg for cement) *Source: CES Edupack 2011*	(unknown)
Embodied CO_2	**2** (4,85-5,36 kg/kg) *Source: CES Edupack 2011*	**2** (0,09-0,09 for concrete) (0,9-1 kg/kg for cement) *Source: CES Edupack 2011*	(unknown)
Durability	**2** (ferrous metals corrode rapidly in hot&wet tropics (Fry, 1982))	**3**	**3**
Afterlife	**2** (recycle > downcycle with high embodied energy)	**1** (landfill or donwcycling for concrete and cement)	**3**
Mechanical performance	**3** (good)	**2** (good for dead and live load, under seismic loading only whithin the appropriate structural system)	**3** (in combination with rebar)
Total score	**18**	**22**	**(18)**

Table 10.2: Building product options for the foundation
Source: Author

Blog (2008) states that testing according to building code standards is very costly and no company is interested in testing the earthbag foundation since profits from this foundation typology are low. This type of foundation is applied in areas prone to seismic activity, even in Haiti.
Table 10.2 shows the scores on the indicators for the three possibilities of the materialization of the foundation. The total score shows that a concrete and cement foundation is the best option, but this is due to a lack of information about the earthbag foundation. The option of the earthbag foundation is chosen as the materialization of the design due to the fact that the raw materials, rubble and earth, are widely available in Haiti. Also, the afterlife is better since the earth and rubble can be reused again.
The option for a materialization of cement with reinforced concrete is also calculated on quantity of material just in case the earthbag foundation is not suitable. These calculations can be found in the appendix.

The building products chosen for the foundation, with the exclusion of joints, are:

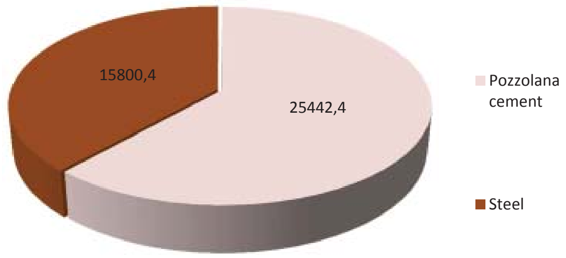
- Bags of polypropylene
- Rubble (or gravel when rubble is unavailable) to fill the bags
- Bamboo reinforcing bars

The quantities of building products in kg, are important to determine the demand. Fig. 10.3 shows the quantities for the two options for the foundation materialization. The total quantity of building materials of option B (earthbag) is much less than option A. The quantity of building materials is not an indicator for the decision making process, but reducing the demand should be the first step when researching sustainable resource management in the building industry and wanting to reduce the waste.

10.2.2 Structure

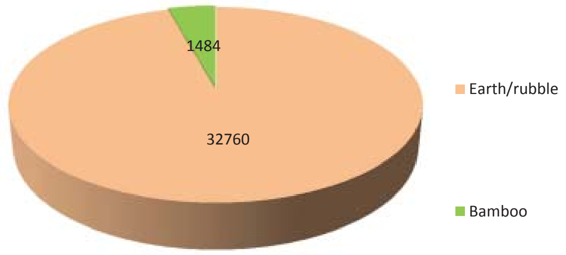
For the materialization of the structural system there are more options of building products available than for the foundation. Two options of a structural typology can be applied with the available building products: one typology with columns and beams and the other where the walls are load bearing (table 10.3).

Option A



Total quantity per 67,32 m²: 41242,8 kg

Option B



Total quantity per 67,32 m²: 34244 kg

Fig. 10.3: Quantities of building products [kg] per 67,32 m² for foundation option A (left) and B (right)
Source: Author

Both can transfer the dead and live loads, but when under seismic loading the elements will be loaded in a different direction. The structural typology of the frame (columns and beams) is in general (with the right type of connections) more flexible and will be able to withstand the seismic loading when materialized with bamboo or wood. The load-bearing wall typology materialized with the wheat straw boards will perform well under seismic loading according to the manufacturer. When materialized with the hemp bricks the seismic performance is unknown. Since the seismic performance is an important aspect, the materialization with hemp bricks is not an option.

The design is three stories high resulting in a building height of around 9 meters. The wheat straw panels are only load bearing up to 7,32 meter. The choice for the structural typology is thus the column and beam system with two options for the materialization (fig. 10.4).

The availability of raw materials for both options is low at this moment in Haiti. Bamboo is not industrially grown at this moment, by the author's knowledge, and the Haitian Pine is an endangered tree specie. Plantations are necessary to grow the raw materials. The growth cycle of bamboo is 6 years before the thickness is large enough to be used as a structural elementg. The growth cycle of the Haitian Pine is around 20 years. Scoring lower on the indicator of availability and also the embodied water use, the Haitian Pine is not the best choice. It does have other advantages which are not included in the indicator list. The Haitian Pine used to overgrow Haiti. Due to the wood logging for fuel and timber this specie is now endangered with extinction, not only in Haiti but in the world (fig. 4.7).

One of the goals for the building industry is to contribute to the protection and expansion of the natural capital of Haiti. The Haitian Pine is a vital part of the indigenous ecosystems in Haiti and thus a motive to choose this option over bamboo even though scoring less on the indicators.

The seismic design of the structural typology requires floors to act as a stiff element so that it is able to withstand the forces. Depending on the materialization of the floor type the structure needs bracing in the floor field.

Building construction in Haiti has to deal with the possibility of termites attacking those elements that possess nutrients. To prevent the wooden structure from being attacked, the elements should not be in direct contact with the ground. The foundation of earthbags is elevated 20 cm above ground level to protect the timber frame.

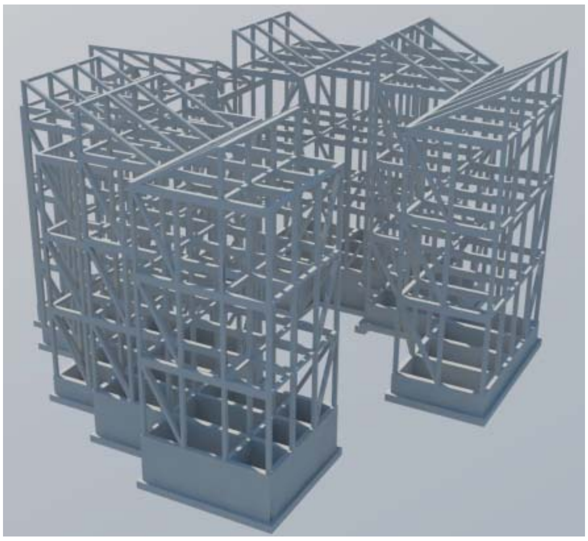


Fig. 10.4: Structural frame of the design
Source: Author

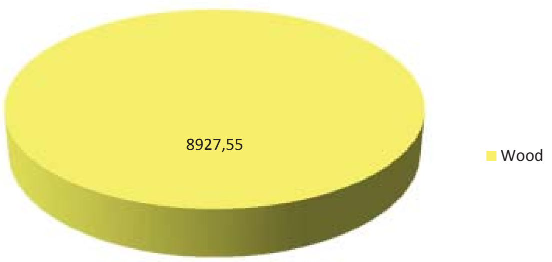
Building product	Bamboo	Haitian Pine	Hemp bricks (Cannabric)	Wheat straw boards (Agriboard)
Availability	**2** (6 years growth cyclus)	**1** (20 years growth cyclus)	**3** (3 months for hemp)	**3** (8-4 months for wheat)
Toxicity	**3**	**3** (with borate preservation treatment)	**3**	**2** (fastner)
Affordability	**2** (1-1,5 €/kg) *Source: CES Edupack 2011*	**2** (1,1-5 €/kg) *Source: CES Edupack 2011*	**3** (0,22 €/kg) *Source: Cannabric*	**3** (0,85 €/kg) *Source: Agriboard*
Embodied energy	**3** (4,1-6 MJ/kg) *Source: CES Edupack 2011*	**3** (7,2-7,96 MJ/kg)	**3** (unknown for the brick, for hemp 38,7-42,8 MJ/kg) *Source: CES Edupack 2011*	**1** (200 MJ/kg) *Source: Agriboard*
Embodied water	**2** (300 - 900 L/kg) *Source: CES Edupack 2011*	**1** (500-1500 L/kg)	**1** (unknown for the brick, for hemp 500-1500 L/kg) *Source: CES Edupack 2011*	**3** (87,6 L/kg) *Source: Agriboard*
Embodied CO_2	**3** (0,299 - 0,33 kg/kg) *Source: CES Edupack 2011*	**3** (0,427-0,472 kg/kg)	**3** (-0,624 kg/kg) *Source: Cannabric*	**3** (-0,87 kg/kg) *Source: Agriboard*
Durability	**2** (highly flammable)	**2** (highly flammable)	**3**	**2** (highly flammable)
Afterlife	**4** (renewable)	**4** (renewable)	**4** (renewable and recyclable, due to natural binder lime)	**4** (renewable)
Thermal performance	-	-	2	-
Mechanical performance	**3** (good under seismic loading, due to low compressive strength no high-rise)	**3** (good under seismic loading, due to low compressive strength no high-rise)	**1** (performance unknown under seismic loads)	**2** (good under seismic loads, loadbearing up to 7,32 m)
Total score	**23**	**21**	**24**	**23**

Table 10.3: Building product options for the structural system
Source: Author

The building products chosen for the structure, excluding the joints, are (for 1 housing unit of three floors):

- 9 columns of 9 m
- 3 columns of 10,6 m
- 15 beams of 2,95 m
- 27 beams of 1,35 m
- 4 roofbeams of 3,35 m
- 12 seismic braces of 2,8 m

The quantities of building products in kg for the structure are shown in fig. 10.5. Since only wood is used for the structure, there is only one material.



Total quantity per 67,32 m^2: 8927,55 kg

Fig. 10.5: Quantities of building products [kg] per 67,32 m^2 for the structure
Source: Author

10.2.3 Roof

The design for the roof of the houses is sloped with an air cavity to ventilate. Needed for the materialization of the design are an outer cladding, structure, weatherproofing, insulation and a ceiling board. The roof structure is part of the structural frame discussed in the previous section and thus is already materialized. The thermal properties of the building materials are important to minimize the indoor heat gain and should therefore be added to the indicator list of the decision making process. The aim is to keep the indoor temperature at the same level as the outdoor temperature. Important is that heat accumulated within the materials during the day, caused by the solar radiation on the outer surface of the building materials, is kept as low as possible. So that during the night indoor temperatures will drop according to the outdoor temperature. The cladding should reflect the solar radiation as much as possible and the insulation/ceiling board should minimize thermal conductivity and have a low heat capacity (storage of heat in material).

Table 10.4 shows the options for the materialization of the roof. For the cladding of the roof there are two options, corrugated bamboo sheets and recycled plastic tiles. The corrugated bamboo sheets are lacking information about the durability. The sheets are produced using formaldehyde as an adhesive resin which should be substituted with at least a NAF (Non Added Formaldehyde) adhesive. The recycled plastic roof tiles seem to be a very good option, but the composition of the tiles is only for 30% recycled plastic and the other 70% is sand. It furthermore contains PVC which is on the black list of materials since it affects the air quality. The afterlife of the recycled plastic roofing tiles is not specified, but will most probably be the landfill due to the low amount of plastic. All these facts have led to the decision to materialized the exterior cladding of the roof with corrugated bamboo roofing sheets, but with the notation that the formaldehyde should be replaced with at least a NAF. To deal with the forces acting on the roof during a tropical storm the sheets should be anchored sufficiently to the supporting structure.

The other two sub-elements of the roof are the insulation layer and the ceiling. There are two options (coconut insulation by Enkev and hemp insulation by Steico) which only serve the purpose of insulating. But there are also two options, both the rice straw boards, who could act as insulator and ceiling. It is

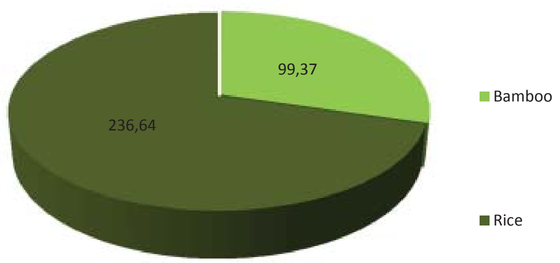
Building product	Corrugated Bamboo Roofing Sheets (INBAR)	Recycled plastic rooftiles (Britanica)	Coconut insulation (Enkev)	Hemp insulation (Steico)	Rice insulation board (ECO-Board)	Rice straw board (Stramit)
Availability	**2** (6 years growth cyclus)	**3** (51.100 ton plastic annually in only PaP)	**3** (15 months from flower to fruit)	**3** (3 months for hemp)	**3** (4-6 months for rice)	**3** (4-6 months for rice)
Toxicity	**2** (includes an adhesive resin)	**1** (contains PVC)	**3**	**3**	**3** (includes NAF)	**3** (no resin added)
Affordability	**3** (0,174 €/kg) *Source: CES Edupack and INBAR*	**3** (0,71 €/kg)	**3** (0,5 €/kg) *Source: Enkev*	**2** (2,43 €/kg) *Source: ecomerchant.co.uk*	**3** (0,25 €/kg) *Source: ECO-Board*	**2** (1,75 €/kg)
Embodied energy	**3** (1,6 MJ/kg) *Source: CES Edupack and INBAR*	**3** (24,6 MJ/kg) *Source: L. Smits, 2012*	**3** (for coir production 7,2-7,96 MJ/kg) *Source: CES Edupack*	**3** (for hemp production, 38,7-42,8 MJ/kg) *Source: CES Edupack*	(unknown)	(unknown)
Embodied water	**2** (for bamboo production 300 - 900 L/kg) *Source: CES Edupack 2011*	(unknown)	**1** (for coir production 500-1500 L/kg) *Source: CES Edupack*	**1** (for hemp production, 500-1500 L/kg) *Source: CES Edupack*	(unknown)	(unknown)
Embodied CO_2	**3** (for bamboo production, 0,299 - 0,33 kg/kg) *Source: CES Edupack 2011*	**3** (0,65 kg/kg) *Source: L. Smits, 2012*	**3** (for coir production 0,427-0,472 kg/kg) *Source: CES Edupack*	**2** (for hemp production, 2,44-2,69 kg/kg) *Source: CES Edupack*	**3** (none due to agricultural waste, certified) *Source: ECO-Board*	**3** (-9,21 kg/kg) *Source: Stramit*
Durability	**2** (highly flammable)	**3**	**2** (flammable)	**2** (less durable when affected by water)	**3**	(unknown)
Afterlife	**4** (renewable)	**1**	**4** (renewable)	**4** (reusable, recyclable and renewable)	**4** (renewable)	**4** (renewable)
Thermal performance	**1** (r=0,12 , for bamboo)	**1** (r=0,1 due to dark colour)	**3** (λ=0,04, C=unknown)	**3** (λ=0,04, C=1700)	**3** (λ=0,065, C=2430)	**2** (λ=0,102, C=unknown)
Mechanical performance	-	-	-	-	-	-
Total score	**22**	**(18)**	**24**	**23**	**(22)**	**(17)**

Table 10.4: Building product options for the roof
Source: Author

best to explore the dual purpose option for the design since it will reduce the quantity of the used materials. A choice between these two options is made for the ECOBoard since it has a lower thermal conductivity and will reduce the heat flow through the roof to the indoor space.

The building products chosen for the roof, excluding the joints, are:
- 20,28 m^2 CBRS
- 3 * 4,93 m^2 insulating rice straw ceiling board

The quantities of the building products for the roof are shown in fig. 10.6 in [kg]. A detail of the roof is shown in fig. 10.7. Since the roof is subjected to the highest amount of direct solar radiation, the thermal performance of the materialized roof is important. Now that the materialization is known, a heat flow calculation can be made. The entire calculation for the heat flow through the roof can be found in the appendix, but now a summary will be given.
The total thermal resistance, R_{total}, of the roof is 0,91 [m^2*K/W]. The outdoor temperature near the roof with a solar insulation of 831 W/m^2 is 66,3 °C. The indoor ceiling temperature will be 41,3 °C. This indoor ceiling temperature could be lowered by painting the CBRS in a bright color and thereby increase the reflection value. During the discussion of the design in the next chapter, these values will be compared with the cement block house.



Total quantity per 67,32 m^2: 336,01 kg

Fig. 10.6: Quantities of building products [kg] per 67,32 m^2 for the roof
Source: Author

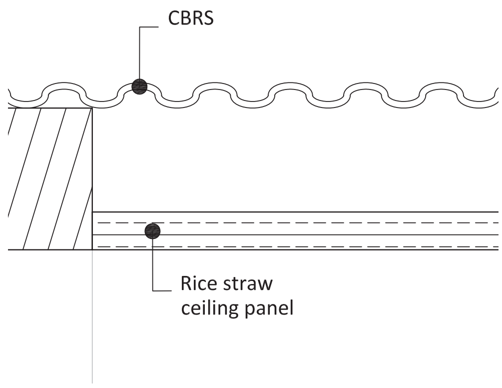


Fig. 10.7: Roof detail with materialization
Source: Author

10.2.4 Floors

There are two options for the materialization of the floors within the database of the sustainable building products. The two options are the prefab wheat straw boards (table 10.5) and a thin structural floor option of bamboo planks with a cement top layer. When the wheat straw option is applied as a floor, there is extra bracing of the floor necessary for seismic design reasons. This will increase the quantities of building products needed for the structure. The option of the thin structural floor, where the top layer of cement acts as the structural stiffness for seismic design, is still in a research phase but is already applied when renovating houses with old wooden floors. According to the University of Bath (2009) this type of floor has an improved diaphragm action, enhanced acoustic and thermal performance. Unfortunately not much data is known and therefore much of the indicator scores could not be determined. Data from the CES Edupack database has served to come up with some of the indicator scores.
Because of the high flammability of the wheat straw board and the uncertainty of the mechanical performance, a choice is made for the bamboo cement floor. The cement which will be used for the top layer of the floor, is lime-pozzolana cement (CP-40). This type of cement is a hydraulic binder which replaces up to 40% of Portland cement in a cement mixture (BSHF, 2012. The ground floor of the design will be a total cement floor due to the possibility of termites affecting the bamboo.

The building products chosen for the floors, excluding

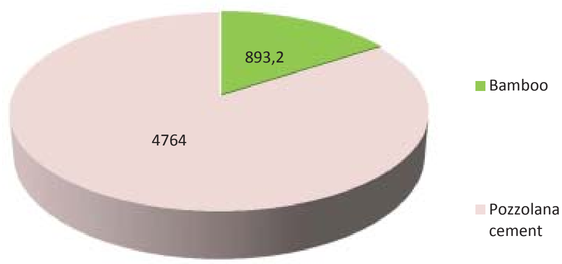
Building product	Bamboo cement floor		Wheat straw boards (Agriboard)
Availability	**2** (6 years growth cyclus)		**3** (8-4 months for wheat)
Toxicity	**3**		**2** (fastner)
Affordability	(unknown)		**3** (0,85 €/kg) *Source: Agriboard*
Embodied energy	**3** Bamboo (4,1-6 MJ/kg) *Source: CES Edupack 2011*	**3** (5,4-6 MJ/kg for cement) *Source: CES Edupack 2011*	**1** (200 MJ/kg) *Source: Agriboard*
Embodied water	**2** (300 - 900 L/kg) *Source: CES Edupack 2011*	**3** (10,8-32,5 L/kg for cement) *Source: CES Edupack 2011*	**3** (87,6 L/kg) *Source: Agriboard*
Embodied CO_2	**3** (0,299 - 0,33 kg/kg) *Source: CES Edupack 2011*	**2** (0,9-1 kg/kg for cement) *Source: CES Edupack 2011*	**3** (-0,87 kg/kg) *Source: Agriboard*
Durability	**3**		**2** (highly flammable)
Afterlife	**4** and **2**		**4** (renewable)
Mechanical performance	**3**		**2** (as a wall element: good under seismic loads, loadbearing up to 7,32 m. Unknown for floor usage)
Total score	**(21)**		**23**

Table 10.5: Building product options for the floors
Source: Author

the joints, are:

- Grounfloor of 14,18 m² lime-pozzolana cement of 0,1 m thick
- Two floors of 14,18 m² bamboo planks of 0,045 m thick
- Two floors of 14,18 m² lime-pozzolana cement of 0,02 m thick

Fig. 10.7 shows the quantities of building materials used for the floors in [kg]. Volume wise the quantities of bamboo are around one third of the total volume for the floors (table 10.7), but due to the higher density of the cement, in [kg] the cement has a much larger part of the total quantities.



Total quantity per 67,32 m²: 5657,2 kg

Fig. 10.7: Quantities of building products [kg] per 67,32 m² for the floors
Source: Author

10.2.5 Facade

The facades of the design do not have to be loadbearing since the typology of the structure is a frame of columns and beams. From the thermal point of view, there are two types of facades in the design: those directly and those indirectly receiving solar radiation. Through a climate responsive design the facades directly receiving solar radiation have been limited by the addition of balconies and vegetation. These balconies shade the facades and offer an outdoor living space. The facades that are shaded by vegetation should still be materialized on receiving direct solar radiation.

The same material properties are important as with the roof: reflect as much solar radiation as possible, a low thermal conductivity and a low heat capacity. The walls are receiving much less direct solar radiation than the roof, because of the high solar angles in Haiti. Therefore the most important thermal material property is that the heat capacity should be minimized to prevent in the storage of heat during the day. Heat accumulation can also occur because of a temperature difference between the outdoor air and the element (here, facade). Therefore, all facades should have a low heat capacity so that at night the indoor space will not be heated up by the thermal radiation of the walls.

Table 10.6 shows the options for the materialization of the facade which is a wide variety compared to other elements of the design. From the table we can conclude that comparing the total indicator scores is difficult because data is lacking for all building products on some indicators.

The facades that do not receive direct solar radiation all have shutters to promote ventilation. The other facades need a different materialization which has to be chosen from table 10.6. The hemp bricks score best on the indicators, but have a high thermal mass (thickness and accumulation capacity) which is not desirable for the directly solar radiated facades. The rice straw board does not score well on the indicator of affordability and the thermal performance indicator. As for the affordability, it has been stated before that this indicator is difficult to assess because of the context in which it is produced and on which the costs are based. The decision for a specific building product should thus never be solely on the indicator of affordability as long as the costs of production in Haiti are unknown.

A combination of the rice insulation board and the plaster from rubble and natural fibres is chosen for the design. For the indicator scores that are known, these products score good.

An additional reason for the choice of a plaster as a facade finishing is to enable the inhabitants to paint their facades. In Haiti, advertising is painted on the

Building product	Rice straw board (Stramit)	Hemp bricks (Cannabric)	Coconut binderless fibre board (WUR)	Rice insulation board (ECO-Board)	Bamboo external cladding (Lamboo)	Plaster from rubble and natural fibres
Availability	**3** (4-6 months for rice)	**3** (3 months for hemp)	**3** (15 months from flower to fruit)	**3** (4-6 months for rice)	**2** (6 years growth cyclus)	**3**
Toxicity	**3** (no resin added)	**3**	**3** (no binding agent needed, uses lignin)	**3** (includes NAF)	**3** (no formaldehyde)	**3** (zero VOC)
Affordability	**2** (1,75 €/kg)	**3** (0,22 €/kg) *Source: Cannabric*	(unknown, not yet in commercial production)	**3** (0,25 €/kg) *Source: ECO-Board*	(unknown)	**3** (made from solid waste and natural fibres)
Embodied energy	(unknown)	**3** (unknown for the brick, for hemp 38,7-42,8 MJ/kg) *Source: CES Edupack 2011*	**3** (for coir production 7,2-7,96 MJ/kg) *Source: CES Edupack*	(unknown)	(unknown)	(unknown)
Embodied water	(unknown)	**1** (unknown for the brick, for hemp 500-1500 L/kg) *Source: CES Edupack 2011*	**1** (for coir production 500-1500 L/kg) *Source: CES Edupack*	(unknown)	(unknown)	(unknown)
Embodied CO_2	**3** (-9,21 kg/kg) *Source: Stramit*	**3** (-0,624 kg/kg) *Source: Cannabric*	**3** (for coir production 0,427-0,472 kg/kg) *Source: CES Edupack*	**3** (none due to agricultural waste, certified) *Source: ECO-Board*	(unknown)	(unknown)
Durability	(unknown)	**3**	(unknown)	**3**	**3**	**2** (medium wear resistance)
Afterlife	**4** (renewable)	**4** (renewable and recyclable, due to natural binder lime)	**4** (renewable)	**4** (renewable)	**4** (renewable)	**2**
Thermal performance	**2** (λ=0,102, C=unknown)	**2** (λ=0,16, C=1113)	(unknown)	**3** (λ=0,065, C=2430)	**2** (λ=0,14, C=unknown)	**2** (low thermal conductivity)
Total score	**(17)**	**(25)**	**(17)**	**(22)**	**(14)**	**(15)**

Table 10.6: Building product options for the facade
Source: Author

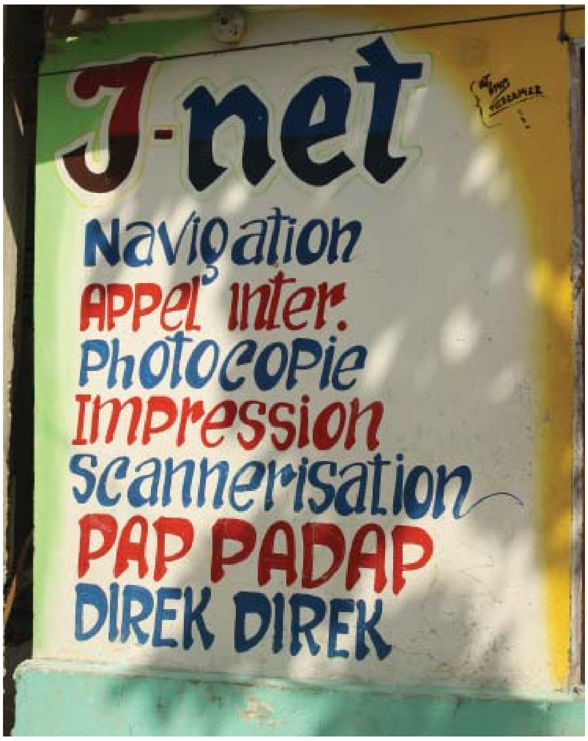


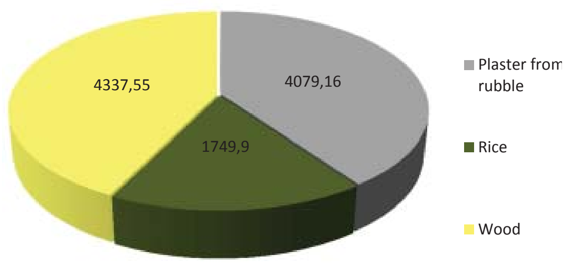
Fig. 10.8: Decorating the facade, advertising
Source: Author

facades of buildings instead of on posters (fig. 10.8).

The building products chosen for the facades, excluding the joints, are:

- 3,78 m² of rice board of 0,058 m thick, 7 per floor
- 37,7 m² plaster from rubble per floor
- 3,78 m² shutters from wood, 3 per floor

Fig. 10.9 shows the quantities of the building materials used for the facades in [kg]. The amounts of wood and the plaster of rubble are almost the same. The amount of rice is around one fifth of the total amount.



Total quantity per 67,32 m²: 10166,61 kg

Fig. 10.9: Quantities of building products [kg] per 67,32 m² for the facades
Source: Author

10.2.6 Veranda or balcony

The outdoor space belonging to the housing unit also needs to be materialized. The structure is already there so only a floor and a balustrade are needed. From table 10.5 we know that flooring options are limited. Since the activity of cooking is taking place at the outdoor space, good fire proofing is of great importance. Therefore, the same option for the floor is chosen as the indoor floor. If fireproofing was not that important, the top layer of cement could have been left out.

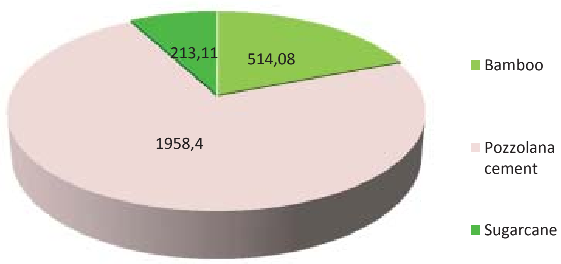
The balconies and veranda need a balustrade. It is chosen to use the technique of clissade for the balustrade. This technique weaves sugarcane or wooden strips into a mat with small openings (fig. 10.10). Through the openings some air can flow.

The building products chosen for the veranda and balconies, excluding the joints, are:

- 5,44 m² of bamboo planks of 0,045 m thick
- 5,44 m² lime-pozzolana cement of 0,1 m thick
- 4 panels of 1,54 m² clissade of sugarcane per floor

Fig. 10.11 shows the quantities of building materials in kg used for the veranda.

Fig. 10.10: Clissade
Source: Cordaid



Total quantity per 67,32 m²: 2685,59 kg

Fig. 10.11: Quantities of building products [kg] per 67,32 m² for the veranda and balconies
Source: Author

10.3 Demand for building materials

The demand for building materials has been determined for a total of three housing unit with a total of 67,32 m^2. Per housing unit this includes four external walls and a veranda or balcony of 5,4 m^2. Table 10.7 shows the demand for building materials for the 3 housing units with a total of 67,32 m^2.

To determine the total demand for building materials by the whole housing block of 27 housing units, we must look at the whole life span of the building. We assume that the total life span of the building will be 50 years (similar to the Cordaid rural shelter). To the determine the demand the life span is divided into 3 phases. The first phase is the construction of the total structure, the number of housing units necessary to house the families living at zone 7 and the supporting facilities. The second phase will be after 25 years when the lifespan of some elements of the housing units of the first phase are at an end and need to be replaced. It is assumed that the remaining housing units are in use. The third phase is at the end of the lifespan of the building, 50 years after phase 1.

10.3.1 Phase 1

0 years

During the first phase the total structure, including the structural frame, floors and roofs. The facilities of the staircases, toilets and sanitation will also be built for all floors during this phase. The amount of housing units built, is the number of households present at this time at the location plus their indicated wish for extra living space. A survey by the collaboration of NGO's who are designing for zone 7, concluded that there are currently 8 households living at the location of which 2 want, and can afford, to double the living space. The sizes of the houses currently at zone 7 are not all the same. That is why during phase 1, a total of 14 housing units will be built. The extra floor space in the design was also to provide in shops for entrepreneurs. During phase 1 two shops will be built at the ground floor level.

Since the total structure (frame+floors+roof) has to be built during the first phase for seismic reasons, a strategy has to be followed to prevent in people breaking down parts of the structure to sell the building materials. Also, from the climate responsive design point of view it was found that structures on poles, where the wind can flow underneath, perform better on indoor thermal comfort. For these two reasons the strategy is taken on to start the building of the housing units from the top floor instead of the ground floor (fig. 10.12). The remaining space at the ground floor can be used as a communal outdoor space for commercial or recreational ends.

During phase 1 the largest amount of building materials will be used as can be seen from the material flow chart in fig. 10.13. The housing units will be the most expensive compared to next phases and the most jobs will be created during this phase.

10.3.2 Phase 2

0-25 years

During phase 2, all other housing units are built. For these housing units only the facade materials have to be constructed.

Since Haiti is subjected to annual tropical storms, it is to be expected that houses will be damaged. Also, the lifespan of the balcony floor, facade and roof are at

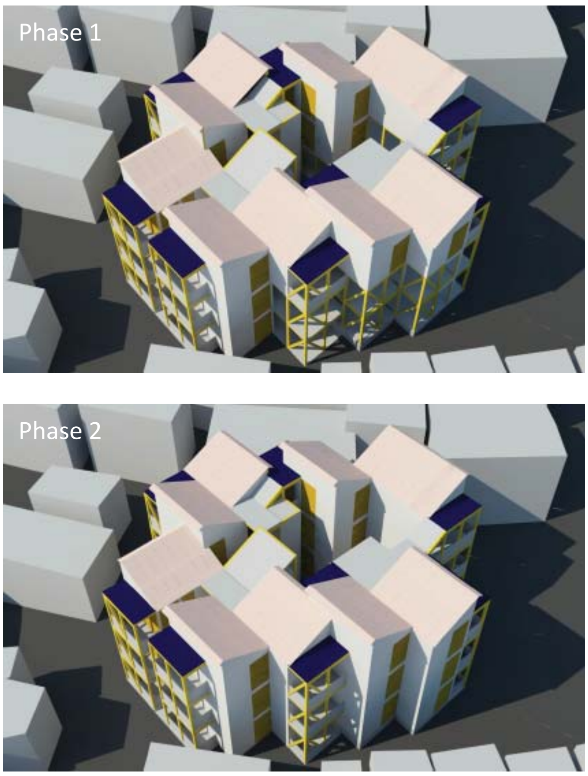


Fig. 10.12: Phase 1 and 2 of the lifespan of the building
Source: Author

Element	Material	Amount [kg]	Volume [m³]	Costs [$]
Foundation	Earthbags	**32.760** *(ρ = 2.400 kg/m³, Source: CES Edupack 2011)*	**13,65**	?
	Bamboo reinforcing bars	**1.484** *(ρ = 700 kg/m³, Source: CES Edupack 2011)*	**2,12**	**2448,6** *(1,65 $/kg, Source: CES Edupack 2011)*
Structure	Haitian Pine columns→ Pine wood	**3833,5** *(ρ = 850 kg/m³, Source: CES Edupack 2011)*	**4,51**	**5060,2** *(1,32 $/kg, Source: CES Edupack 2011)*
	Haitian Pine beams	**3496,05** *(ρ = 850 kg/m³, Source: CES Edupack 2011)*	**4,113**	**4614,79** *(1,32 $/kg, Source: CES Edupack 2011)*
	Roof structure Haitan Pine	**455,6** *(ρ = 850 kg/m³, Source: CES Edupack 2011)*	**0,536**	**601,39** *(1,32 $/kg, Source: CES Edupack 2011)*
	Haitian Pine bracing	**1142,4** *(ρ = 850 kg/m³, Source: CES Edupack 2011)*	**1,34**	**1507,97** *(1,32 $/kg, Source: CES Edupack 2011)*
Floors	Bamboo floor	**893,2** *(ρ = 700 kg/m³, Source: CES Edupack 2011)*	**1,276**	?
	Pozzolano cement	**6.806,4** *(ρ = 2.400 kg/m³, Source: CES Edupack 2011)*	**2,836**	**359,38** *(0,0528 $/kg, Source: CES Edupack 2011)*
Roof	CBRS → Bamboo	**99,37** *(ρ = 700 kg/m³, Source: CES Edupack 2011)*	**0,142**	**3,89** *(0,039 $/kg, Source: INBAR)*
	Rice straw insulation panel → Rice straw	**236,64**	**0,59**	**78,09** *(5,28 $/m², Source: Eco-board)*
Facade	Finishing plaster → Rubble (65%) + natural fibres + cement (35%)	**4079,16** *($ρ_{cement}$ = 2.400 kg/m³, Source: CES Edupack 2011)*	**1,700**	**86,15** *(40% of Pozzolano cement: 0,02112 $/kg)*
	Rice straw board	**1749,9** (ρ = 380 kg/m³)	**4,605**	? (x $/m², Source: Stramit)
	Wooden shutters	**4337,55** *(ρ = 850 kg/m³, Source: CES Edupack 2011)*	**5,103**	**5725,57** *(1,32 $/kg, Source: CES Edupack 2011)*
Veranda	Bamboo floor	**514,08** *(ρ = 700 kg/m³, Source: CES Edupack 2011)*	**0,734**	?
	Pozzolano cement	**1958,4** *(ρ = 2.400 kg/m³, Source: CES Edupack 2011)*	**0,816**	
	Balustrade of woven sugar-cane fibres (clissade)	**213,11** (ρ = 288,3 kg/m³)	**0,7392**	**70,33** *(unknown for sugarcane. 0,33 $/kg for coir, Source: CES Edupack 2011)*

Table 10.7: Building product quantities per element of the design of three housing units with a total of 67,32 m²
Source: Author

their end and have to be replaced. To make an indication of the extra building materials that are needed to repair the damage or replace elements, an additional 100% of the roof and facade unit materials built in phase 1 will be added to the total demand for the amount of building materials.

The repair and replacement will bring a waste flow with it, consisting out of the damaged or weathered facade elements and the roof elements. Table 10.8 has listed the afterlife of the elements. The closed facade element is materialized as a rice panel with a plaster as an outer layer. The outer plaster layer has a life span of 25 years and thus needs to be replaced. The life span of the rice board is unknown, but the assumption is made that it can still be used after 25 years. But due to the wet connection between the layer of plaster and the board, the whole element has to be replaced. This so-called wet connection and is not ideal when regarding the end of life of the products. The outer plaster layer will become solid waste since it is not biodegradable due to the cement content. The rice panel will become biodegradable waste if separation is possible. The other element of the facade are the shutters. These are materialized with wood. At the end of life this can be recycled into particle boards.

The roof is materialized as CBRS (bamboo) and at the end of life will become biodegradable. The material flow, input and output, can be seen in fig. 10.14.

10.3.4 Phase 4: end of life

After 50 years

At the end of life phase of the building, the elements will be disassembled. It was stated before that mechanical fastening is preferred since this will improve possibilities for reusing or recycling of the elements.

At this phase, we can calculate the total mount of building materials consumed by the design which is 655,98 ton (fig. 10.15). Of this total amount:

- 48% is reusable
- 36% is recyclable
- 10% is biodegradable
- 7% is solid waste

27 housing units have been constructed over a period of 50 years. If knowledge was present about the job creation within the Haitian building industry, this could have been calculated. Unfortunately, this is lacking and it would not be correct to implement job creation data of the Netherlands due to the different context.

The material flows of the three different phases will be visualized on the following pages.

Design elements	Life span [years]	Afterlife
Foundation	100+	Reusable
Wooden structure	(unknown)	Recyclable
Floors	When exposed to the exterior, 25	Recyclable (cement) and biodegradable (bamboo)
Facade	25	Solid waste (plaster) and biodegradable (riceboard)
Roof	Roofing sheets: 15-30	Biodegradable
Balcony fenestration	(unknown)	Biodegradable

Table 10.8: Lifespan and afterlife of building products
Source: US Department of Housing and Urban Development, 2002

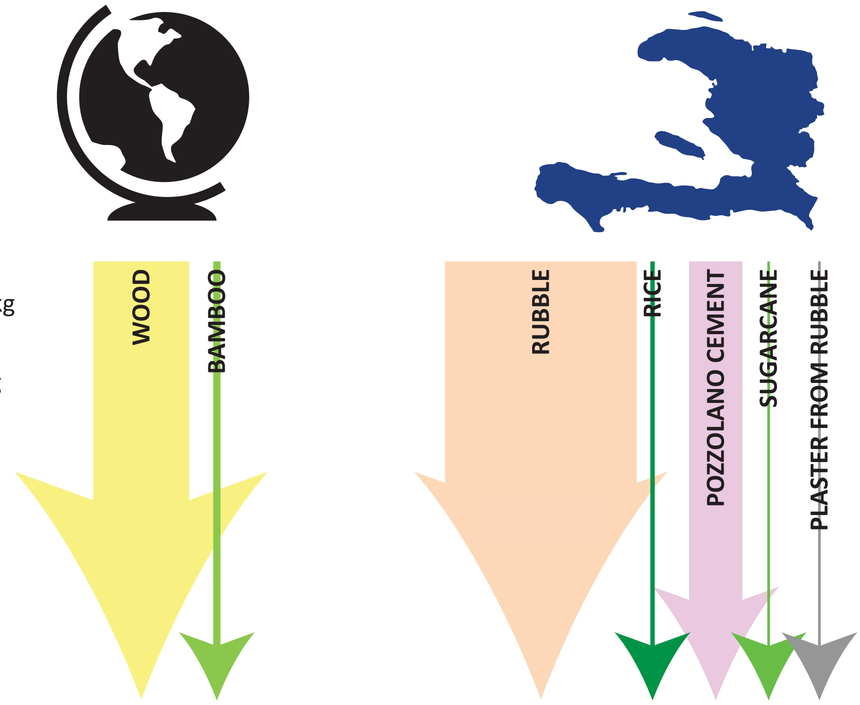
PHASE 1

0 years

MATERIAL INPUT

Wood
111.460,7 kg

Bamboo
27.392,2 kg



Earth or rubble
312.600 kg

Rice board
16.529,6 kg

Pozzolano cement
90.051,6 kg

Sugarcane
1.243,2 kg

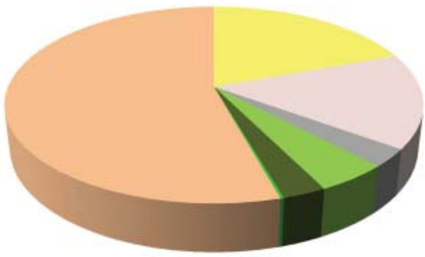
Plaster from rubble
16.761,6 kg

16
UNITS

$10.359,73

(unknown)
JOBS

Total building material
576.038,8 kg



MATERIAL OUTPUT

Fig. 10.13: Material flow phase 1
Source: Author

PHASE 2

0-25 years

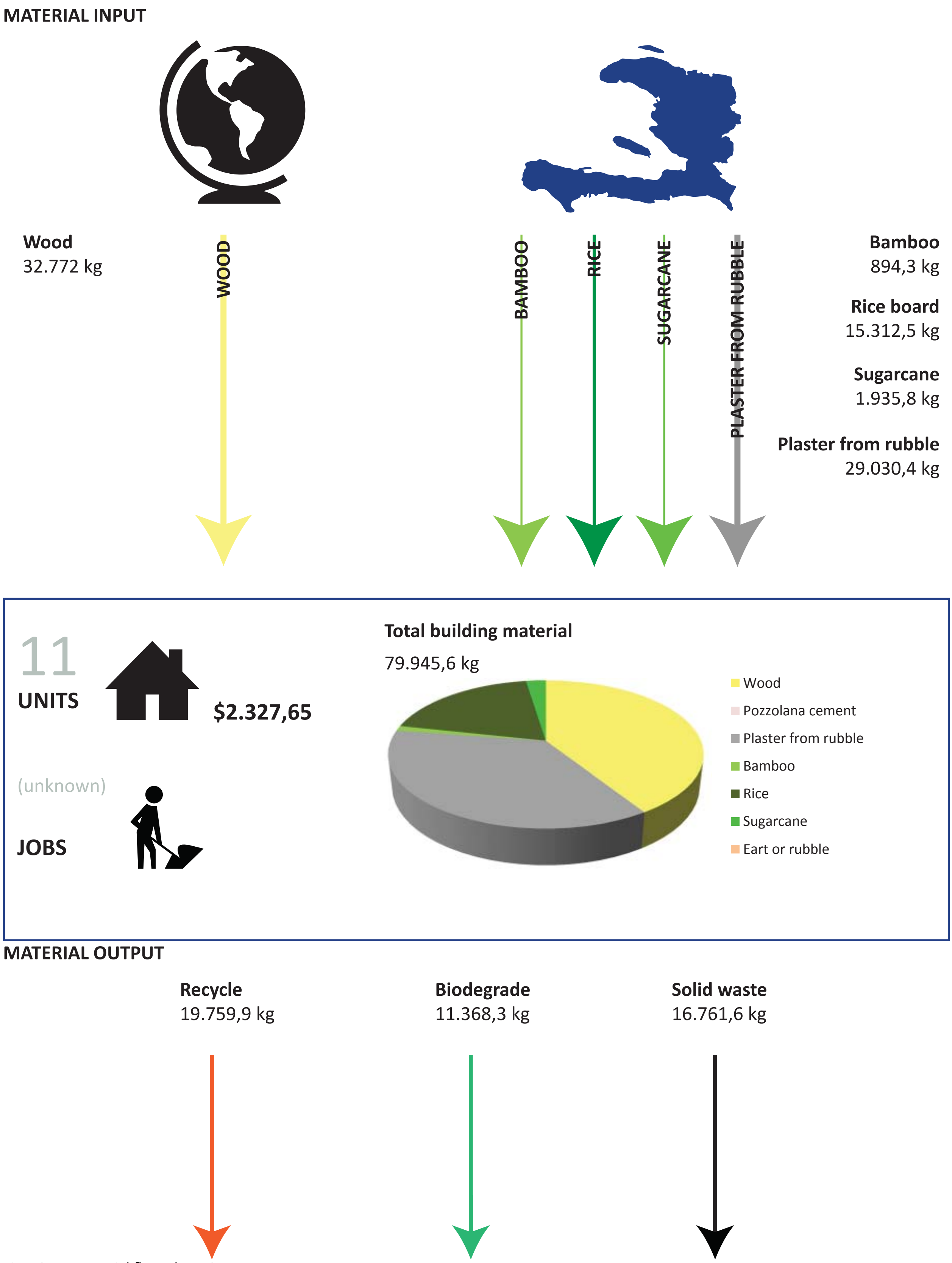


Fig. 10.14: Material flow phase 2
Source: Author

PHASE 3
End of life of building

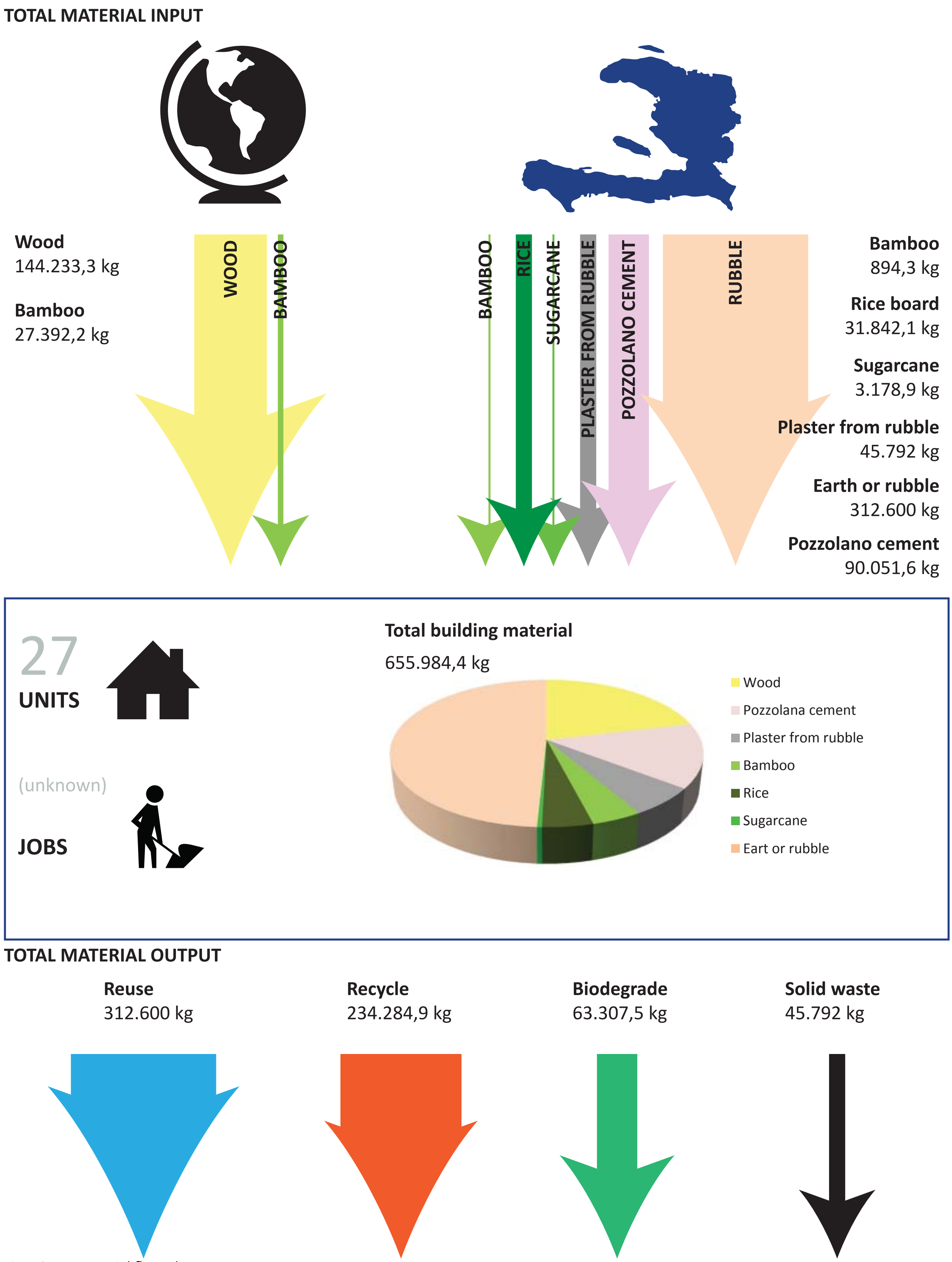


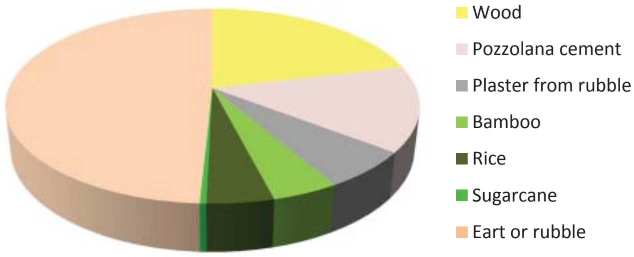
Fig. 10.15: Material flow phase 4
Source: Author

SUMMARY

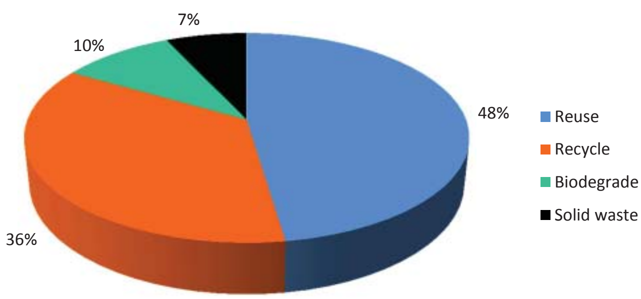
For the design of the building, with 27 housing units and supporting functions, the total demand for building materials is calculated for the whole life span of 50 years. The materialization is decided on by indicators. At the end of life of the building and during the life span of the building, waste of building materials is present.

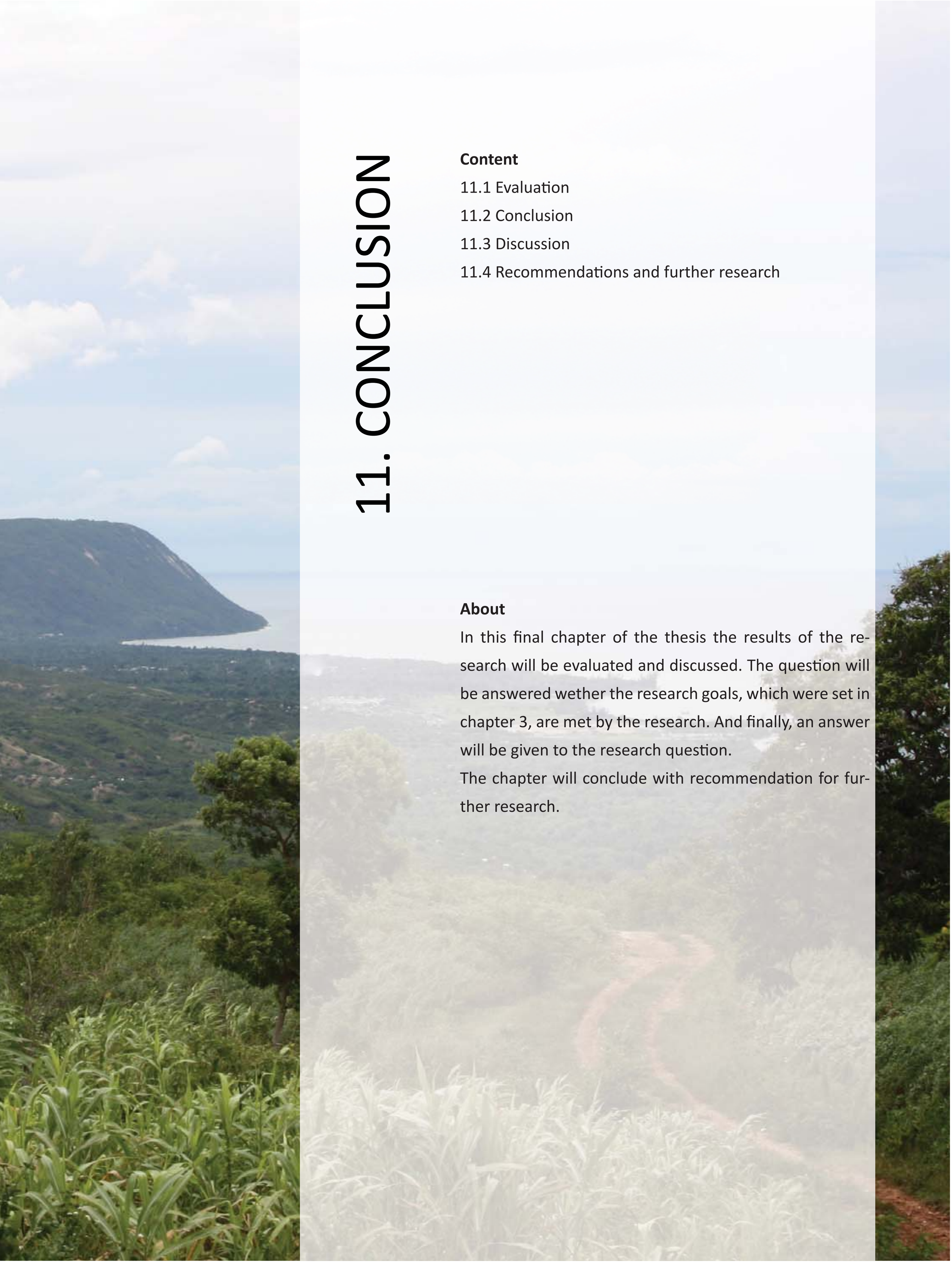
27
UNITS

Total building material
655.984,4 kg



Afterlife of the building products





11. CONCLUSION

Content

About

In this final chapter of the thesis the results of the research will be evaluated and discussed. The question will be answered wether the research goals, which were set in chapter 3, are met by the research. And finally, an answer will be given to the research question.
The chapter will conclude with recommendation for further research.

11. CONCLUSION

In the context of urbanized Haiti, can the building industry with a climatically responsive redesign of the high-density urban neighbourhoods be committed to ignite economical, environmental and social development which increases the resilience towards disasters? (research question of thesis)

The motivation for this research came after a thorough analysis of Haiti after the devastating earthquake on January 12 2010. Multiple problems from the political, social and environmental sphere were indicated as causes of the undeveloped state of Haiti, with high unemployment and high illiteracy rates, a low economic development and an environment subjected to degradation and hazards as a result.

Not all problems could be solved within this thesis. Indicators of the resilience and sustainability theory have determined the scope of the research. This final chapter will evaluate the results of the research, the design, on the indicators and will compare the design with the NGO design and/or the existing situation.

The objective of the research is to develop Haiti through a sustainable building industry which uses local resources to produce sustainable building materials for the local market. The results will be the creation of jobs and a regeneration of the ecosystems of Haiti by growing certain indigenous tree species and specific crops. The cultivation of crops which benefit the food production are favourable above others for obvious reasons. The growing of crops at lands devastated by the environmental degradation will increase the resilience towards landslides and floodings.

The objective for the built environment is to become more resilient to natural and man made hazards and more sustainable through the implementation of a climate responsive building design and the materialization of the building. The building industry as a whole should create jobs, diminish its impact on the environment by reducing wastes and emissions and should stimulate the development of Haiti.

11.1 Evaluation on the indicators

In chapter 3 the indicators were determined for the scope of the research. They indicate those parts of the resilience and sustainability theory through which the building industry can meet the objectives and solve the problem statement. The outcomes of the research are implemented into the design which can be seen as the result of the research. The design will now be evaluated on the indicators to see if the research goals were met. The design will be compared with the NGO design for zone 7 and the existing situation where possible.

Indicators Resilience

Increase thermal comfort (health)

In the present day situation and in the proposed design for zone 7 by the collaboration of NGO's, the materialization of the buildings are cement blocks, concrete and sometimes CRS of a metal as a roof. The research has indicated that these materials are not suitable for the hot and humid climate and they can result in thermal discomfort as was found by a fieldwork survey. The research focussed on improving the indoor thermal comfort level by passive thermal strategies and climate responsive features, whereby the health conditions and thus the social resilience are improved. The evaluation of the design on indoor thermal comfort in comparison with the NGO design and the existing situation is shown in table 11.1. Evaluating wether the indoor thermal comfort level is increased, is done by three parameters: the ceiling temperature, the facade temperature at the indoor surface and the applied passive thermal strategy.

The amount of heat flow through the roof and fa-

	Thesis design	NGO design	Existing situation
Ceiling temperature [°C]	41,3 (calculated, see appendix)	49,3 (calculated, see appendix)	36,2 (CRS of galvanised iron roof, average of 4 measured houses)
Facade temperature [°C]	33,5 (calculated, see appendix)	40,0 (calculated, see appendix)	unknown
Passive thermal strategy	• Airflow, cross ventilation by floor to ceiling high shutters • Light facade materialization, ρc for 1 m^2 of facade = $0,56*10^5$	• Airflow, cross ventilation by 1/3 of the facade high ventilation bricks • Cement blocks accumulate heat during the day, ρc for 1 m^2 of facade = $2,5*10^5$	• Airflow, by shutters and ventilation bricks

Table 11.1: Evaluation indoor thermal comfort
Source: Author

cades during the day, determines the outdoor heat gain which can cause in a rise in indoor temperature. A significant increase in temperature causes in thermal discomfort. It is possible that through the passive thermal cooling strategy the thermal discomfort is kept low.

The parameters to determine wether or not the indoor thermal comfort is increased are calculated under steady state conditions. The calculations can be found in the appendix. From table 11.1 we can conclude that the thesis design performs better than the NGO design on this first and second parameter. The existing situation seems to perform best on the first two parameters. These temperatures were measured by the author during a fieldwork survey and basing assumptions on these values in comparison with the calculations would be wrong since the climatic conditions are not exactly known. For instance, the solar radiation on the roof might have been much lower at the time of measuring compared to the highest amount which is used for the calculations.

The calculated surface temperature for the ceiling was determined with an ambient temperature of 37,2 °C. The calculation for the facade was with an ambient temperature of 30 °C. According to Koenigsberger (1965) an increase of the ceiling temperature of around 5 °C above the ambient air temperature is acceptable. This would imply that the ceiling temperature for the design is within the acceptable range and will not cause in thermal discomfort.

All buildings have implemented the passive thermal strategy of airflow to ventilate the indoor space. However, the building scale level of implementation is different. The design has floor to ceiling high shutters in opposite facades and single banked rooms to promote cross-ventilation. The NGO design implements small shutters which have a height of around 1/3 of the total facade height. They are placed at the top of the facades on every floor. Evaluating this implementation with the theory on how to ventilate in the hot and humid climate, this will result in an airflow only at the top of the indoor space. The airflow in the hot and humid climate provides for the human body in an opportunity to loose heat by evaporation. This can not be met if the airflow is only at the top of the indoor space since than it will only remove the warm air. Same holds for the way the ventilation bricks or shutters are implemented in the existing situation. The statement that floor to ceiling high shutters provide in a higher level of thermal comfort is underlined by the Haitian building typology of the Gingerbread houses. These houses have floor to ceiling high shutters and these houses are perceived as thermally comfortable by the users.

Another passive thermal strategy is related to the materialization of the roof and the facades. It was explained that a material of a significant thickness and density will accumulate heat, such as cement and earth. This is desirable in hot and arid climatic zones were temperatures during the day are high and drop during the night. This is however very unwanted within the hot and humid climatic zones such as Port-au-Prince. The NGO design and the existing situation are materialized with cement. Cement of a significant thickness has a high heat storing capacity. For the materialization of the facades of the research design, a materialization is chosen which has a low heat storing capacity. It is a so-called light facade which does not stores heat during the day.

	Thesis design	NGO design	Existing situation
Seismic design	• Braced structural frame of wood with stiff floors	• Confined masonry	• None
Tropical storm design	• Proper connection to the foundation • Sloped roof • Outward hinging doors and shutters	• Proper connection to the foundation • Heavy structure	• Proper connection to the foundation
Landslide mitigation	• Proper drainage • Water catchment diminishes the amount of water needing drainage during heavy rainfall • Vegetation • Semi-permeable bricks provide in water infiltration during light rainfall	• unknown	• Drainage is present, but unable to deal with large amount of water

Table 11.2: Evaluation increasing resilience to natural hazards
Source: Author

Evaluating the thermal comfort level on the three parameters shows an improvement by the design in comparison with the NGO design and the existing situation.

Decrease vulnerability to natural hazards

The natural hazards which pose a risk at the design location are earthquakes, tropical storms and landslides. Table 11.2 shows the measurements taken by the two designs and those that are prominent in the existing situation to reduce the vulnerability of the built environment to the natural hazards. Due to the earthquake, the focus lies more on the seismic design than the other natural hazards, even though the landslides have a higher risk on occurrence.

One of the reasons why the event of the earthquake turned into a disaster was because of the lack of seismic design in the buildings. Both the thesis design and the NGO design have a seismic design strategy, but they are different due to a different materialization. The strategies both decrease the vulnerability of the building towards earthquakes and will prevent in disaster.

Tropical storms are an annual returning natural hazard where the air pressure differences acting on the house pose the greatest danger on disaster. Vulnerable elements are the roof and facade, if consisting out of sheeting, and openable elements such as doors and windows. The design of the thesis has a proper connection to the foundation and has provided in outward hinged doors and shutters. The slope of the roof minimize the risk on the failure of the roof. The design is more vulnerable to tropical storms than the NGO design, since it is not a heavy structure.

The location of the design is a steep slope of a hill which has a high risk on the occurrence of a landslide. A landslide in Haiti is caused by a combination of heavy rainfall and inability of the soil to absorb the water due to the absence of vegetation. The thesis design has taken several measures, which are listed in table 11.2, to mitigate the risk on the occurrence of a landslide. If one occurs, all designs are vulnerable so the prevention of one must be considered. It is unknown to the author wether the design of the NGO's takes landslide mitigation into account. In the existing situation there is drainage present (fig. 6.13), but this seems insufficient to deal with a large amount of water.

The design has taken all the measures to decrease the vulnerability of the built environment to natural hazards. The NGO design has taken similar measures, so in comparison with each other they score similar. They both have improved the resilience of the built environment to natural hazards in comparison with the existing situation.

Stimulate economic growth

Economic development starts with the increase of the purchasing power of the Haitians. With very high unemployment and illiteracy rates plus a low GDP per capita, economic development starts with the creation of jobs with a reasonable wage. The design implements sustainable building products for the materialization which are produced in Haiti with local raw material resources. The whole life cycle of the building products is located in Haiti, which means that jobs are

created in Haiti.
Jobs are also created during the construction of the building, the repair or renovation during the life phase of the building and at the end of life when the building is demolished. It is not known exactly how many jobs are created during the construction phase of the building.
The design has extra floor space for entrepreneurs to set up their businesses. These businesses can also attribute on a small scale to job creation. The inner courtyard can also harbour an economic activity which is favourable for people who are bound to their houses. This can for instance be the case for household members who take care of the children.
The created jobs by the research will provide in an income for the household and will increase the purchasing power and GDP per capita. It has not been possible to make an estimation about the exact number of job creation, but it will definitely improve the existing situation.

Off-grid buildings (infrastructure)
Resilience to man made hazards is more difficult to obtain due to the unpredictability of the hazard. Buildings which are not connected to the grid, which is the cities infrastructure of electricity, sewage and water, are more resilient to some man made hazards than those that are connected. In the existing situation, there is no connection to sewage and water and only limited connection to electricity. The toilets in the existing situation are mostly pit latrines and water is bought from water selling points.
The design of the thesis has implemented small PV panels to provide in the necessary electricity. Sanitation is provided in by communal urine diverting toilets and washing facilities. The waste from the toilets is stored in drums and transported to a composting site outside the city. After some time it can be used as a fertilizer by farmers. Since it is a system which is depended on several parties, it maybe is not as resilient to hazards as it seems to be in theory.
The sloped roofs of the building catches the rainwater and stores it in tanks. The rainwater can be used to replace a part of the demand of 15 L per person per day of water. However, it is not sufficient so additional water is still needed to provide in the daily demand. This water has to be bought.
The evaluation shows that the design is not fully off-grid and is thus still vulnerable to specific hazards.

Reduce carbon output
CO_2 is one of the emissions contributing to climate change. 5% of global CO_2 emissions is produced during the production of cement. From the total amount of building materials which is used by the design during its whole life span, only 13,7% is a newly produced cement product. In the existing situation, around 95% of the materialization is cement based. The materialization of the design of the thesis diminishes the CO_2 emissions significantly by being mainly materialized with non-cement products.
The emissions are also diminished due to the fact that only locally (in Haiti) produced building materials are implemented in the design. The transportation distances are small and thus the CO_2 emissions due to the burning of fossil fuels, will be diminished. The NGO design is materialized with cement which is imported and thus have larger transportation distances with higher CO_2 emissions.
After the demolishing of the building, 10% of the total amount of building materials is labelled as biodegradable (fig. 11.1). From these materials energy can be gained through burning, which is called biomass. During this process CO_2 will be produced, but this is the same amount as when the products are left to biodegradation by natural processes. So the CO_2 emission will not be greater when used as biomass.

Indicators Sustainability

Micro climate responsive

The climate is divided by the research into three parts: the macro, meso and micro climate. The micro climate includes those aspects of the topography and environment of a location which influence the climate. These aspects can strengthen the climatic parameters of the meso climate. For example, the materialization of the facades of buildings with cement in a high density composition can increase the ambient air temperature compared to the meso climatic weather data. The design has to respond to the micro climatic aspects and make sure that it will not eventually cause in indoor thermal discomfort. Table 11.3 shows the climate responsive features of the thesis design, the NGO design and the existing situation.

The climate responsive features described in the table either diminish the heat load on the facades (by the veranda, balcony, vegetation and pavement type), diminish the indoor heat load (outdoor cooking) or promote airflow.

From the research it was concluded that ventilation by airflow should be promoted to the maximum since in the hot and humid climate it is the only possible was for the human body to loose heat (by evaporation). The design of the building is a stepped row housing block which creates high and low air pressure zones when affected by airflow. These zones are created at both sides of the house and promote cross ventilation. Not all facades of the design are suitable to be materialized as shutters due to the direct solar radiation which should be blocked from the indoor space. Shutters are unable to serve both as a solar radiation barrier (closed) and a ventilation promoting element (open). Therefore veranda's and balconies block the direct solar radiation on the west and east sides of the houses. If the solar radiation is blocked, the facades can be materialized with shutters.

To the author's knowledge of the NGO design, the only climatic responsive feature are the inner courtyards. In the existing situation some veranda's and balconies were observed, but they were not the standard. The evaluation shows that micro climate responsiveness of the design of the research is better than that of the NGO design and the existing situation. This will result in a thermally more comfortable buildings.

Conserve natural resources

Haiti is subjected to large scale environmental degradation started by the long time wood logging. Reforestation programs have been set into motion and since wood is a highly wanted building material, sustainable forest management is the strategy to prevent in making the same mistake again. The demand for wood by the design is over 20% of the total demand for building materials (fig. 11.3). This is due to the fact that the structural frame and the shutters are materialized with wood.

The other building products, which will be locally produced, all have a raw material resource found or grown in Haiti. There lies a danger in the depletion of the nutrients in the soil. The strategy of polyculture should be implemented to prevent in soil degradation. The indicator of the conservation of natural resources

	Thesis design	NGO design	Existing situation
Climate responsive features	• Stepped rowhouses create high and low pressure zones to promote cross ventilation • Veranda or balcony to shade facades and to offer a space for outdoor daily activities • Vegetation to shade facades and offer shade to the outdoor space • Outdoor cooking • Because of the phasing, the ground floor is open to airflow • Semi permeable pavement bricks reflect less solar radiation	• Courtyard for outdoor daily activities	• Outdoor cooking • Sometimes a veranda or balcony

Table 11.3: Evaluation micro climate responsive building
Source: Author

is important to stop the environmental degradation that has already devastated large parts of rural Haiti. From the evaluation it follows that the research of this indicators has fallen a bit out of the scope of the thesis. The interrelated research part of De Ruiter (2012), who researched the carrying capacity of the land for the growing of specific crops, has gone more into depth on this indicator.

Reduce waste

Reducing the amount of solid waste is the first step towards efficient resource management of which the goal is to have no waste at all. Fig. 11.1 shows the afterlife of the building products at the end of lifespan of the building. Fig. 11.2 shows the same but than for the NGO design. The total amount for building materials is:

	Demand for building materials [kg]	**Afterlife: solid waste [kg]**
Thesis design (27 housing units)	635.646	39.398
NGO design (17 housing units)	790.785	319.831

Table 11.4: Evaluation reduce waste
Source: Author

The total demand from the NGO design is slightly less, but the number of housing units is different and the calculation does not include the supporting functions such as sanitation and vertical transport (table 11.4). The NGO demand calculation does also not take into account repair or renovation during the lifespan of the building.

Table 11.4 shows that the solid waste has been significantly reduced by the thesis design. The afterlife of the materials used for the NGO design is for 40% resulting in solid waste, the thesis design has only 7% solid waste. The reduction of solid waste by the design is significantly large, but there is still room for improvement since not all solid waste has been turned into a resource for new processes.

Culture responsive

For every design it is important that it suits the needs and desires of the user. For the design of the thesis this means that it should be Haitian culture responsive. Off course, we will not know wether it will be accepted as long as it is not tested by building and using the design. But some cultural aspects that are important have been implemented into the design.

An assessment by Cordaid in Villa Rosa concluded that the average household size is 5,5 person and the average house is 14 m^2, which is very small according to western standards. But when one knows that most activities during the day take place outside their house, and thus they actually only sleep inside their house, it becomes more understandable. The average housing size of the design is 14 m^2 and an additional 5 m^2 of outdoor space (veranda or balcony). The housing block is designed in a way that several units can be linked to each other by an indoor door to form a larger house size. This flexibility is necessary when responding to the future needs and the possible growth of the wealth of the inhabitants. Future population growth by urbanization an the natural population growth will increase the demand for housing units. The design has responded to this by providing in extra housing units. The design only had to provide in 14 housing units, but due to the future population growth an the stimula-

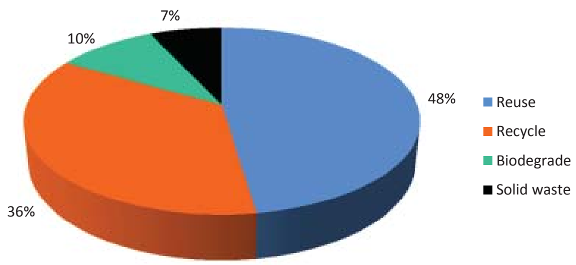


Fig. 11.1: Afterlife of building products at the end of life of the building of the thesis design
Source: Author

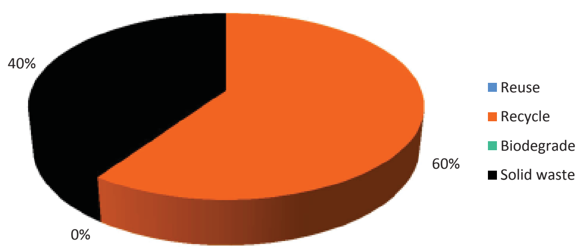


Fig. 11.2: Afterlife of building products at the end of life of the building of the NGO design
Source: Author

tion of entrepreneurship, 13 extra units are provided for by the design.
Cultural expression through the design of the house might also be a desire for some users of the building. Voodoo is an important part of the Haitian culture and comes to expression by wood carvings and the use of colour. The closed facade part have an outer layer of cement which can be painted in colours according to the needs of the user. Off course, from the climatic point of view these colours should be bright to reflect as much solar radiation as possible.

Maximize water efficiency
Drinking water is becoming a scarcity in the world, especially the developing countries. Maximizing water efficiency is a must to relieve some pressure on the system providing in water. Water efficiency within the scope of the research can be maximized in two ways: during the production of the building materials and during the user period of the building. During the production of building materials, water is used in various ways for example for cooling purposes or to wash a product. It has been difficult to determine the water usage of the production process of building materials, since companies do not give full disclosure about their production processes. The CES Edupack database provides in data about the water usage, but this is an assumption based on the conventional production process.
In the design rainwater is collected to substitute a part of the daily demand for drinking water. However, the amount the can be collected is insufficient to supply in the total daily demand and additional drinking water has to be bought by the residents. There is no space within the housing block for the treatment of grey water. If there was more space, this could be implemented and the water efficiency could be maximized to maybe being totally independent. The grey water is now drained down the hill. It is a possibility to treat the water at the bottom of the hill, but this has not been researched.

Affordability
A very important aspect for the success of the design is the affordability. What is affordable in the Netherlands may not be affordable in Haiti. The costs for a housing unit for phase 1 and 2 have been calculated (table 11.5).

	Costs [$]
Housing unit phase 1	10.359,73
Housing unit phase 2	2.327,65

Table 11.5: Housing unit costs of the design
Source: Author

These calculations are based on the costs of the building products. A notation has to be taken about these costs. The costs of a building product is the sum of raw material costs, labour costs, machinery costs, transportation costs and profit. The costs of the building products in the database are contextualized in the western societies and will thus probably be higher than when the product would be produced in Haiti.
This would imply that the costs for the housing units are lower than those in table 11.5. The costs for a housing unit in phase 1 is significantly higher than for the other phase. This is due to the fact that at the first phase the total structure is build together with the supporting functions of vertical transportation and sanitation. If a cooperation or a governmental body would become the owner of the building block, these costs could be equally divided amongst all the housing units. The costs of a housing unit would then be the same for all phases.

Reduce toxicity
During the production of building materials, chemicals might be added to increase the durability. The chemicals might be toxic and would pose a danger during the user period of the building or at the afterlife phase of the building product. It is best to avoid this and only use sustainable measures to increase the durability of a product. Some have been discussed in the thesis.
It is also possible that raw materials have to be glued to come to the end product. Formaldehyde is a type of adhesive which is used in for example fibreboards. It is labelled as a carcinogen which means that it is a cancer-causing substance. Avoiding this adhesive is the strategy to follow.

Maximize energy efficiency

Just as with maximizing the water efficiency for the production process of building materials, the lack of full disclosure by the producing companies makes it hard to evaluate this indicator. The embodied energy is all energy, other than from biofuels, required during the primary production process to produce the product by the housing units. This energy could be supplied for by renewable sources such as solar or wind energy. Solar energy is implemented in the design as the primary source of energy supply for electric products. Special produced PV panels for the Haitian market should provide in the necessary energy needed for the daily activities.

The fuel for cooking is charcoal made from wood and is one of the reasons for the deforestation. Changing this fuel into a sustainable fuel such as briquettes made from paper, would help solve the problems. The research did not focus on this aspect, but should have been done to strengthen the research on maximizing the energy efficiency.

Maximize durability

The life span of the building has been set to 50 years. The technical life span of the building products is sometimes longer, so the afterlife of the building productcan be reuse or recycle. When trying to maximize the durability of a product we should ask this ourselves from the point of view of sustainability. Is it still desirable to increase the durability when a chemical has to be applied to the product or not? If the durability of the product is already as long as the life span of the building it might be better to not apply the chemical and let the afterlife of the building product be biodegradation. It is a trade off between resource efficiency, costs and sustainability.

11.2 Conclusion

The evaluation of the design, which is the result of the research, on the indicators has resulted in table 11.6. The scores reflect on the research question and wether the development is stimulated by the research and design. The development should increase the resilience towards disasters caused by natural and man made hazards. The research question divided the development into an economical, environmental and social sphere. The research will now be discussed in regard to wether or not it stimulated the development.

Economical development

An objective stated in chapter 3 was to ignite economic development through a sustainable building industry with as a result the creation of jobs. Jobs created by the design can be divided into three categories: jobs created during the production of the building product, jobs created during the construction phase of the building and jobs created in and around the building (local entrepreneurship). The discussion will focus on

Evaluation of the indicators on the increase of resilience to disaster	
Indicator	**Score**
Increase thermal comfort	
Decrease vulnerability to hazards	
Stimulate economic growth	
Off-grid buildings	
Reduce carbon output	
Micro climate responsive	
Conserve natural resources	
Reduce waste	
Culture responsive	
Maximize water efficiency	
Affordability	
Reduce toxicity	
Maximize energy efficiency	
Maximize durability	

Table 11.6: Evaluation of the indicators (green = significant increased resilience, white = little increased resilience, orange = no increase in resilience

Source: Author

the jobs created through the building industry.

The research with the design as a result has shifted from the import of almost all building materials to producing them in Haiti with local raw material resources (chapter 10). This is a swift from jobs in foreign countries, to job creation in Haiti. Unfortunately, it has proven to be impossible for the scope of the research to underpin this statement with a reliable number of the amount of jobs which are created. Smits (2012) determined in her research that the production of rice boards would provide in 72 full-time jobs per year with an annual production capacity of 3,6 million m^2 of rice board. This number of jobs is based on the production process in a western country with high-tech machinery and a low amount of manual labour. Numbers could thus be larger when implementing the small-scale and decentralised strategy of industry described in chapter 4. This number only reflects the amount of jobs created during the production process of the rice board. Jobs are also created during the growing of the crop or the raw material extraction, the transportation between the different phases of the life cycle of a building product and during the afterlife.

The construction phase of the building and also the renovation during the lifespan of the building, create jobs. Knowledge by the author about the Haitian building industry and the job creation during the construction phase of a building, are lacking and thus the total job creation can not be determined. What can be calculated is the future demand for housing due to the urban growth and natural growth of population of Port-au-Prince. Table 11.7 shows the expected population growth of Port-au-Prince for similar neighbourhoods as the design location. The design of the thesis could thus be implemented on a large scale to satisfy in the demand for housing. Over a period of 50 years, this results in the construction of 9.124 housing blocks.

In table 11.8 the demand for building materials is calculated for the design of the research and the NGO design (cementblock house). This table also shows the amount of building materials needed over the period of the lifespan of the building, 50 years, and the afterlife of the building products after when building is demolished.

If more knowledge is gained about the total job creation during the production of the building products,

Expected population growth in desification areas of Port-au-Prince (Forsmann, 2009) and amount of residential buildings needed	
Annual growth Port-au-Prince	115.000
Annual rural-urban migrants	75.000
Rural-urban migrants adding to the densification	25.000
People adding to the densification in 50 years	1.250.000
Number of people per one housing block	137
Number of buildings needed to accommodate the urban growth in 50 years	(1.250.000/137) = 9.124

Table 11.7: Demand for housing blocks due to urban growth in a period of 50 years
Source: Author and L. Smits (2012)

Demand for building materials		
	Thesis design	NGO design
Number of housing blocks needed	9.124	(1.250.000/94) = 13.298
Total demand for building materials [ton]	**5.799.635**	**10.515.856**
Wood [ton]	1.232.435,6	
Pozzolano cement [ton]	821.630,8	6.175.038
Plaster from rubble [ton]	359.471	
Bamboo [ton]	254.459,8	
Riceboard [ton]	255.331,8	
Sugarcane [ton]	24.143,3	
Earth or rubble [ton]	2.852.162,4	
Concrete [ton]		4.253.115,3
Steel [ton]		87.703
Afterlife		
Reuse	49% 2.852.162,4 ton	0%
Recycle	35% 2.054.066,4 ton	60% 6.262.741
Biodegrade	9% 533.934,9 ton	0%
Solid waste	6% 359.471 ton	40% 4.253.115,3

Table 11.8: Demand for building materials by the urban growth of Port-au-Prince over a period of 50 years
Source: Author, after L. Smits (2012)

the job creation could be calculated. But the fact that production has moved from foreign countries to Haiti is suffice to say that jobs are created on a large scale during a period of 50 years and probably longer.

Environmental development

The environment includes both the natural and built environment. For the natural environment the objective was to put a halt to deforestation and the loss of ecosystems; promote the use of local raw material resources for the production of building products and especially those coming from crops whose first purpose is to provide in food; to reduce toxic emissions coming from the building industry and to stimulate efficient resource management.

When wanting to put a halt to the deforestation and the loss of ecosystems, one should first determine the causes of the deforestation. In Haiti the main cause is that the fuel for cooking is charcoal which is derived through the burning of wood. Replacing the charcoal with another sustainable and affordable fuel such as briquettes would take away the root cause. The research did not focus on this aspect which can also be seen from the score on the indicator of maximizing the energy efficiency. A second step would be to research ways of how to ignite reforestation projects. This is not within the scope of the research. The research of De Ruiter (2012) did implement this important step into the regeneration of Haiti's forests and ecosystems.

The first selection criteria for building products to be included into the database, is the possibility of production with Haitian raw material resources. These local raw materials can either be already part of the natural capital or can be grown in Haiti. The research has thus met the goal of promoting the use of local resources as raw materials.

It was stated in the thesis that 5% of global CO_2 emissions come from cement production. The design has diminished the use of cement as much as possible. The pozzolano cement, which is used in the design, only accounts for 13,7% of the total mass of building materials (fig. 11.3). In the NGO design the cement use accounts for 58,7% of the total mass of building materials. If concrete is regarded as cement, than the percentage is even 97,2% (fig. 11.4). CO_2 emissions, which contribute to climate change, have been reduced significantly.

The addition of toxic chemicals to building products poses a danger to the human health during the user period of the building and possibly also during the afterlife phase. The research has indicated in which phases of the life cycle of a building product, toxic chemicals might be added. Alternative solutions, although only few, were presented. Some of them are only in a research phase yet, but it does prove that there is awareness about the problem and that changes are at hand.

Efficient resource management is obtained when there is no waste generated and when the life cycle of a building product would be a closed loop. Unfortunately, this is not the case with all materials used for the design. Some materials will become solid waste which means that none of the resources are recovered.

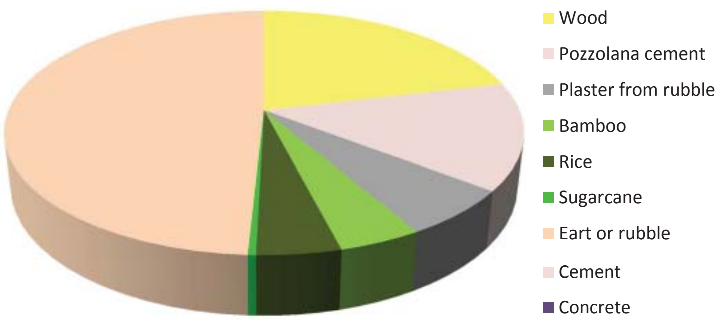


Fig. 11.3: Material use of the thesis design
Source: Author

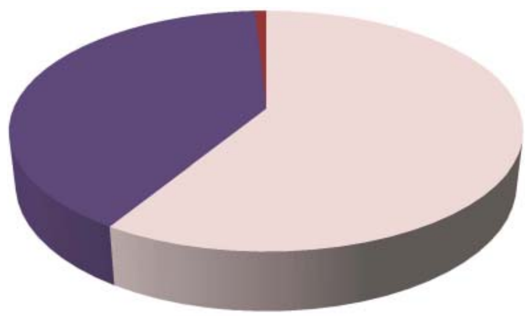


Fig. 11.4: Material use of the NGO design
Source: Author

The objective for the development of the built environment is to increase the resilience to disasters, caused by both natural and man made hazards. A map of the occurrence of natural hazards is a useful tool to visualize which natural hazards pose a risk on disaster at the location. The design has anticipated to these risk and is resilient to them. When a natural hazard occurs it will not result in disaster.

Obtaining resilience to man made disasters is a lot harder to accomplish. To begin with, there is no predefined list of man-made hazards. What can be done is to increase the resilience by being self-dependent as much as possible. The design has made an effort by being independent of the infrastructure of electricity, water and sewage. It has succeeded on being independent of electricity and sewage, although the sanitation system is still somewhat vulnerable to both natural and man made hazards. The water system consists out of rainwater catchment which replaces some of the daily demand for water by the residents. It is however not sufficient and additional water has to be bought. The research did not investigate on grey water purification to reuse the water. This is a potential which could be further investigated.

Social development

The creation of jobs in the building industry will not only stimulate the economy, but it will also increase the wealth of those involved. The purchasing power of those employed will increase and so will the living standards. It is a chain reaction.

A part of a person's well-being is determined by the indoor thermal comfort level. Especially during the night, temperatures should be within the comfort range to be able to recover from heat stress incurred during the day. It has been made clear during the evaluation of the design that the indoor thermal comfort level has been increased by the climate responsive design. As far as possible within the scope of the thesis, social development is stimulated by the design.

The earthquake of January 2010, which resulted in a catastrophic disaster, was the motive to start the research. After a thorough research into Haiti's history and present day situation, it was found that there is a list of problems which cripple Haiti and stop development. A research question was formulated and by indicators of the theory, the research was started. The outcomes of the research were implemented into the design which was evaluated on the indicators of the theory and compared with the existing situation and the NGO design for the same location. The research has been evaluated on wether or not the objectives were met.

The research question of the thesis is:

In the context of urbanized Haiti, can the building industry with a climate responsive design of the high-density urban neighbourhood be committed to ignite economical, environmental and social development which increases the resilience towards disasters?

From the evaluation the answer to the research question is that yes, there is a huge potential for Haiti to develop through a sustainable building industry and hereby increase the resilience towards disasters caused by natural and man made hazards. It became clear during the evaluation that a lack of data about the building products and their production processes have obstructed the results of the research. The total number of jobs created both during the life cycle of the building products and at the construction site could not be determined.

The evaluation and the scores on the indicators show that the focus of the research has been on the development of a climate responsive design for the high density urban neighbourhoods and on the materialization of the design with sustainable building products. Some smaller indicators have had less attention on the research and here lies potential on improving the research and design even more.

A generic objective of the research was to find a solution for the climate unresponsive building in similar neighbourhoods in a similar climatic zone. A solution is found for the context of Haiti and the design can be tested in other cities such as Rio de Janeiro and Caracas on the thermal performance.

11.3 Discussion

It has already been mentioned that a lack of data has obstructed some results of the research, especially on the job creation but also on the climate analysis. Another point of discussion where the lack of data has put its mark on, is the determination of the indicator scores for the selection of the materialization of the elements of the design. The scores are now mainly based on the intuition of the author.
The database of sustainable building products is never complete so hopefully the lacking data will be provided for by companies soon.
Based on the evaluation of the research by the indicators it becomes clear that the focus of the research was on climate responsive design and some indicators of the sustainable building product part. Maybe the amount of indicators was too much, although the results of the research are good.

11.4 Recommendations and further research

Comparing the research with the existing situation and the NGO design show the potential of the research and the improvements which could be made. This is the first step towards the development of Haiti and so recommendations would be to continue this research.

The research contains several parts on different scale levels which could be researched more in depth:

- Implementation of grey water purification systems in the urban high density neighbourhoods of Port-au-Prince to increase the water efficiency
- Develop the toolbox of climate responsiveness of the hot and humid climate into a larger database accessible to for instance NGO's
- Develop similar toolbox for other climatic zones
- Extend the research into and database of sustainable building products, not only for Haiti but also other developing countries
- Perform a better and more extensive research into the perception of tropical thermal comfort

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APPENDICES

Appendix A: Black list building products ingredients
Appendix B: Characteristics of warm and humid climates
Appendix C: Meso climate weather data of Port-au-Prince
Appendix D: Design drawings
Appendix E: Rainwater catchment potential calculation
Appendix F: Heat flow calculations design
Appendix G: Heat flow calculations NGO design
Appendix H: Quantities of building materials calculation of the design
Appendix I: Quantities of building materials calculation of the NGO design

APPENDIX A

Black list (building) product ingredients:

- Phthalates (softners for PVC plastics)

  Abbreviated as DBP (di-n-butyl phthalate) and DEP (diethyl phthalate). DEHP, BzBP, DMP
- Heavy metals

  Release of toxics into the environment during several phases of production. Examples are arsenic, cadmium, cobalt, chromium, copper, mercury, manganese, nickel, lead, tin, and thallium (indicated by the EU as the eleven elements of highest concern)
- Halogenated Flame Retardants (HFRs)

  Disrupt thyroid (Dutch: schildklier) and estrogen hormones
- Perfluorocarbons (PFCs) mostly used in textiles such as Goretex

  Negative health effects and ozon depleting
- Polyvinyl Chloride (PVC), a versatile resin

  Cannot be recycled, very bad for the environment for many reasons during whole production phase
- Formaldehyde and Urea Formaldehyde (UF), substance of glues and adhesives.

  Possibly causing cancer. Best is No-Added Formaldehyde (NAF). Examples are MDI (methylene diphenyl isocyanate) and PVA (polyvinyl acetate), but these are still from fossil fuels. Soy-based resin technology is natural a NAF.
- Vollatile Organic Compounds (VOCs)

  Contribute to unhealthy indoor air quality, low level toxic emissions in paints. In formaldehydes.

APPENDIX B

	Equatorial	Island; trade wind
Temperature: Daily range (average)	-12 °C - 9,4 °C	-9,4 °C
Day-time air temperature (mean max. d.b. in shade)	Usually 29,4-32,2 °C. Rarely exceeds 32,2 °C; during rain-storm may fall below 26,7 °C. Hardly ever above skin temperature of human body.	29,4 - 32,2 °C
Night-time air temperature (mean min. d.b. in shade)	23,9 - 26,7 °C; on clear nights in low 21,1 °C	18,3 - 23,9 °C
Annual range	Slight seasonal variation; -15 - -12,2 °C	Fairly small seasonal variation; -12,2 °C
Sky temperature	About the same as surface air temperature. Sky important source of radiant heat.	At night, when cloedness, below air temperature.
Humidity: vapour pressure; absolute humidity	25 - 30 mb	17,5 - 25 mb
Relative humidity	55 - 100 %	55 - 100 %
Rainfall: annual rainfall	High; usually over 2032 mm and may exceed 5080 mm	Fairly high, 1270 - 2133 mm; marked local variation due to topography
Other characteristics of rainfall	May exceed 508 mm in wettest month; usually 254 - 381 mm. In heavy storm, 51 - 75 mm may fall in an hour. Close to Equator, usual for rain to fall in early afternoon.	Usually 178 - 254 mm in wettest month. In a cyclone, up to 254 mm may fall in single storm. Driving rain likely on windward coast.
Sky conditions: general appearance	Cloudy; 6/10 - 9/10. Sky bright when thinly overcast or when white cumulus clouds do not obscure sun. Dull when thickly overcast.	Clear or partly cloudy; 4/10. Except during storms, when dark and dull. Blue skies, especially on windward coasts of low brightness.
Ground conditions: general appearance	Luxuriant vegetation; abundant shade Green predominates, but bare ground usually red or brown.	Depends on rainfall. Vegetation less luxuriant and lighter green. Very bright light-coloured coral rock and sand.
Soil moisture	Usually damp. High water table; ground may be waterlogged.	Usually dry, with fairly low water table.
Air movement	Low, especially in jungles; but strong during rain squalls, wind gusts of 40 km/h or more.	On windward coasts, wind may blow steadily at 24 km/h or more. In trade wind zone, prevailing wind N.E. and E., northern hemisphere; S.E. and E., southern hemisphere.
Other characteristics	High humidity accelerates mould and algal growth and rotting. Thunderstorms frequent, but high proportion of electric discharges to air.	Risk of tropical cyclones (hurricanes). Close to coast, corrosion due to salt in atmosphere is marked.

Table A: Characteristics of warm and humid climates
Source: Fry, 1982 pp 18

APPENDIX C

Dry bulb temperature	January	February	March	April	May	June	July	August	September	October	November	December	Annual	Period	Number of years
Absolute maximum [°C]	33,9	35,4	36,7	36,7	37,1	37,2	37,8	37,9	38,0	36,8	35,6	33,9	38,0	1864-1966	41
Mean daily maximum [°C]	30,8	31,3	32,3	32,9	33,4	34,5	35,0	35,1	34,1	33,2	32,2	31,2	33,0	1951-1966	20
Mean daily average [°C]	24,6	24,9	25,6	26,3	26,7	27,6	28,0	27,8	27,1	26,6	25,9	25,0	26,3	1864-1960	54
Mean daily minimum [°C]	22,5	21,7	22,4	22,8	23,4	24,2	25,1	24,4	24,1	23,7	23,2	22,3	23,3	1951-1966	20
Absolute minimum [°C]	16,7	15,0	17,2	16,1	18,9	17,8	20,0	19,8	19,4	18,9	17,8	15,6	15,0	1864-1966	41

Precipitation	January	February	March	April	May	June	July	August	September	October	November	December	Annual	Period	Number of years
Monthly mean [mm]	31,6	46,4	72,6	168,3	215,8	98,6	80,5	151,2	166,7	171,3	85,8	32,9	1321,7	1921-1970	50
Monthly maximum [mm]	161,8	276,2	314,7	419,3	489,6	344,6	158,5	274,7	455,6	370,9	308,1	161,2	1937,7	1863-1970	92-95
Monthly minimum [mm]	0,0	0,0	7,6	4,6	61,6	8,0	1,8	15,0	29,0	51,5	4,2	0,0	817,0	1863-1970	93-95
Daily maximum [mm]	72,9	58,4	89,4	98,6	218,4	101,0	71,0	129,1	146,8	139,7	228,6	91,4	228,6	1863-1966	88-91

Humidity	January	February	March	April	May	June	July	August	September	October	November	December	Annual	Period	Number of years
Daily mean air pressure [hPa]	1015,7	1015,7	1015,1	1014,4	1013,8	1014,5	1015,2	1014,1	1012,8	1012,5	1013,2	1014,7	1014,3	1951-1960	10
Daily mean RH [%]	65,0	63,0	64,0	68,0	73,0	68,0	64,0	68,0	73,0	76,0	72,0	68,0	69,0	1888-1921	29
Mean RH at 07:00h [%]	74,0	74,0	73,0	74,0	76,0	73,0	71,0	75,0	79,0	80,0	78,0	75,0	75,0	1888-1965	70
Mean RH at 13:00h [%]	46,0	46,0	47,0	50,0	52,0	48,0	46,0	50,0	52,0	54,0	52,0	48,0	50,0	1951-1966	16

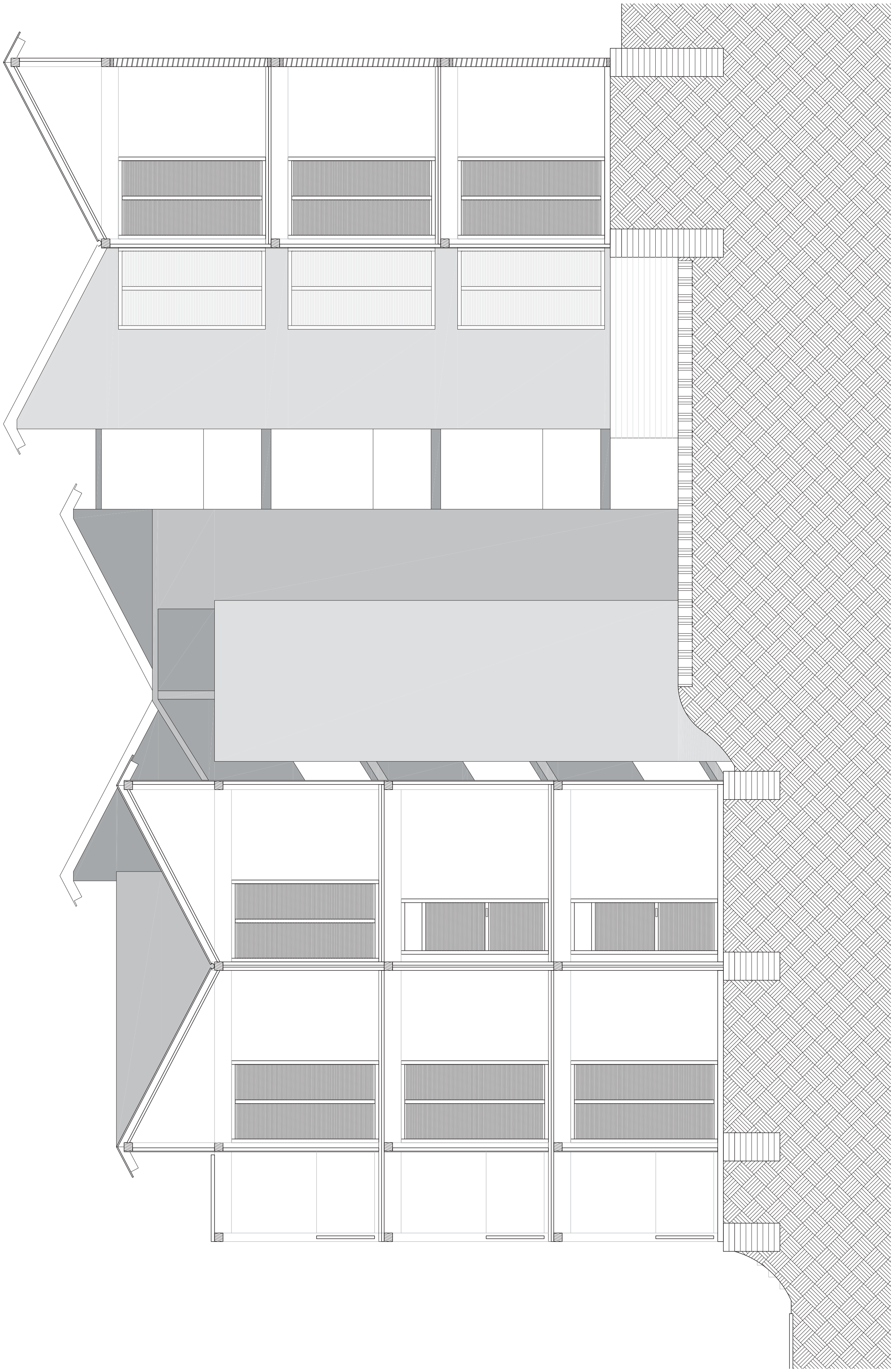
Wind	January	February	March	April	May	June	July	August	September	October	November	December	Annual	Period	Number of years
Daily mean air wind speed [m/s]	3,1	3,2	3,2	2,9	2,8	3,3	3,5	3,1	2,8	2,4	2,6	2,7	3,0	1892-1925	12
Mean wind speed at 07:00h [m/s]	2,5	2,4	2,3	2,2	2,2	2,7	2,6	2,0	1,7	1,7	2,1	2,4	2,2	1892-1925	27
Mean wind speed at 13:00h [m/s]	4,1	4,5	4,9	4,6	4,1	4,8	5,1	4,9	4,2	3,6	3,3	3,6	4,3	1892-1925	27
Number of days with storm	0,8	0,8	2,2	5,3	11,7	14,0	14,6	16,4	19,5	14,1	5,5	1,6	106,8	1891-1925	20

Sky condi-tions	January	February	March	April	May	June	July	August	September	October	November	December	Annual	Period	Number of years
Insolation [kWh/m²/day]	4,17	4,81	5,48	5,82	5,84	6,35	6,29	5,99	5,65	4,98	4,24	3,92			
Monthly mean hours of sunshine [h]	273,0	254,0	279,0	255,0	251,0	243,0	273,0	270,0	234,0	226,0	246,0	254,0	3058,0	1891-1921	25
Daily mean hours of sunshine [h]	8,8	9,0	9,0	8,5	8,1	8,1	8,8	8,7	7,8	7,3	8,2	8,2	8,4	1891-1921	25
Percent-age of the possible length of sunshine [%]	79,0	79,0	75,0	68,0	63,0	62,0	67,0	68,0	64,0	62,0	73,0	74,0	70,0	1891-1921	25
Daily mean percentage clouds [%]	27,0	31,0	39,0	48,0	54,0	48,0	42,0	44,0	51,0	48,0	37,0	31,0	42,0	1891-1921	28
Number of bright days	17,0	12,0	12,0	6,0	5,0	4,0	7,0	5,0	4,0	5,0	9,0	19,0	105,0		15
Number of cloudy days	1,0	2,0	2,0	3,0	5,0	4,0	2,0	3,0	4,0	3,0	2,0	1,0	31,0		15
Mean percentage cloudy at 21:00h [%]	37,0	47,0	61,0	73,0	73,0	62,0	62,0	67,0	74,0	67,0	51,0	41,0	60,0	1891-1915	19

Table B: Weather data Port-au-Prince
Source solar insolation data: gaisma.com
Source other: Moeller, 2011

APPENDIX D

GROUNDFLOOR 1:100



APPENDIX E

Rainwater harvesting potential for redesign Cite Meriken zone 7.

Design information

Roof surface available for rainwater harvesting: 131 m^2

Demand

According to the The Sphere Project (2011) a person uses 15 L of water per day for drinking, cooking and personal hygiene. The total population within the design is: 5,5 person per house (average family size according to Cordaid assessment) times 27 houses (3 storeys with 9 houses) makes up a total population of 149 persons. The total demand of water per day will be: 149 * 15 = **2.235 L**. Annually this will be 815.775 L/year.

Annual Yield

Calculations with the climatic data of Moeller (2011):
Cumulative rain: 1321,7 mm/year
Average rain per day: 3,6 mm

The potential annual harvest is calculated by:
131 [m^2] * 1,3217 [m] = 173,1 m^3 which corresponds to 173.142,7 L/year.

The demand for water is larger than the potential harvest of rainwater. There is a deficit of 642.632 L/year. The harvesting surface have to be increased or other means of water have to be found.

Storage tank sizes

A harvest coefficient of 85% has to handled for leakage, spilling or unsuitability of the rainwater.
There will be a storage tank for every two houses, making the harvesting surface:
3 storage tanks for 28 m^2 with an annual yield of 0,85*28 [m^2]*1,3217 [m] = 31,46 m^3 > 31.460 L/year
Demand for 1 container: 5,5*6*15 = 495 L/day
1 storage tanks for 14 m^2 with an annual yield of 0,85*14 [m^2]*1,3217 [m] = 15,73 m^3 > 15.730 L/year
Demand for container: 5,5*3*15 = 247,5 L/day

Basic survival water needs

Survival needs: water intake (drinking and food)	2.5–3 litres per day	Depends on the climate and individual physiology
Basic hygiene practices	2–6 litres per day	Depends on social and cultural norms
Basic cooking needs	3–6 litres per day	Depends on food type and social and cultural norms
Total basic water needs	7.5–15 litres per day	

Source: The Sphere Project, 2011, pp. 98

1 container for 33 m^2 with an annual yield of 0,85*33 [m^2]*1,3217 [m] = 37,07 m^3 > 37.070 L/year

Demand for container: 5,5*6*15 = 495 L/day

The maximum precipitation per day is: 228,6 mm. Which for a roof surface of 28 m^2 would result in 6400 L rainwater. This accounts for a half to a third of the annual precipitation.

APPENDIX F

Heat flow through the roof

The total thermal resistance of the roof structure is expressed as:

$$r_c = \left(\frac{t_1}{\lambda_1} + \frac{t_2}{\lambda_2} + ...\right) \text{ [m}^2\text{*K/W]}$$

Where λ_1 = conductivity of the first layer

λ_2 = conductivity of the second layer

t_1 = thickness of the first layer

t_2 = thickness of the second layer

The total thermal resistance is expressed as:

$R_{total} = r_{outdoor} + r_{construction} + r_{indoor}$ [m^2*K/W]

and,

$U = 1/R_{total}$ [W/m^2*K]

The r-value is calculated by:

$r = 1/\alpha$

Where α is the heat transfer coefficient. There are three ways to transfer heat: radiation, convection and conduction.

Calculation for Cite Meriken design.

Calculated for the highest amount of solar radiation. From the climatic data it follows that June, with an insolation of 6,35 kWh/m^2/day, is the month with highest amount of solar radiation. The daily mean hours of sunshine for this month is 8,1. The insolation per hour of sunshine will be:

6,35 / 8,1 = 0,78 kW/m^2 > 780 W/m^2

The solar radiation describes a sine function with the maximum around 12:00. The data of the hourly solar radiation is unknown, but we can approach it by the sine function:

$$q \int_0^{1/2 *(3600*24)} \sin\left(\frac{2\pi}{3600 *24} t\right) dt \qquad t=0 \text{ equals } 06{:}00\text{h}$$

To calculate the maximum heat flow through the roof, we want to know the maximum solar radiation.

6,35 kWh/m^2/day = 2,286 *10^7 J/m^2/day

q = 831 W/m^2

For the heat flow calculation on the west facade we need to know the solar radiation at 15:00h.

t = (9*3600)

q = 587 W/m^2

Heat flow through the roof

The chosen roof design is a double solid roof which means there is an air cavity between the outer layer (roof sheets) and the inner layer (ceiling) of the roof. For the calculation of the thermal resistance the air cavity has to be taken into account. The formula will change into:

$R_{total} = r_{outdoor} + r_{construction} + r_{cavity} + r_{indoor}$

The outer layer, roofing sheets, is materialized as CBRS (corrugated bamboo roofing sheets). The thermal properties are:

Material	Thickness [m]	Conductivity, λ [W/m*K]	Absorption coefficient, a (short wave solar radiation)
CBRS	0,007	0,18 (Source: CES Edupack 2011)	0,7
Air	0,1	0,026	-
Rice straw board	0,04	0,065	-

$r_{construction} = (t/\lambda)_{CBRS} + (t/\lambda)_{Rice\ straw\ board} \rightarrow (0{,}007/0{,}18) + (0{,}04/0{,}065) = 0{,}654\ [m^2*K/W]$

$r_{outdoor} = 0{,}04\ [m^2*K/W]$

$r_{indoor} = 0{,}13\ [m^2*K/W]$

$r_{cavity} = 1/\alpha_{cavity}$

$\alpha_{cavity} = \alpha_{radiation} + \alpha_{conduction} + \alpha_{convection} = 5{,}5 + (0{,}026/0{,}1) + 5{,}67 = 11{,}43$

$R_{total} = r_{outdoor} + r_{construction} + r_{cavity} + r_{indoor} \rightarrow 0{,}04 + 0{,}654 + (1/11{,}43) + 0{,}13 = 0{,}91\ [m^2*K/W]$

$\rightarrow U = 1/R_{total} = (1/0{,}91) = 1{,}097\ [W/m^2*K]$

With the total thermal resistance for the roof construction we can determine the heat flow through the construction due to the solar radiation. This will be a stationary heat transfer calculation which in reality will not be the case since the houses within the design are ventilated.

The Sol Air temperature (fig. C.1) is a combination of the convection and radiation at the outside of the solar radiated surface (here the roof) and the outdoor temperature. It is calculated by:

$$T_{SAT} = T_{outdoor} + \left(\frac{a_z * q_z}{\alpha_e}\right) \quad [°C]$$

Where $T_{outdoor}$ = outdoor temperature [°C]

a_z = absorption coefficient for short wave solar radiation

q_z = solar insolation [W/m^2]

α_e = total heat transfer coefficient (conduction, convection and radiation) at the outer surface [W/m^2 * K]

$\alpha_e = 20\ W/m^2$

The solar insolation on the roof will be 831 W/m^2 (June) and since we are calculating the heat flow in a worst case scenario we take the absolute maximum dry bulb temperature of 37,2 °C as the outdoor temperature.

$$T_{SAT} = 37{,}2 + \left(\frac{0{,}7 * 831}{20}\right) = 66{,}3\ °C$$

Considering that the indoor temperature will be the same as the outdoor temperature the heat flow through the roof structure will be:

$q_i = U\ (T_{SAT} - T_i)\ [W/m^2]$

q_i = 1,097 * (66,3 - 37,2) = 31,9 W/m²

The ceiling temperature will be:

$$q_i = \left(\frac{T_{io} - T_i}{r_i}\right) \text{ [W/m}^2\text{]}$$

$$31{,}9 = \left(\frac{T_{io} - 37{,}2}{0{,}13}\right) \rightarrow T_{io} = 41{,}3\ °C$$

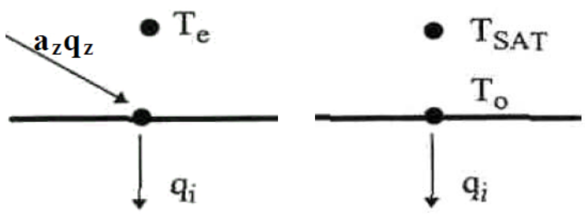


Fig. C.1: Sol Air temperature
Source: Kennisbank Bouwfysica, 2005, pp. 5

Heat flow through the facade

The materialization of the facade is a layer of recycled plaster on a rice straw board. The thermal properties are:

Material	Thickness [m]	Conductivity, λ [W/m*K]	Absorption coefficient, a (short wave solar radiation)
La Terre plaster	0,015	Low → for clay 0,92 (Source: Bouwfysisch tabellarium)	High → 0,7
Rice straw board	0,058 (Source: Stramit)	0,102 (Source: Stramit)	-

$R_{total} = r_{outdoor} + r_{construction} + r_{indoor}$
$r_{outdoor}$ = 0,04 [m²*K/W]
r_{indoor} = 0,13 [m²*K/W]
$r_{construction}$ = (0,015/0,92) + (0,058/0,102) = 0,58 [m²*K/W]
R_{total} = 0,04 + 0,58 + 0,13 = 0,75 [m²*K/W]
→ U = 1/ R_{total} = (1/0,75) = 1,32 [W/m²*K]

The direct solar radiation on the facade is less than that affecting the roof. Also, when the direct solar radiation affects the facade, the temperature is lower than the daily maximum.

$$T_{SAT} = T_{outdoor} + \left(\frac{a_z * q_z}{\alpha_e}\right) \quad [°C]$$

$T_{outdoor}$ = 30 °C
a_z = 0,7
q_z = 587 W/m²
α_e = 20 W/m²

$$T_{SAT} = 30 + \left(\frac{0{,}7 * 587}{20}\right) = 50{,}55\ °C$$

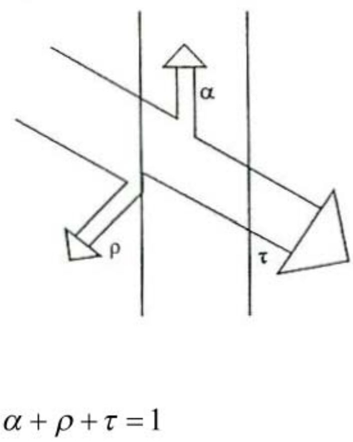


Fig. C.2: Reflection, absorption and transmission of heat
Source: Kennisbank Bouwfysica Tabellarium warmte, 2005, pp. 3

The heat flow through the structure will be:

$q_i = U (T_{SAT} - T_i)$ [W/m²]
q_i = 1,3 * (50,55 - 30) = 26,7 W/m²

The temperature at the indoor surface of the facade will be:

$$q_i = \left(\frac{T_{io} - T_i}{r_i}\right) \text{ [W/m}^2\text{]}$$

$$26{,}7 = \left(\frac{T_{io} - 30}{0{,}13}\right) \rightarrow T_{io} = 33{,}5\ °C$$

Additional thermal (long-wave) radiation may cause in a higher heat load on the outside of the facade, a higher heat flow through the facade and a higher indoor surface temperature.

APPENDIX G

Heat flow through roof (NGO design)

$R_{total} = r_{outdoor} + r_{construction} + r_{indoor}$ [m²*K/W]

$r_{outdoor} = 0,04$

$r_{construction} = t/\lambda \rightarrow 0,2/0,85 = 0,23$

$r_{indoor} = 0,13$

$R_{total} = 0,405$ m²*K/W

$U = 1/R_{total} \rightarrow 1/0,405 = 2,47$ W/m²*K

$$T_{SAT} = T_{outdoor} + \left(\frac{a_z * q_z}{\alpha_e} \right) \quad [°C]$$

$$T_{SAT} = 37,2 + \left(\frac{0,91 * 831}{20} \right) \rightarrow 75,0 \text{ °C}$$

$q_i = 2,47 * (75,0 - 37,2) = 93,4$ [W/m²]

$$\rightarrow 93,4 = \frac{T_{io} - 37,2}{0,13} \quad \rightarrow T_{io} = 49,3 \text{ °C}$$

Heat flow through facade (NGO design)

$R_{total} = r_{outdoor} + r_{construction} + r_{indoor}$ [m²*K/W]

$r_{outdoor} = 0,04$

$r_{construction} = t/\lambda \rightarrow 0,15/0,85 = 0,18$

$r_{indoor} = 0,13$

$R_{total} = 0,346$ m²*K/W

$U = 2,89$ W/m²*K

$$T_{SAT} = T_{outdoor} + \left(\frac{a_z * q_z}{\alpha_e} \right) \quad [°C]$$

$$T_{SAT} = 30 + \left(\frac{0,91 * 587}{20} \right) \rightarrow 56,7 \text{ °C}$$

$q_i = 2,89 * (56,7 - 30) = 77,2$ [W/m²]

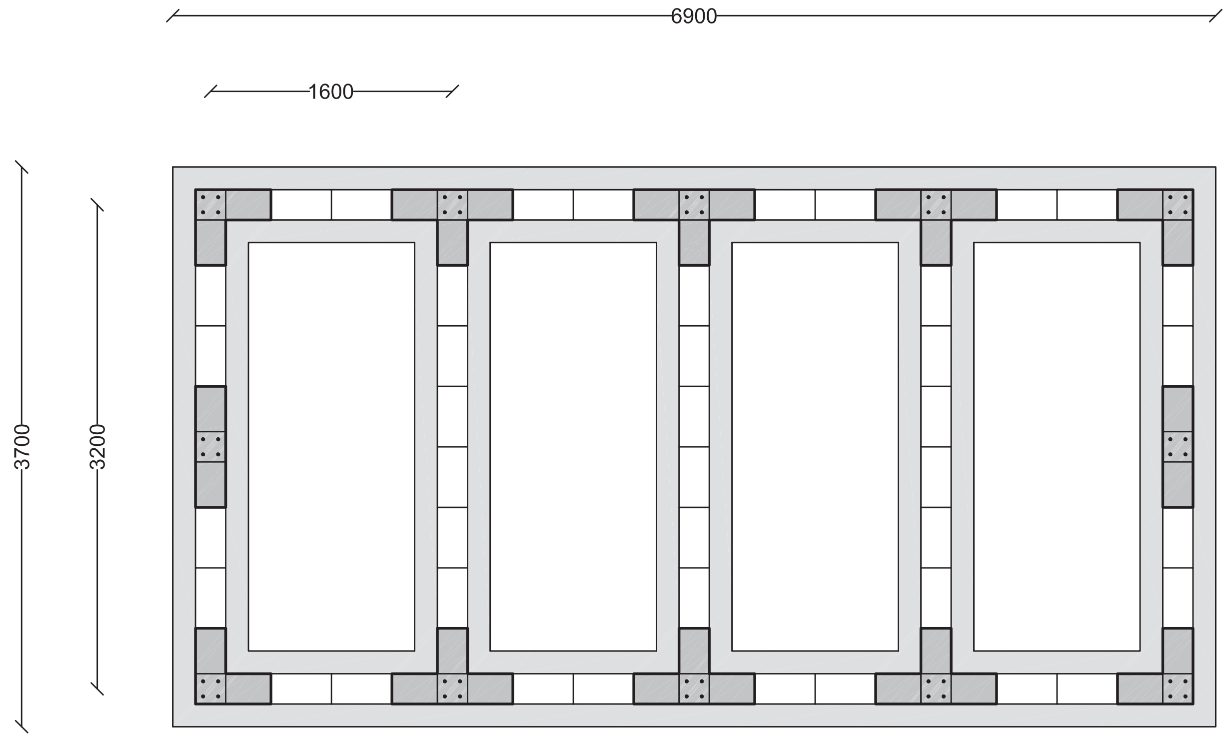
$$\rightarrow 77,2 = \frac{T_{io} - 30}{0,13} \quad \rightarrow Tio = 40,0 \text{ °C}$$

APPENDIX H

Calculation of the quantities of the building products for the design.

Foundation option A

	Profile (l*b) [m]	Length [m]	Number	Volume [m³]
Strip footing	0,5*0,3	2,7	5	2,025
	0,5*0,3	6,9	2	2,07
				4,095
Blocks	0,2*0,2	0,4	198	**3,17**
Plinth beam	0,2*0,15	3	5	1,5
	0,2*0,15	6,6	2	0,396
				1,896
Plinth beam reinforcing steel bars	Section of 0,015	3	(4*5)	0,9
	Section of 0,015	6,6	(4*2)	0,36
				1,26
Columns	0,2*0,8	0,6	6	0,576
	0,2*1,2	0,6	6	0,864
				1,44
Column reinforc-ing steel bars	Section of 0,015	1,1	(4*12)	**0,792**



Foundation plan 1:50

Foundation option B

	Profile (l*b) [m]	Length [m]	Number	Volume [m³]
Earthbags	0,5*0,05	2,7	5*20	6,75
	0,5*0,05	6,9	2*20	6,9
				13,65
Reinforcing bamboo bars	Section of 0,02	1	2*5*5	1
	Section of 0,02	1	2*14*2	1,12
				2,12

Structure

	Profile (l*b) [m]	Length [m]	Number	Volume [m³]
Columns	0,2*0,2	10,6	3	1,272
	0,2*0,2	9	9	3,24
				4,512
Beam A	0,3*0,2	2,95	15	2,655
Beam B	0,2*0,2	1,35	27	1,458
				4,113
Roof beam	0,2*0,2	3,35	4	**0,536**
Bracing	0,2*0,2	2,8	12	**1,34**

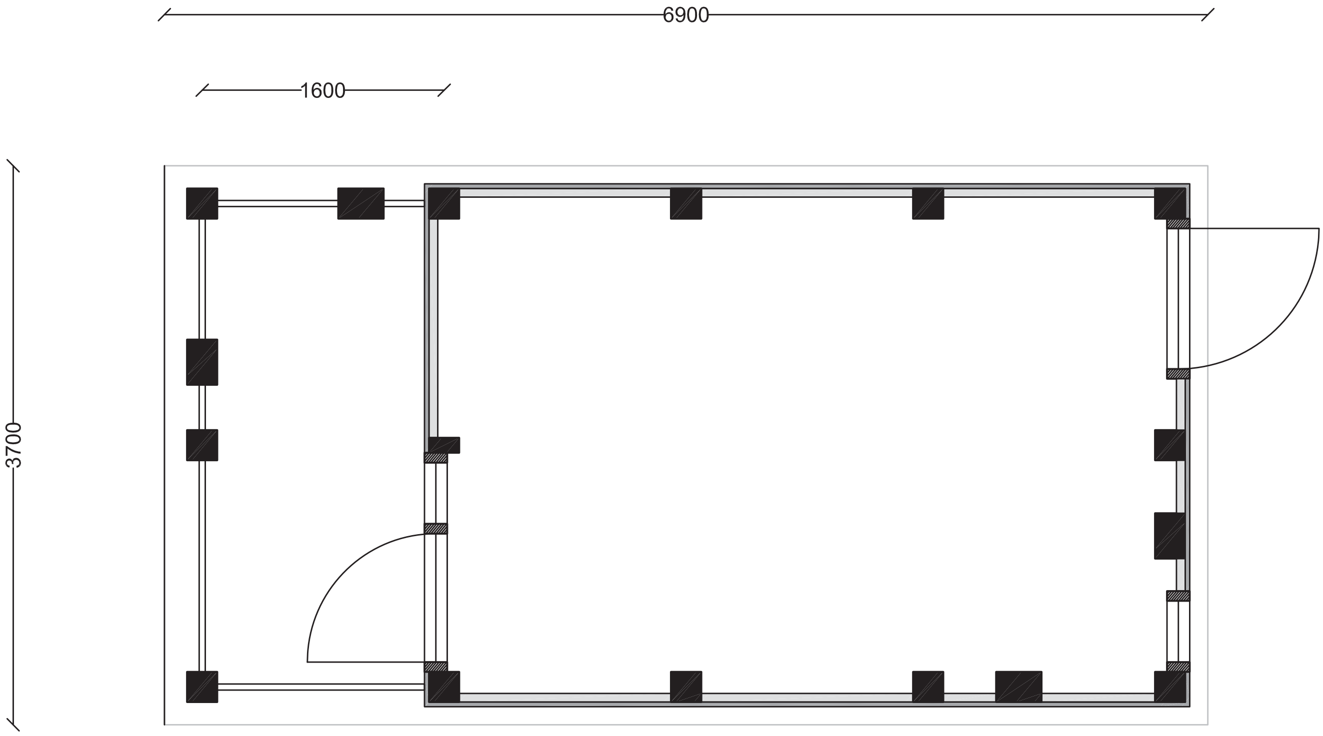
Floors

Thin structural flooring

	Profile (l*b) [m]	Thickness [m]	Number	Volume [m³]
Groundfloor	3,05*4,65	0,1	1	**1,418**
Supporting layer (bamboo)	3,05*4,65	0,045	2	**1,276**
Top layer (ce-ment)	3,05*4,65	0,05	2	**1,418**

Roof

	Profile (l*b) [m]	Thickness [m]	Number	Volume [m³]
Roofing sheets	5,2*3,9	0,007	1	**0,142**
Insulation	1,45*3,4	0,04	3	**0,59**



Facade

	Profile (l*b) [m]	Thickness [m]	Number	Volume [m³]
External layer (cement)	12,59*3	0,015	1*3	1,700
Supporting layer (rice board)	1,4*2,7	0,058	7*3	4,605
Shutters (windows and doors)	1,4*2,7	0,15	3*3	5,103

Veranda

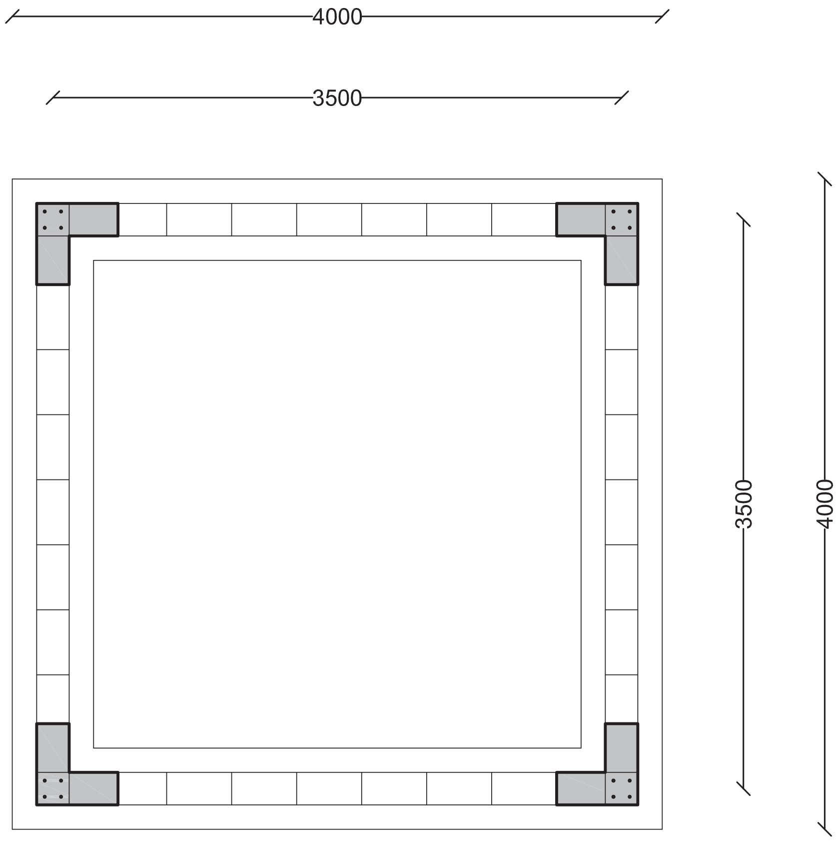
	Profile (l*b) [m]	Thickness [m]	Number	Volume [m³]
Supporting layer of the floor (bamboo)	3,4*1,6	0,045	3	0,7344
Top layer of the floor (cement)	3,4*1,6	0,05	3	0,816
Balustrade	1,4*1,1	0,04	4*3	0,7392

APPENDIX I

Calculation of the quantities of the cement house.

Foundation

	Profile (l*b) [m]	Length [m]	Number	Volume [m³]
Strip footing	0,5*0,3	4,0	2	1,2
	0,5*0,3	3,0	2	0,9
				2,1
Blocks	0,2*0,2	0,4	128	**2,048**
Plinth beam	0,2*0,15	3,7	2	0,222
	0,2*0,15	3,3	2	0,198
				0,42
Plinth beam reinforcing steel bars	Section of 0,015	3,7	(4*2)	0,0052
	Section of 0,015	3,3	(4*2)	0,0047
				0,0099
Columns	0,2*0,8	0,6	4	**0,384**
Column reinforc-ing steel bars	Section of 0,015	1,1	(4*4)	**0,0031**



Foundation plan 1:50

Structure

	Profile (l*b) [m]	Length [m]	Number	Volume [m³]
Columns	0,2*0,2	6	4	**0,96**
Column reinforcing steel bars	Section of 0,015	6	4*4	**0,017**
Ring beam	0,3*0,2	3,7	2*2	0,888
	0,3*0,2	3,3	2*2	0,792
				1,680
Beam reinforcement steel bars	Section of 0,015	3,7	4*2*2	0,0104
	Section of 0,015	3,3	4*2*2	0,0093
				0,0197

Floors and roof

	Profile (l*b) [m]	Thickness [m]	Number	Volume [m³]
Beam A	0,3*2,9	0,2	6	**1,044**
Beam B	0,225*0,8	0,2	18	**0,648**
Blocks	0,2*0,2	0,4	72	**1,152**

Facade

	Profile (l*b) [m]	Thickness [m]	Number	Volume [m³]
Blocks	0,2*0,2	0,4	576	9,216