



Solutions for a natural ventilation system

For houses in a climate with weak natural forces

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Abstract

This project is a cooperation between our Bachelor thesis and a voluntary project in the Amazon region of Colombia. The main purpose is to implement and understand what factors to take into consideration when designing a natural ventilated system in a tropical climate like the Amazon region and at the same time decrease the current indoor pollution that are emitted from cooking areas.

By conducting a field study in the area, uncertainties became facts and two physical models were built in a smaller Amazon village. The actions made in the field are supported by calculations and literature through the report. Assessments on several implementable natural vented designs show that the preferable design finally result in two cob ovens, considering economic and environmental sustainability. The advantages are the availability of material, the use of natural ventilation and reduced amount of firewood.

Natural ventilation appears to be a good solution for sites like the village in the Amazon region, but careful consideration of design and material is required to produce a feasible and functioning unit. Additionally, it is preferable implementing one stove per household rather than stoves in common areas, because it gives the viable sense of ownership and therefore increases the maintenance. In order to maintain and develop the indoor environment it is also important, for the inhabitants, to be aware of the problem indoor air pollution is causing. Finally, increased awareness about the possibility of implementing solutions that uses natural ventilation leads to smart and simple options where mechanical ventilation is not required.

Resumen

Este proyecto es una colaboración entre nuestra tesis de la licenciatura y un proyecto voluntario en la región del Amazonas de Colombia. El principal propósito es implantar y comprender qué factores hay que tener en cuenta a la hora de diseñar un sistema de ventilación natural en un clima tropical como la región del Amazonas. Al mismo tiempo, se pretende reducir la actual contaminación interior que es emitida desde las zonas de cocina.

Al realizar el estudio de campo en la zona, las incertidumbres se convirtieron en hechos y se construyeron dos modelos físicos en un pequeño pueblo amazónico. Las acciones llevadas a cabo en la zona están respaldadas por cálculos y literatura a lo largo de todo el informe. Las valoraciones sobre posibles diseños de ventilación natural muestran que el diseño preferible resulta ser finalmente dos hornos ‘cob’, todo ello considerando la sostenibilidad económica y medio ambiental. Las ventajas son la disponibilidad de material, el uso de ventilación natural y la reducción de la cantidad de leña.

La ventilación natural resulta ser una buena solución para lugares como el pueblo en la región del Amazonas, pero se debe de tener cuidado con el diseño y material a emplear para producir una unidad viable y operativa. Además, es preferible disponer de una cocina por casa en lugar de cocinas en zonas comunes porque proporciona sentido de la propiedad y, por tanto, aumenta el mantenimiento que ello implica. Para preservar y desarrollar el medio ambiente, los habitantes también deben ser conscientes del problema que la contaminación de aire interior está causando. Finalmente, el incremento del conocimiento sobre la posibilidad de implementar soluciones que usan ventilación natural, conduce a opciones inteligentes y simples donde no se necesita ventilación mecánica.

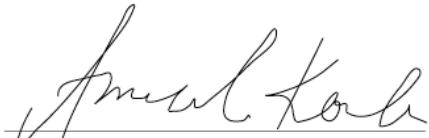
Preface

Execution of this Bachelor thesis would not have been possible without funding from Minor Field Studies Scholarship Programme, MFS, which is funded by the Swedish International Development Cooperation Agency, Sida.

The fieldwork would never have turned out this way without the fantastic cooperation and assistance from all of the people living in the village Puerto Rico. Thanks to Pastor Carlos Gomez, Ana Maria Tenazou and Pilar Ruiz we have gotten guidance and help with a lot of practical issues on site. We would also like to send our greatest gratitude to Eliceo Matapi who was very interested in our project and made us realizing the use of local building materials. With his expertise and support we were able to believe in the idea through the whole process.

Without the founder of Ankarstiftelsen, Börje Erdtman, the project would never have been more than an idea. His encouragement helped us achieve a memory for a lifetime. A special thanks to our Supervisor Angela Sasic Kalagasidis who always believed in us from the beginning, supported us and guided us through the process.

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Mathilda Larsson

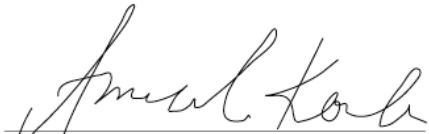
Prólogo

La realización de esta tesis de licenciatura no habría sido posible sin la subvención del Programa de Becas para “Minor Field Study” [estudios de campo de menor envergadura] el cual está fundado por la Agencia Sueca de Desarrollo Internacional, Asdi.

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1. Introduction

This section presents relevant background information about the project and the aim of the experience. The problem description is to clarify and illustrate the problem in the village to understand what needs to be improved and interpret the aim of the project.

1.1 Background

In developing countries the use of simple and traditional cooking stoves is common. The heat is created from burning of, in most cases, biomass and coal since it is easy to collect. This process produces hazardous contaminants when the combustion is incomplete. Consequences are poor indoor climate and air pollution - both causing severe health damage. World Health Organization (WHO, 2007) mentions that “indoor air pollution was responsible for more than 1.5 million deaths and 2.7% of the global burden of diseases” in 2000. Examples of symptoms are, among others: asthma, cancer, eye diseases and perinatal mortality (Bruce et al., 2000). Women and children are the ones that spend most of their time around the cooking area, which is resulting in the highest rate of diseases of women and young children (Duflo et al., 2008).

Many societies around the world nowadays have access to conveniences such as mechanical ventilation, while smaller villages in developing countries often lack this kind of comfort. Therefore, a good and environmentally friendly alternative could be the use of natural ventilation. Natural forces such as stack effect and wind are the two driving forces. Stack effect involves temperature and density differences between inside and outside air as well as height between air openings. In a tropical climate where the weather conditions are stable, with both high average temperature and humidity, the greatest challenge is to ensure stable ventilation throughout the year. In order to get a reliable and effective system, designs and components needs to be tested and adapted to local climate conditions. (Ehrlemark, 1995)

The purpose of natural ventilation is to create a healthy indoor environment with fresh air, which can be implemented with fewer components than a mechanical system. To ensure a stable temperature and humidity in a building, several aspects have to be considered both when mechanically and naturally vented. In a colder climate, insulation is necessary to keep the inside temperature at a comfortable level, while cooling is the main purpose for acceptable indoor climate in tropical areas. In rural sites, households with low income use low quality fuel that might lead to exposure to toxic pollutants indoors. Ventilating the pollutants, using improved cooking stoves or using fuel with better properties can avoid this problem. An improved cooking stove uses fuel with higher efficiency and often includes a chimney, which removes the toxic pollutants. When using high quality fuel rather than biomass the exposure to toxic pollutants decreases but better fuel can be costly and therefore not feasible in some rural areas, see Figure 1. Natural ventilation can be adapted when ventilating the pollutants, using natural forces and creating a smart design might reduce the indoor air pollution. (Duflo et al., 2008)

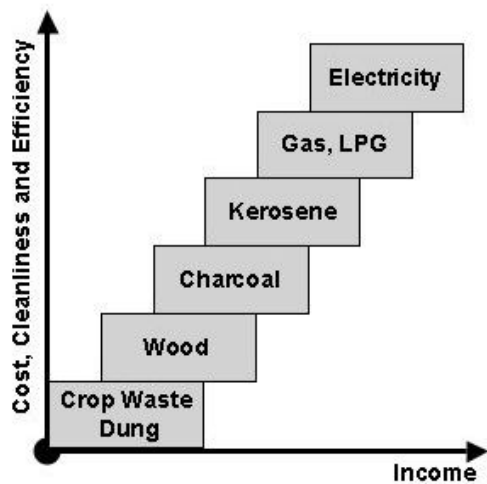


Figure 1: Diagram of fuel based on income (Holdren & Smith, 2000)

The Amazon region is known for its tropical rainforest climate and the city Leticia, is located in the southernmost part of Colombia. The average temperature is 27 degrees Celsius and the humidity normally is around 85% (Weatherspark, 2014). Even higher humidity up to 99% can be found in rainforest areas all around the city. Over the year the temperature only varies by a few degrees and the rainy season is from December to May¹.

80 kilometers upstream from Leticia, an Indian village named Puerto Rico is situated, as pointed out in Figure 2. All goods are transported by boat on the Amazon and Loretoyacu River. The dwellers of Puerto Rico are settlers and have their roots from indigenous people called Ticuna. Ankarstiftelsen, a Swedish voluntary organization, has presented a problem with a poor indoor climate in Puerto Rico. A thirteen-year long relationship with the village has developed strong connection and many contacts. Ankarstiftelsen has brought great development and improved quality of the village mainly by building two schools and improve the availability of safe drinking water².



Figure 2: Map of the area (Google Maps)

¹ Pilar Ruiz, inhabitant of Puerto Rico (interviewed 1 January 2014)

² Börje Erdtman, founder of Ankarstiftelsen (interviewed 17 July 2013)

1.2 Problem description

The village Puerto Rico has around 40 households and they cook their food on poorly functioning cooking stoves. They rely on wood for cooking which can be found in the village, see Figure 3. Earlier, when houses were provided with roofs made of palm leaves, smoke from the cooking area was able to pass between the leaves and kept the roof from insects that reside in the palm leaves. When the transportation through the Amazon River and the collaboration with Ankarstiftelsen increased, the living standard in the village also improved. The houses were provided with roof made by metal plate under the palm leaves, which was found as a good solution against rain leakage, see figure 4. However the airtight roof plates substantially worsen the evacuation of smoke from the houses and the people that spend the most time in this area, mainly women and children, started to suffer from eye injuries among other symptoms.



Figure 3: Interior of a household kitchen in Puerto Rico



Figure 4: Exterior of a household kitchen in Puerto Rico

This problem is due to poorly ventilated houses and the cooking stoves, which release a high level of toxic pollutants. The households have no or little access to electricity and efficient fuels, therefore a cheap and simple design of a natural ventilation system may contribute significantly (Duflo et al., 2008). Due to poor knowledge about the importance of a good ventilated indoor climate this problem was not predicted. The palm leaves provided a better indoor air quality, since the smoke was able to evacuate, but did not fulfill the requirements due to rain leakage¹.

¹ Börje Erdtman, founder of Ankarstiftelsen (interviewed 17 July 2013)

In the two school kitchens, women work for a small salary and the problem with smoke occurs here as well. The kitchens have large air leakages that are displayed in Figure 5 and 6. There are approximately 40 children in the major school and they get served three meals a day and therefore the stoves are frequently used many hours a day. The women working here are unsatisfied with their working environment and want an improvement¹. For this reason, practical experiments in these conditions make a good foundation for discovering missing facts about the situation where the problem occurs. Due to lack of knowledge and uncertainties about the climate in the village, the actual field study provides substantial information. (Ehrlemark, 1995)



Figure 5: Exterior of the major school kitchen



Figure 6: Interior of the major school kitchen

1.3 Aim

The aim of the project is to design and test a natural ventilation system into a climate with weak forces of nature and in households with low living standard. To implement this action in the area, a field study makes it possible to investigate current cooking habits and surrounding climate. Specifically, a vital part of the project is to bring a safer and healthier everyday cooking environment and explain the problem to the inhabitants in the village Puerto Rico. The opportunity to build a construction should be given any family regardless of the economic situation. Finally, the fieldwork with support from calculations and literature surveys will hopefully make a solid foundation for future similar projects.

¹ Ana Maria Tenazou, Chief of Puerto Rico (interviewed 31 December 2013)

2. Method

The project can be divided into three parts to clarify the structure of the report. The process of the operation is described in each part below.

2.1 Literature study

Mainly, scientific articles and essays from universities around the world have been studied to get relevant information that covers the subjects in this report. During the field study in Colombia, Spanish lessons were taken to improve the communication and make collaboration with the population easier. The literature study has been an on-going process that supplemented the other two parts simultaneously throughout the project.

2.2 Minor field study

The field study was done during an eight-week period in the Amazon region of Colombia, which is described more in detail in Appendix 1. Investigating the area around Leticia revealed the substantial information about conditions, both physical and geographical, in which the people live. The field work contained study of suggested area, measures of climate values and interviews with families in the village Puerto Rico where the systems were built.

First, the goal was to build only one physical model, a sheet metal hood as an exhaust system for the smoke. With nothing else but personal experiences within the subject regarding stoves and chimneys, an investigation in the field was done.



Figure 7: Installed chimney in another village called Puerto Triunfo

While visiting another nearby village, we realized that the implemented construction in their school kitchen did not fulfill its purpose even though they had gotten a high chimney with a hood attached. The problem was the combination of unsealed walls in the kitchen and the large distance between the cooking place and the hood, which can be seen in Figure 7.

After interviews with the inhabitants, the primary idea of installing a hood was considered as a non-preferable option and instead building models in a different design with local materials since metal would create higher cost. Other materials were considered after meeting different persons, one with experience of building with clay.



Figure 8: Previous cooking place in minor school kitchen



Figure 9: New base for the construction



Figure 10: Kneading process with ashes (1), grass (2), clay (3) and water (4)



Figure 11: First model with flexible tree branch reinforcement

The previous cooking place, shown in Figure 8, was the building site for the first model. Three types of material were collected; clay from the ground, dried grass and ash from fireplaces. The three components were mixed with water and the time-consuming kneading process made a uniform composite, see Figure 10. The base was created from wooden boards and packed soil, which was compact enough to hold the construction in place, see Figure 9. Forming and pressing the clay mixture was an interesting part of the work since it determines the appearance. Finally it was put on the tree branch frame as seen in Figure 11.



Figure 12: Steel mesh reinforcement

The second model, built in the school kitchen for elder children, was made with the similar mixture but in a larger scale and with different reinforcement, see Figure 12. A large, two meter high sheet metal chimney was finally assembled to the unit. All material, except the chimney and the steel mesh, was found in the village. Visits with one-week intervals, made it easier to discover any development and enabled good

contact with locals. Bad weather conditions and deficiencies in communication affected the final product negatively. To bring our idea to live on after the field study period ended, it was important to inform about the risks with exposure and how to prevent them.

2.3 Calculations

The final design of the model was supported by calculations. Different heights and proportions of the chimney were compared when calculating the pressure difference from density, temperature and wind speed. The result displays the pressure difference on the model and if an acceptable value is reached. The temperature along the chimney was calculated to understand the impact of different proportions. Mass flow was determined, mainly to understand the equations and the impact from an external source. By using Matlab, iterations were made to calculate accurate values of the pressure difference, mass flow and temperature.

3. Ventilation theory

Historically, before the electricity, households utilized natural ventilation. Houses had poor insulation and with large air leakage, air could run through the house more easily. Due to electricity and when the design of buildings changed, the use of mechanical ventilation increased. Today mechanical ventilation systems, with fans and ducts are dominating the market and are influencing the design of the buildings. (Kleiven, 2003)

With an increased awareness of the environmental impacts of energy use from mechanical ventilation system, the natural ventilation system can be used instead or at least be replaced with a combination of mechanical and natural ventilation. By using the natural force effectively the mechanical ventilation can be minimized to periods when the natural ventilation does not suffice. This ‘mixed-mode ventilation’ (Kleiven, 2003) is a good alternative and it is important to maintain the knowledge of natural ventilation. Natural ventilation is also important in societies where mechanical ventilation cannot be used due to limited resources.

When designing a ventilation system ASHRAE (American Society of Heating, Refrigerating and Air Conditioning Engineers) standards can be used as guidelines. ASHRAE 62 publishes standards and guidelines for adequate ventilation rates and maintenance of indoor environments. (ASHRAE, 2013)

3.1 Natural ventilation

Natural ventilation is a process using natural forces when removing air through an indoor space without a mechanical system. The driving pressures from natural ventilation are low compared to a mechanical ventilation system and it is therefore important to use the natural forces efficiently when designing a natural ventilation system (Kleiven, 2003). Natural ventilation uses not only natural forces to achieve a valuable ventilation system. The design of natural ventilation system will differ based on e.g. location, indoor layout, external elements, building type and local climate. It is therefore important to be aware of the different elements influencing a natural ventilation system when designing the entire system. (Walker, 2010)

Natural ventilation uses natural forces of wind, temperature and moisture content in air to create a pressure difference according to Kleiven (2003). The stack effect, often referred as *thermal buoyancy* and *chimney effect*, is caused by the height of the stack and difference in density between inside air and outside air. Outgoing warm smoke, for example from a stove, has lower density than the surrounding air and thus it rises. If the building is airtight the smoke will rise upward and stop rising when the smoke has the same density as the surrounding air. The air density alters at different relative humidity and temperature.

Wind causes different pressures on buildings, depending on wind speed and direction. The pressure is either negative or positive depending on the location of the opening in relation to the wind direction and speed. The windward side of the building gets a positive pressure and

the leeward side a negative pressure. Neighbouring buildings, vegetation and topography are influencing the wind direction and therefore important to be aware of when designing a system. Wind often causes greater pressure compare to the stack effect where the temperature differences are small. Already at low wind speeds the wind pressure will be dominating. (Ehrlemark, 1995)

Different design strategies can increase the airflow by creating a larger pressure difference along the chimney. Either by using wind turbines on the chimney when wind is present or taking advantage of solar radiation, by painting the chimney black, can increase the airflow. Solar radiation can enhance the stack effect by heating the interior surface, which increases difference in temperature and pressure. (Autodesk, 2011)

3.2 Cooking area

According to Maxwell (1999), the two main purposes of kitchen ventilation are:

- 1 – To maintain an environment that is comfortable and safe
- 2 – Develop the safety for the people residing in the area

In order to satisfy these, an exhaust hood is needed for gathering the effluent. The hood is suitably installed above the heat source in combination with a chimney, which eases the natural way of flow. Depending on what heat source is used, the type and size of released contaminants differs.

Electric heat is one example of non-polluting source. Since the energy exchange occurs in a closed system, the emissions will be no other than from the cooking itself. Other processes, like the combustion of using wood or charcoal as source increases the risks of hazardous emissions. The combination of damp wood and the high humidity makes it inevitable to keep the fuel for drying which in turn, when combusted, produces higher emissions of dangerous gases. (Liss, 2005)

Inefficiency and waste of energy is common among traditional cooking places, which normally are open fires directly on the ground or on a table. When food needs to be prepared rapidly, an open fire serves the purpose well, but the pollutants cannot be controlled since the combustion process takes place in open air. However, smart design of already existing fireplaces can help both reducing the amount of energy waste and contamination levels. (Bryden, 2006)

3.3 Health impact from air pollution

In a world where still half of the population use unprocessed biomass fuel while cooking, indoor air pollution causes significant health problem. In places with limited access, resulting in poor electricity and insufficient transport capacity, households often use wood as fuel for their stoves since it is renewable and easy to collect. Therefore, human activity is the source of most indoor air pollution in developing countries (WHO, 2012). Indoor burning of biomass fuels leads to 20-100 times higher indoor air pollution than the World Health Organization's air quality guidelines (PCIA, 2011). The simple stoves usually do not have hoods and therefore not vented properly, causing the smoke to stay in the room. If smoke from the fuel

source is separated from the cooking place in an early stage, the exposure of pollutants decreases (Smith, 2002).

Combustion of wood is causing a chemical reaction between oxygen and hydrocarbons in the material. The reaction is mostly producing carbon dioxide, CO₂ and water. When CO₂ is not properly burned, the color- and odorless carbon monoxide, CO, is the main pollution gas emitted (DeWerth, 2001). Other gases emitted are carbon dioxide, particulate matter and other toxic pollutants (Dadkhah-Nikoo et al., 1994). Inhalation of CO causes headache, because it binds to haemoglobin, which decreases the oxygen transport in the blood. When particles are inhaled they become potentially hazardous and the smallest particles are captured in the lungs (DeWerth, 2001).

The high humidity in the Amazon region is influencing the high moisture content in the wood. With increased moisture content follows lower combustion temperature, which eventually means more emissions of CO (Dadkhah-Nikoo et al., 1994). The health risks are proportional to the level of exposure to the smoke. Some of the far most common diseases that come with exposure are: COPD (chronic obstructive pulmonary disease), lung cancer, tuberculosis and eye diseases (Smith, 2002). In January 2014 two doctors and a nurse completed a five-day expedition in the Amazon region with treating about hundred patients per day. Several persons, exclusively women, have clear signs of eye disorders and some cases of COPD as a consequence from residing around the cooking area many hours during the day¹.

¹ Gunilla Werme, nurse (interviewed 30 January 2014)

4. Design of stoves

Presented models below are selected and described in terms of feasibility and are all listed because they are implementable in a place like Puerto Rico. In section 4.2, materials are described briefly, mainly to clarify properties of the materials presented in the different constructions in 4.1.

4.1 Selected types of stoves

Lorena stove

A cook stove, see Figure 13, made in clay, sand and dried grass, which all can be found in Puerto Rico. The stove has a sealed fire chamber and the smoke goes through a closed system. When designing a Lorena Stove, different amount of potholes can be chosen depending on what is needed. The saucepans can be sealed in the potholes to increase the surface area and efficiency. If possible, bricks can be used as a frame, but it is also possible to construct the whole unit in cob material. (Magerwa, 2004)

Cob oven

An oven, see Figure 14, made out of a composite of clay, ashes and dried grass, which all can be found in Puerto Rico. Recommended time to dry is one to two months, depending on the thickness of the construction and climate. Reinforcement can be used to increase the durability and different types of reinforcement are tree branches and steel bars/mesh¹. Flexible tree branches can be found in the village Puerto Rico while steel has to be transported by boat from Leticia.

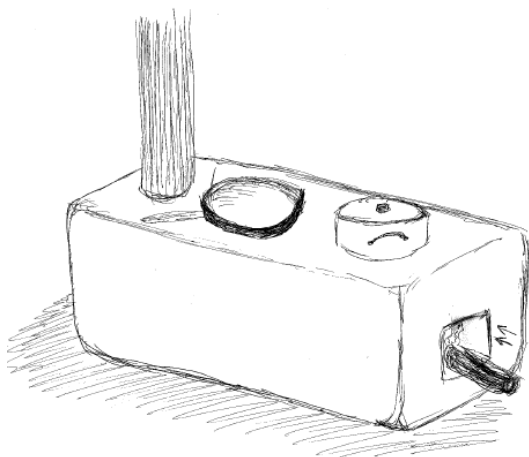


Figure 13: Sketch of 'Lorena stove'

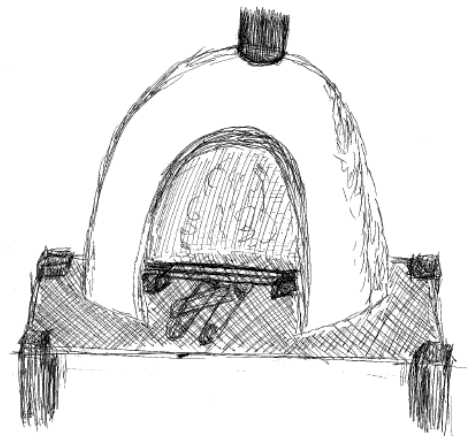


Figure 14: Sketch of 'Cob oven'

¹ Eliceo Matapi, Leticia (interviewed 5 January 2014)

Concrete oven

An oven, see Figure 15, made out of concrete and reinforcement. Different types of factors are affecting the concrete strength e.g. size of aggregates, water-cement ratio and cement-replacement materials. To increase the durability, steel reinforcement or bricks need to stabilize the construction (Burström, 2001). Concrete and reinforcement have to be imported from Leticia to Puerto Rico when building a concrete oven and the concrete will be mixed by hand.

Brick oven

An oven, see Figure 16, made out of bricks and mortar. This is a good alternative since an oven made of bricks has high heat capacity from the start. Unfortunately, bricks and mortar are not available in Puerto Rico and hence need to be transported from Leticia. In alternative to mortar, cob can be used, not only for holding the bricks together, as a layer on the surface to increase the durability¹.

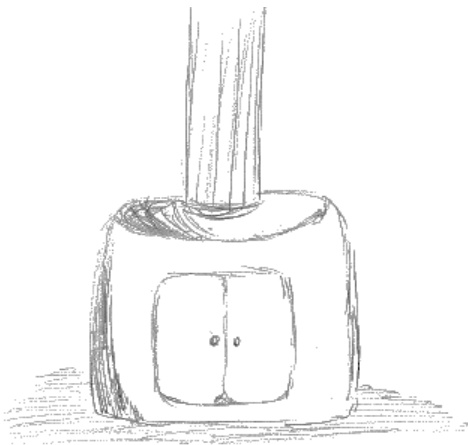


Figure 15: Sketch of 'Concrete oven'

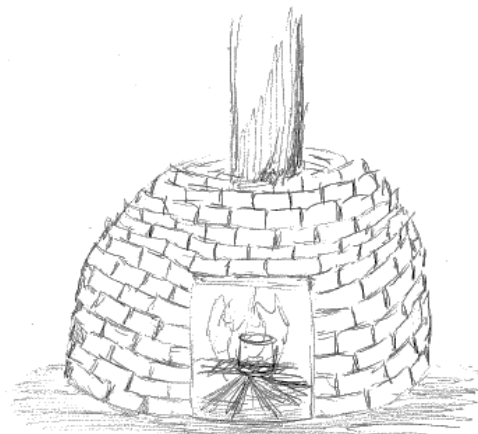


Figure 16: Sketch of 'Brick oven'



Figure 17: Sketch of 'Chimney hood'

Chimney hood

A hood, see Figure 17, made out of sheet metal placed over the existing fireplace to gather the smoke. To attach different parts to each other, welding is required. A welding process has to be performed by a person with experience that cannot be found in Puerto Rico; therefore it needs to be completed in Leticia before transporting. The ungainly construction requires a larger boat and implicates higher costs.

¹ Eliceo Matapi, Leticia (interviewed 5 January 2014)

4.2 Applicable material

Cob generally consists of different constellations with clay, but it originates from the English way of building with mud. This implies a construction without any special kind of form or structure. Commonly cob contains clay, sand, water and straw. The mixture needs to be processed thoroughly by trampling or kneading, which allows more even material. To ensure higher stability, straw or fibrous material is an important part of cob. To facilitate the shaping water is often added to the mixture. To work with cob, no special skills are required and therefore almost any person can build with it. Since cob construction is commonly handwork it might be of interest that all the material is natural and gentle to the skin. In addition, a result can be achieved without special or advanced tools. (Smith, 2014)

Many countries have been using clay and soil as construction material for ages. The primary benefit of usage is the availability; it is possible to find clay easily and nearby in almost all populated locations around the world. Also, the ecological aspect must be taken into consideration and the material poses no health risks. Clay, along with other material, swells with increased water content and shrinks when drying out, which could jeopardize the final product. Depending on varieties in mixture composition, different properties can be achieved according to Smith (2014).

Concrete is one of the most common building materials in the world. Concrete is composed of cement, water and coarse and fine aggregate. Cement replacement materials such as fly ash can be used as a pozzolanic ingredient and can incorporate to the final strength. Chemical admixtures can be added before or during mixing and are mainly to reduce the cost and change into favourable properties. Concrete is weak in tension why reinforcement is added to carry tensile loads. To achieve concrete strength and hardness, concrete has to cure properly. The three first days are the most critical in the hardening process and in around four weeks the final strength is reached. Due to the exothermic setting of the concrete, overheating needs to be avoided during these weeks. (Burström, 2001)

Bricks or other ceramic material can be made out of different materials such as sand and lime, concrete or clay and are either fire hardened or air-dried. Fire dried bricks are strong and versatile which makes it a good foundation for building, mostly due to its resistance against creep and plastic deformation but also to external influences, such as heat or wind. When the material is fire hardened it requires a great amount of energy. (Burström, 2001)

Sheet metal used as a hood has to be stainless due to durability and ease of maintenance. The most common joining method is welding and while performing this, the steel is both melted down quickly and then cooled by surrounding air. Large tension will occur in the material, which is why weldable steel has good qualities for the purpose. Folded sheet could be an alternative. (Burström, 2001)

5. Evaluation process

Two months stay in the Amazon region of Colombia provided valuable information for this project and at least one model was expecting to be installed in one household.

There are several possible models or designs that can be established in a place like Puerto Rico and some of them are listed above in chapter 4. An evaluation as a weighting matrix will present the theoretically best model based on the chosen criteria. Seven constructions, named A-G, are chosen and evaluated with different criteria. All constructions have a chimney, can be constructed in Puerto Rico and it is assumed that all models have approximately the same efficiency of ventilating the smoke.

5.1 Weighting matrix

A weighting matrix gives a good basis and provides survey when choosing the final construction. The criteria that are brought up are the most relevant and important for this project. All factors are given a number in table 1 on a five point rating system, 1 – Poor, 2 – Fair, 3 – Average, 4 – Good and 5 – Excellent. Finally, the importance of different criteria is weighted in percentage in a local perspective, see table 2.

In this chapter the different criteria is described:

- *Economic sustainability* - The total costs of the material and maintenance of the construction
- *Environmentally friendly* - An evaluation of the building processes and chosen materials impact on the environment
- *Availability of materials in the village* - The availability of materials for the villagers
- *Assembly and building process* - Identification of time spent, availability and simplicity of the building process
- *Durability* - Evaluation of life span of the construction and material
- *Fuel efficiency* - Identification of how much fuel is needed for each construction
- *Maintenance* - To maintain the durability and purpose of the construction

A - Lorena Stove
B - Cob oven, steel mesh reinforcement
C - Brick oven with cob
D - Cob oven, tree branch reinforcement
E - Chimney hood in sheet metal
F - Concrete oven
G - Brick oven with mortar

Also, the criteria have been valued one by one, which ultimately creates the matrix in Table 2.

Table 1: First evaluation without the importance of different criteria in a local perspective

Criteria	A	B	C	D	E	F	G
Economic sustainability	5	4	3	5	3	2	1
Environmentally friendly	5	4	4	5	3	2	2
Availability of materials in the village	5	4	3	5	3	3	3
Assembly and building process	1	5	5	3	3	5	5
Durability	3	4	5	2	5	5	5
Fuel efficiency	5	4	4	4	1	3	3
Maintenance	3	3	4	2	5	4	5

Table 2: The final result where the different criteria are weighted

Criteria		A	B	C	D	E	F	G
Economic sustainability	30%	1,5	1,2	0,9	1,5	0,9	0,6	0,3
Environmentally friendly	10%	0,5	0,4	0,4	0,5	0,3	0,2	0,2
Availability of materials in the village	25%	1,25	1	0,75	1,25	0,75	0,75	0,75
Assembly and building process	15%	0,15	0,75	0,75	0,45	0,45	0,75	0,75
Durability	7%	0,21	0,28	0,35	0,14	0,35	0,35	0,35
Fuel efficiency	5%	0,25	0,2	0,2	0,2	0,05	0,15	0,15
Maintenance	8%	0,24	0,24	0,32	0,16	0,4	0,32	0,4
Final result	100%	4,1	4,07	3,67	4,2	3,2	3,12	2,9

6. Result

The results are presented below in separate sections depending on different approach.

6.1 Chosen construction

The result shows that Lorena Stove, cob oven with tree branch and cob oven with steel mesh reinforcement got the highest scores. The complexity of building a Lorena stove, mainly due to drying time, was influencing the selection why a decision that the two cob ovens are chosen as the winning constructions.

The winning concepts from the matrix evaluation are: cob oven with tree branch and cob oven with steel mesh reinforcement. The material cob was modified to the local materials and two constructions were made in two school kitchens in the village. These models were chosen mainly due to the local conditions and the inhabitants' ability to build their own construction with low transportation and material costs.

6.2 Field study

Two constructions were built, together with the locals, in public areas due to justification and to make sure that not just one single family could benefit from the project. Observations in the field made it clear that the houses are not airtight but that the problem with the smoke still remains. The dominating wind direction is from northeast and although the wind is not reliable as a natural force, it is important to protect the fireplace from wind since even low wind speed influence the path of the smoke. The opening of the two constructions is therefore directed opposite to the wind at southwest direction.



Figure 18: Measurements, 1st model

The first model, see Figure 18, was made on a new base with a frame out of wooden boards packed with soil. Into the soil, tree branches were attached as reinforcement and cob was surrounding the branches. Figure 19 is to illustrate the path of the smoke depending on front opening size. Because of difficulties to evaluate whether the construction was strong enough, no metal chimney was attached to this construction. Instead, a small flue outlet made of cob was put on top of the stove and to force the smoke upwards through the outlet, the size of the front opening was created smaller than the second model. The second construction was built, due to the higher frequency of use, in

slightly greater dimensions, see Figure 20. A new base was constructed and instead of using tree branches, steel mesh reinforcement was used. On top of the steel mesh a two meter high sheet metal chimney was attached with cob, as shown in Figure 21.

A construction made out of cob has to dry for at least one month but the instructions were not followed properly by the inhabitants. The early use of both models was causing cracks which were repaired when revisiting Puerto Rico. The two constructions both fulfill the main purpose of eliminating the smoke.

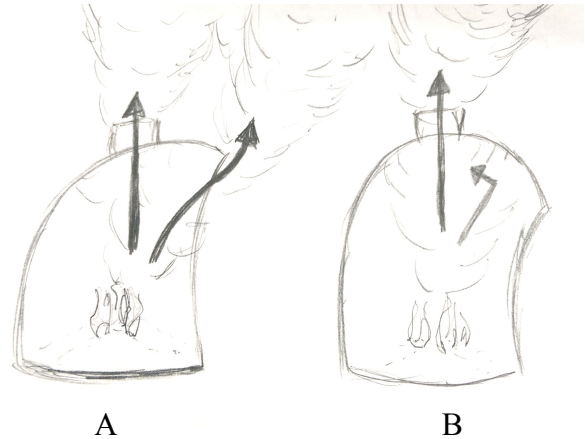


Figure 19: Smoke evacuation depending on opening size, A with larger and B with smaller opening



Figure 20: Measurements, 2nd model



Figure 21: 2nd model from behind

6.3 Calculations

In order to determine whether a construction is feasible or not, certain calculations have to be done. The focus on the calculations is the pressure differences on the second model since the construction has a two-meter long chimney. The minimum-value, when ventilating a room, is a pressure difference of 0.2 Pa according to Camfil (2014).

The mean temperature in the chimney can be calculated as follows:

$T_{mean} = LMTD + T_0$, where T_0 is the outside temperature and LMTD the logarithmic mean temperature difference

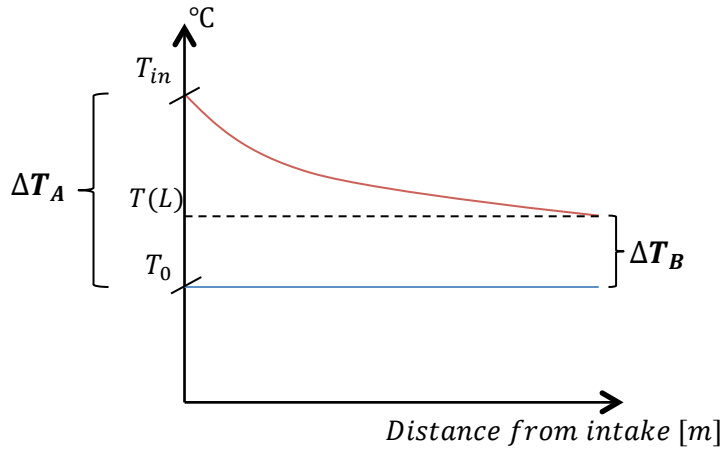


Figure 22: Diagram of the temperature along the chimney (red line) and outside temperature (blue line)

The temperature in the chimney is non-linear and is represented by the red line in Figure 22. The combustion temperature of wood is around 160-200 degrees Celsius (Recknagel et al., 2010) and the temperature of smoke, T_{in} , is estimated to be 100 degrees Celsius due to cooling, which occurs between the fireplace and the inlet. The temperature in the chimney, $T(x)$, can be calculated as:

$$T(x) = T_0 + (T_{in} - T_0) \cdot e^{-x/l_c}$$

with x [m] as distance from intake of the chimney.

The logarithmic mean temperature difference, LMTD can be calculated as followed:

$$LMTD = \frac{\Delta T_A - \Delta T_B}{\ln \frac{\Delta T_A}{\Delta T_B}}, \text{ where}$$

$$\Delta T_A = T_{in} - T_0 \text{ and } \Delta T_B = T(L) - T_0 \text{ as shown in Figure 22.}$$

The pressure difference ΔP , can be calculated in two different ways due to difference in temperature and density. Where the smoke density and air density are different this formula can be adapted:

$$\Delta P = (\rho_{air}(T_0) - \rho_{smoke}(T_{mean})) \cdot g \cdot z$$

ΔP can also be calculated as:

$$\Delta P_T = z \cdot 3456 \cdot \left(\frac{1}{T_0} - \frac{1}{T_{mean}} \right)$$

With help from Matlab, see Appendix 2, iterations give an accurate value of ΔP . Different heights and dimensions of the chimney were calculated and the final result is presented in table 3 and 4.

Table 3: Values of ΔP [Pa] with three different dimensions

Height [m]	ΔP , 10x10 cm	ΔP , 15x15 cm	ΔP , 20x20 cm
1	0.47	0.57	0.61
2	0.63	0.98*	1.11
3	0.77	1.28	1.54
4	0.93	1.43	1.90

Table 4: Values of ΔP_T [Pa] with three different dimensions

Height [m]	ΔP_T , 10x10 cm	ΔP_T , 15x15 cm	ΔP_T , 20x20 cm
1	1.58	1.62	1.64
2	3.05	3.17*	3.23
3	4.46	4.68	4.79
4	5.81	6.15	6.32

*The design of the chimney in Puerto Rico.

The values used in the equations are taken directly from published tables in Hagentoft (2001).

$\alpha = 8 \text{ W/m}^2\text{K}$, with no wind present

$$c_{pa} = 1.0035 \cdot 10^3 \text{ J/kgK}$$

The density of air is 1.290 kg/m^3 at 273K with 80-90% relative humidity and can be calculated as follows at different temperature, t: $\rho_{air} = 1.290 \frac{\text{kg}}{\text{m}^3} \cdot \frac{273}{273+t}$

The density of air at the designing outside temperature, 42 degrees Celsius is:

$$\rho_{air42} = 1.290 \frac{\text{kg}}{\text{m}^3} \cdot \frac{273}{273 + 42} \approx 1.118 \text{ kg/m}^3$$

The density of smoke is 1.33 kg/m^3 at 20 degrees Celsius (Recknagel et al., 2010). This gives the smoke density at 273K:

$$1.33 = x \cdot \frac{273}{273 + 20} \rightarrow x = 1.427 \text{ kg/m}^3$$

$$\rho_{smoke} = 1.427 \frac{\text{kg}}{\text{m}^3} \cdot \frac{273}{273 + T_{mean}}$$

To calculate T(x) the characteristic length, l_c [m], has to be calculated:

$$l_c = \frac{c_{pa} \cdot M}{L_0 \cdot \alpha}$$

Where L_0 is the exposed area per unit length along the channel and the air mass flow rate, M [kg/s] is defined by: $M = V \cdot A$

V is the volume [m³] of the smoke in the chimney: $= \sqrt{\frac{2 \cdot p_w}{\rho_{smoke}}}$, where $p_w = |\Delta P|$

The result in table 3 shows that the second model, with a chimney, has a pressure difference just below 1 Pa. This displays that the model reaches the acceptable value over 0.2 Pa.

When calculating the pressure difference as in table 4, no consideration of the difference in density of smoke and surrounding air is taken. In table 3 this is considered and the difference between table 3 and table 4 is significant. To be sure not to overestimate the pressure difference when designing a system it is important to distinguish the use of the equations.

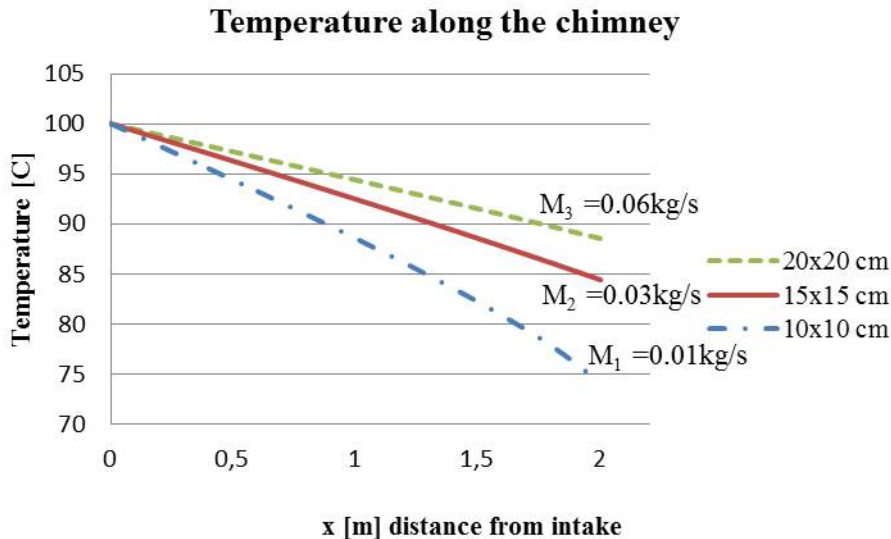


Figure 23: Diagram of smoke temperature in the chimney

Figure 23 shows the temperature in the chimney, $T(x)$, M_1 , M_2 and M_3 are the mass flow for the different dimensions and they are increasing with increasing dimensions. In practice, the mass flow is limited by the mass flow from the fireplace. This is not considered in the equations and therefore a sensitivity analysis has to be done. The mass flow from the fireplace is estimated to be as 0.033kg/s as a mean value from M_1 , M_2 and M_3 . With a fixed M the result of ΔP is displayed in table 5 for design with a two meter chimney.

Table 5: Values of ΔP with fixed M

Dimension	ΔP
2 m and 10x10 cm	1.15
2 m and 15x15 cm	1.02
2 m and 20x20 cm	0.89

The result in table 5 shows that the pressure difference will decrease with increasing dimensions of the chimney. This displays the reality better but requires that the mass flow from the fireplace is measured which was not done in Puerto Rico. Also, friction loss is not taken into consideration in the calculations. With decreased dimensions the friction loss will increase and therefore this might be considered when choosing a dimension of the chimney. (Abel et al., 2008)

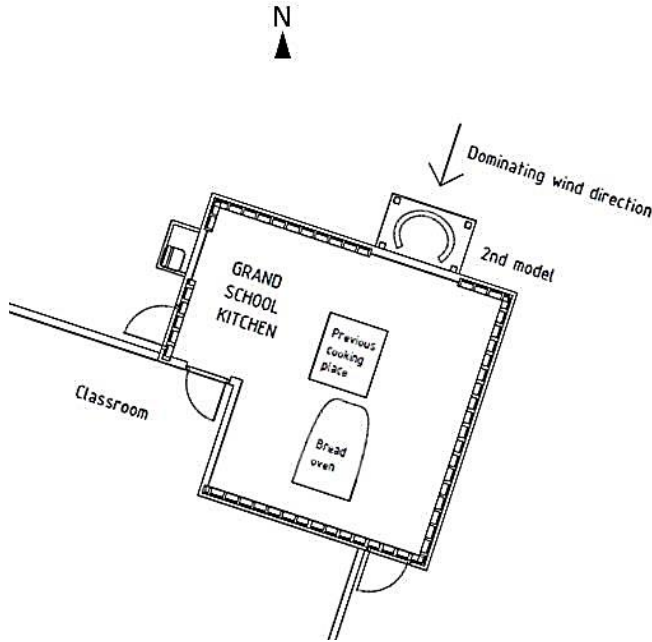


Figure 24: Situation plan of the major school kitchen with previous cooking place

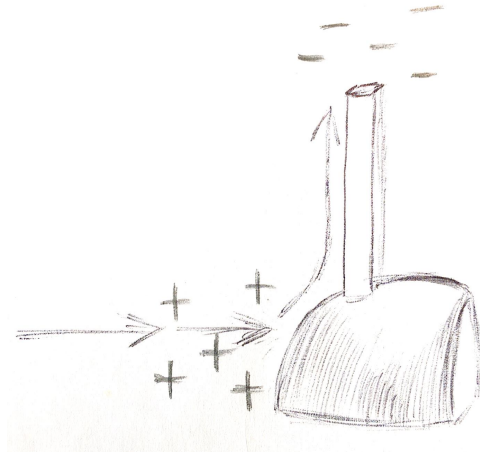


Figure 25: The wind speed behaves as pressure when meeting an obstacle, positive pressure on the windward side and negative pressure at the end of the chimney

The buildings, in which the constructions were built, have large air leakage which will not create pressure difference when wind is present. The dominating wind direction is from northeast and the opening of the construction is located at southwest which can be displayed in Figure 24. This will cause a pressure difference on the model in Figure 25 and the pressure difference due to wind can be calculated as follows:

$$\Delta P_w = (C_p - C_{pi}) \cdot \frac{\rho_{air42} \cdot v^2}{2}$$

where v is the wind speed [m/s],

$C_p = 0.4$ for low rise building and wind angle: 0° ,

$C_{pi} = -0.5$ with roof pitch angle less than 10° .

To reach the same pressure difference, ΔP as the chimney in Puerto Rico, the required wind speed can be calculated:

$$v = \sqrt{\frac{2 \cdot \Delta P_w}{(C_p - C_{pi}) \cdot \rho_{air42}}} = \sqrt{\frac{2 \cdot 0.9836}{(0.4 - (-0.5)) \cdot 1.118}} = 1.398 \text{ m/s}$$

This shows that already at 1.4 m/s the pressure difference due to wind will be dominating but requires that wind is present. In Puerto Rico wind is rarely present and therefore not reliable.

7. Discussion

The challenge of a project like this is not only technical, the social and cultural are two other important aspects. This field study shows that there are some serious and complicated problems in the region. When cooking food in poorly ventilated kitchens using wood as fuel for the stoves, the risk of obtaining severe health problems is high.

The primary idea, building a hood and chimney would not have involved the people and due to the low average economical standards they would not be able to build their own. The hood and chimney would in that case be a finished product in Leticia and transported by boat to the village. This process would create high costs and not engage the inhabitants when solving the problem. When building on location with resources that are familiar to the people, it might trigger new ideas and encourage them to take initiatives. In practice it is though obvious that people in the village would put more interest in a more developed system, such as a gas stove, than a simple clay stove which is why the apprehension was lack of interest or dissatisfaction of building with clay. On the contrary, it turned out to attract people, both kids and elderly, since clay were already a natural product for them. In this way it was easier to create participation and the project created a good collaboration rather than just a charity project.

Clay constructions are sensitive to dehydration as well as any material that contains water. The faster it dries, the higher risk of cracking and breaking. The period of drying and repairing the construction when cracks occur are the two important aspects to maintain the durability. With the extremely high humidity in Puerto Rico in combination with water in the mixture, the most time consuming part is to let the water evaporate naturally. After this period, a good idea is to use the stove increasingly to harden and strengthen the material. Otherwise, the completed unit requires very little maintenance except repairing cracks. In Puerto Rico the inhabitants started to use the stoves too early, against our recommendations which led to cracks in the constructions. These cracks were repaired during our revisit but should, if new cracks occur, be adjusted by the inhabitants after the field work. The issue in our perspective with implementing stoves in public areas is mainly the fact that nobody particular is in charge, which perhaps caused the carelessness of using the stove too early. When there is nobody feeling responsible it might cause an act of neglect and ignorance which eventually leads to a non-functioning device with poor maintenance. Instead, the ideal situation would be to have one stove per household which encourages each family to keep an eye on possible repairing and updating acts themselves.

Small cracks may occur even though the drying time is sufficient. This makes the steel mesh reinforcement a preferable alternative compared to tree branch reinforcement. The heat from the fireplace may destroy the tree branches and the durability will deteriorate. In another aspect it is preferable using a cob oven with tree branch reinforcement rather than using a poorly functioning cooking stove with no ventilation at all. Branches can be found in the village and are costless compared to steel mesh reinforcement. With the low economic situation in the village this is a good alternative without external help. If the inhabitants are going to build their own without external guidance they have to comprehend the health risks

that cooking on poorly functioning stoves creates, otherwise the situation will be the same as before.

Inhabitants of Puerto Rico are people who want to see change and progression but can be perceived as passive in certain contexts. They strive for better qualifications to manage possible flooding, drought and other threats to the community. However, the problem with the poorly ventilated kitchens has been ignored due to the lack of knowledge and probably because the long-term effect is difficult to assess. If the inhabitants do not find this as a problem, they will not maintain the construction nor build their own. A two months stay is a short period of changing the habits and clarifying the problem with a poor indoor climate and the importance of a healthy cooking environment. Therefore it is important continuing to emphasize the problem and increase the knowledge in Puerto Rico.

To reduce the health risks the cooking situation today expose, changing the fuel may be a better alternative. Using better fuel is costly and having gas as fuel compared to wood differs a lot in price. With the inhabitants' low income in Puerto Rico, aiming for better fuel becomes complicated and the problem will not change within near future without changing the cooking environment. Natural ventilation can improve the scenario without expensive machines and is still an important aspect when changing fuel.

Studies on natural ventilation and how it works is suitable for increasing and maintaining the knowledge in developing countries but might as well be implemented in countries where mechanical ventilation already dominate. Effective use of natural forces can be an alternative or a complementary technique to reduce unnecessary energy consumption. More research about implementable options of natural ventilation would contribute to increased consciousness and possibly lead to take action and extra consideration before installing a brand new mechanically vented system. When developing countries starts to prosper and evolve, they strive to achieve the same standards as in developed countries. Better infrastructure, high-technology systems and higher incomes are some of the achievements to strengthen the country status. To put a small project like this in a greater perspective, it seems motivated to begin with natural ventilation instead of mechanical in terms of starting in the right direction. If developed countries exposed more advantage of natural ventilation, the developing countries would follow. Still, the accessibility of cheap and comfortable mechanical systems has set a standard of having mechanical system in every building. To change the common behavior, natural ventilation is an important knowledge for all of us.

8. Conclusions

Before the fieldwork, no sufficient information about the village and climate were available why it was important to do the fieldwork. By collecting data and implementing two physical models, more accurate evaluation was possible when writing our Bachelor thesis. Knowledge about the important factors when designing a natural ventilation system has been achieved by visiting Puerto Rico and its surroundings. The inhabitants have to know how the construction works and understand the consequences from unhealthy indoor climate since they are supposed to maintain the product by themselves. Involving them in the process automatically makes the project viable and more sustainable.

Cob oven with tree branch reinforcement are costless and can be built by any family in Puerto Rico. With a cob oven, a new discovery was that less wood has to be used to reach the same temperatures as before whilst cooking. This reduces the amount of firewood and eases the workload for people using it. The main concern using cob is that cracks may occur. To reduce the risk, the period of dehydration has to increase and also choosing a private area for the stove with somebody in charge. These factors are crucial, especially since they influence the maintenance and durability.

The two finished models fulfill the purpose of eliminating the smoke and the indoor air pollution level decreases due to the fact of smart design and use of natural forces. The constructions were situated with the location of the opening away from the dominating wind direction and in combination with the design of the constructions the wind was not influencing the smoke. With support from calculations, the pressure difference is acceptable when attaching a chimney, which indicates a well designed model. Although the first model does not have a chimney, the design of the stove is more important since there are nearly no natural forces affecting the model. The two models shows that different types of aspects, smart design and use of natural forces are influencing a natural vented system. With this observation natural ventilation is a useful tool in rural areas.

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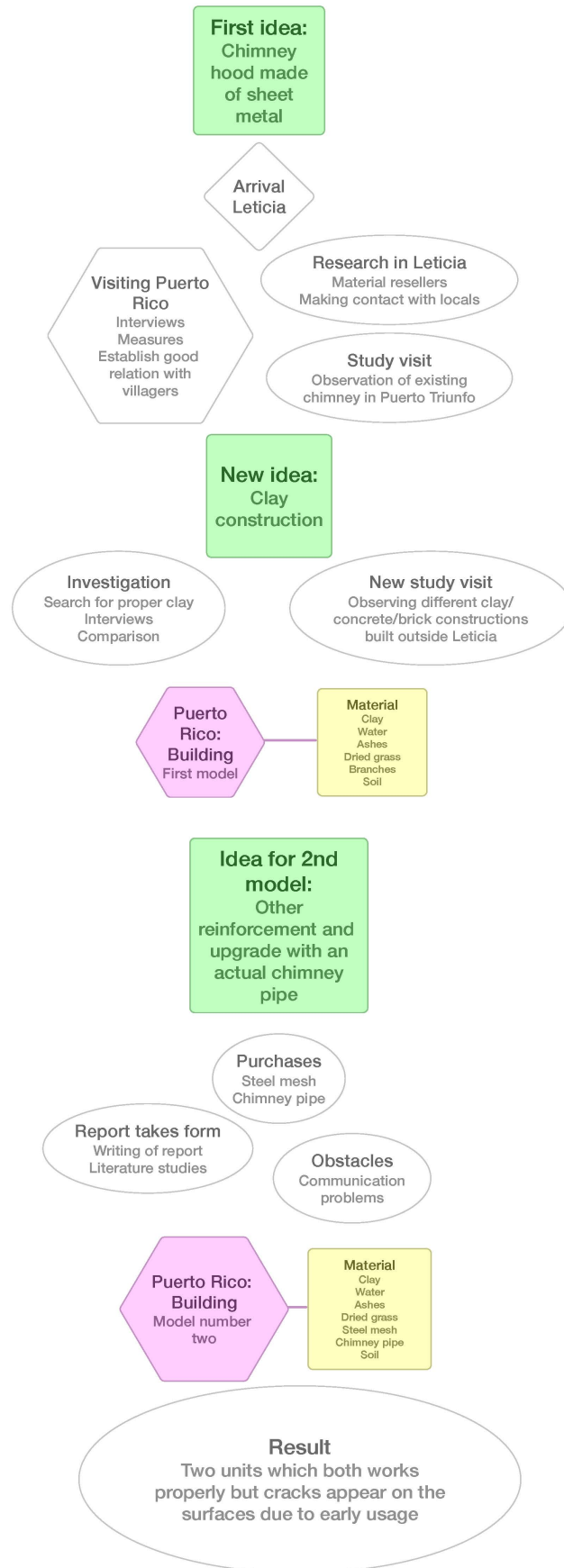
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Appendices

Appendix 1 – Flow chart of the field study

Appendix 2 – Matlab calculations

Flow chart of the field study



Matlab calculations

```

%-----%
%
%           Pressure difference from:
%   deltaP=z*3456*(1/(T0+273)-1/(Tmean+273))
%
%-----%
clc
clear all
close all
alpha=8;                               %With no wind present
cpa=1.0035*10^3;
Tin=100;                                %The estimated temperature at the opening
T0=42;                                  %The designing outside temperature
A=0.1*0.1;                               %Area 10x10 cm
L0=0.1*4;
%A=0.15*0.15;                           %Area 15x15 cm
%L0=0.15*4;
% A=0.2*0.2;                             %Area 20x20 cm
% L0=0.2*4;
pair=1.118;

%1m long chimney
Tmean=100;                               %Input value
for i=1:20
psmoke=1.427*(273/(Tmean+273));
deltaP1=abs(1*3456*(1/(T0+273)-1/(Tmean+273)));
V=sqrt(2*deltaP1/psmoke);
M20=V*A;
lc=(cpa*M20)/(L0*alpha);
T1=T0+(Tin-T0)*(exp(-1/lc));             %Temperature at the end of the chimney
deltaTA=Tin-T0;
deltaTB=T1-T0;
LMTD1=(deltaTA-deltaTB)/(log(deltaTA/deltaTB));
Tmean=T0+LMTD1;                         %Mean temp difference
end

disp('deltaP with z=1m')
disp(deltaP1)

%2m long chimney
Tmean=100;                               %Input value
for i=1:20
psmoke=1.427*(273/(Tmean+273));
deltaP1=abs(2*3456*(1/(T0+273)-1/(Tmean+273)));
V=sqrt(2*deltaP1/psmoke);
M20=V*A;
lc=(cpa*M20)/(L0*alpha);
T1=T0+(Tin-T0)*(exp(-2/lc));             %Temperature at the end of the chimney
deltaTA=Tin-T0;
deltaTB=T1-T0;
LMTD1=(deltaTA-deltaTB)/(log(deltaTA/deltaTB));

```

```

Tmean=T0+LMTD1; %Mean temp difference
end

disp('deltaP with z=2m')
disp(deltaP1)

%3m long chimney
Tmean=100; %Input value
for i=1:20
psmoke=1.427*(273/(Tmean+273));
deltaP1=abs(3*3456*(1/(T0+273)-1/(Tmean+273)));
V=sqrt(2*deltaP1/psmoke);
M20=V*A;
lc=(cpa*M20)/(L0*alpha);
T1=T0+(Tin-T0)*(exp(-3/lc)); %Temperature at the end of the chimney
deltaTA=Tin-T0;
deltaTB=T1-T0;
LMTD1=(deltaTA-deltaTB)/(log(deltaTA/deltaTB));
Tmean=T0+LMTD1; %Mean temp difference
end

disp('deltaP with z=3m')
disp(deltaP1)

%4m long chimney
Tmean=100; %Input value
for i=1:20
psmoke=1.427*(273/(Tmean+273));
deltaP1=abs(4*3456*(1/(T0+273)-1/(Tmean+273)));
V=sqrt(2*deltaP1/psmoke);
M20=V*A;
lc=(cpa*M20)/(L0*alpha);
T1=T0+(Tin-T0)*(exp(-4/lc)); %Temperature at the end of the chimney
deltaTA=Tin-T0;
deltaTB=T1-T0;
LMTD1=(deltaTA-deltaTB)/(log(deltaTA/deltaTB));
Tmean=T0+LMTD1; %Mean temp difference
end

disp('deltaP with z=4m')
disp(deltaP1)

```

```

%-----%
%
%           Pressure difference from:
%           deltaP=z*9.82*(pair-psmoke)
%
%-----%
clc
clear all
close all
alpha=8;                               %With no wind present
cpa=1.0035*10^3;
Tin=100;                                %The estimated temperature at the opening
T0=42;                                   %The designing outside temperature
A=0.10*0.10;                             %Area 10x10 cm
L0=0.10*4;
% A=0.15*0.15;                           %Area 15x15 cm
% L0=0.15*4;
% A=0.2*0.2;                               %Area 20x20 cm
% L0=0.2*4;
pair=1.118;

%1m long chimney
Tmean=100;
for i=1:20
psmoke=1.427*(273/(Tmean+273));
deltaP1=abs(1*9.82*(pair-psmoke));
V=sqrt(2*deltaP1/psmoke);
M20=V*A;
lc=(cpa*M20)/(L0*alpha);
T1=T0+(Tin-T0)*(exp(-1/lc));             %Temperature at the end of the chimney
deltaTA=Tin-T0;
deltaTB=T1-T0;
LMTD1=(deltaTA-deltaTB)/(log(deltaTA/deltaTB));
Tmean=T0+LMTD1;                          %Mean temp difference
end

disp('deltaP with z=1m')
disp(deltaP1)

%2m long chimney
Tmean=100;
for i=1:20
psmoke=1.427*(273/(Tmean+273));
deltaP1=abs(2*9.82*(pair-psmoke));
V=sqrt(2*deltaP1/psmoke);
M20=V*A;
lc=(cpa*M20)/(L0*alpha);
T1=T0+(Tin-T0)*(exp(-2/lc));             %Temperature at the end of the chimney
deltaTA=Tin-T0;
deltaTB=T1-T0;
LMTD1=(deltaTA-deltaTB)/(log(deltaTA/deltaTB));
Tmean=T0+LMTD1;                          %Mean temp difference

```

```

end

disp('deltaP with z=2m')
disp(deltaP1)

%3m long chimney
Tmean=100;
for i=1:20
psmoke=1.427*(273/(Tmean+273));
deltaP1=abs(3*9.82*(pair-psmoke));
V=sqrt(2*deltaP1/psmoke);
M20=V*A;
lc=(cpa*M20)/(L0*alpha);
T1=T0+(Tin-T0)*(exp(-3/lc));           %Temperature at the end of the chimney
deltaTA=Tin-T0;
deltaTB=T1-T0;
LMTD1=(deltaTA-deltaTB)/(log(deltaTA/deltaTB));
Tmean=T0+LMTD1;                       %Mean temp difference
end

disp('deltaP with z=3m')
disp(deltaP1)

%4m long chimney
Tmean=100;
for i=1:20
psmoke=1.427*(273/(Tmean+273));
deltaP1=abs(4*9.82*(pair-psmoke));
V=sqrt(2*deltaP1/psmoke);
M20=V*A;
lc=(cpa*M20)/(L0*alpha);
T1=T0+(Tin-T0)*(exp(-4/lc));           %Temperature at the end of the chimney
deltaTA=Tin-T0;
deltaTB=T1-T0;
LMTD1=(deltaTA-deltaTB)/(log(deltaTA/deltaTB));
Tmean=T0+LMTD1;                       %Mean temp difference
end

disp('deltaP with z=4m')
disp(deltaP1)

```