Sustainable building products for the lower income groups of Santa Cruz de la Sierra in Bolivia

“Think Globally, Act Locally”

Building technology thesis essay

Sustainable building products for the lower income groups of Santa Cruz de la Sierra in Bolivia

"Think Globally, Act Locally"

To obtain the degree of Master of Science
At the faculty of Architecture, Delft University of Technology
Master directions Building technology and Architecture
Certificate Sustainable engineer

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Summary

The current building materials and methods for the construction of low cost housing in Santa Cruz de la Sierra were analysed on their cultural acceptance, cradle to cradle qualities, affordability and climatic adaptability. This resulted in a list of materials that are recommended for use as building material for the construction of low cost housing in the current situation. Cement and concrete do not score high, especially on the cradle to cradle topic, however these are perfect materials in this climate for making the foundations and the ground floor. It should be noted that a good alternative is currently not present. Walls of clay bricks and roofs of ceramic roof tiles are the perfect raincoat in this climate and are also culturally attractive. In fact, the local people construct quite adequately with the materials they already have at this point.

Potential future building materials that do not yet exist in Santa Cruz were also studied. The reason to search for alternative building materials is to create a more diverse building material market which can take away the stress on clay products. This study resulted in two potential materials that could be examined more in depth: Bio stone and Natural fibre reinforced natural materials. Unfortunately, both materials are still in development in the Netherlands and important local information from Santa Cruz was missing. Therefore, it is decided not to do further research into these materials, perhaps they can be studied in the future. The use of waste materials is advised against. Maybe, further research can be done in waste materials of industries when searching for other potential building materials for Santa Cruz de la Sierra in the future.

Bamboo, a plant that also grows in Santa Cruz de la Sierra, but not often used as building material, is explored more into detail. Bamboo is a more affordable alternative to wood and a more sustainable solution than concrete. Additionally, bamboo as a construction material has the advantages of being light and having the ability to handle high tensions. The bamboo plant grows very quickly, which results in a relatively quick production of construction material. As a studied modern building material, bamboo is relatively new and therefore a lot of research opportunities are available. For example, a research into a more sustainable and cost effective preservative, which will provide combined protection against bio-degradation and fire or a research into jointing techniques.

The decision was made to conduct a further research into the jointing technique of bamboo stems. The reason for this decision was that this is a more building related research allowing for a better integration with the architecture thesis. After analysing different jointing techniques, the Delft wire lacing jointing technique was chosen for further research. This technique is easy to learn and a node can be produced quickly.

Some tests were performed under a pressure bench to determine how forces are translated from one bamboo stem into another. The construction has been calculated to determine what strength the nodes need to have to be able to transfer the forces. From the calculation it follows that the maximum force that has to be transferred is 26,7 kN.

The result of the first test was not very pleasant for the construction of the house. The joint could only handle 6kN, which is far too low for the calculated construction and additionally the node slid 15 cm. Therefore, improving the nodes was necessary. Two improved joints were tested: a rubber intermediate between the bamboo stems to improve the force transmission and prevent sliding, and an extra iron wire placed perpendicularly on the already present iron wires which has the effect of pulling these wires together.

Adding rubber to the joint will not improve the joint. Because of the intermediate, the bamboo stems are sliding even more than without the rubber. However, the rubber is damping these small scale movements. The addition of an extra metal wire on the other hand indeed shows an improvement. Unfortunately, the joint is still not capable of transmitting the calculated 26,7 kN. Therefore it is advisable to make use of the Chinese method until a better solution is found. The Chinese method is the addition of an extra bamboo stem to prevent the bamboo stems from sliding.

The goal of this research was to develop a building product or detail that supports the development of a sustainable and affordable house for the lower income groups in Santa Cruz de la Sierra. The building product should be locally available, not harm the environment, deal with the local conditions, be culturally accepted, stimulate a community based process and maybe even develop a local economy.

Bamboo was found to be the best option for these criteria. The bamboo species Guadua Chachoensis is locally available, although it is not often used as a building material. Unfortunately, bamboo has to be protected against fungal attack. Therefore, chemical preservation liquids, like Borax, are necessary. Preferably, research into non-chemical preservatives should be done, so a more environmental friendly product can be realised. When using bamboo as a building material in a semi-tropical climate, the bamboo has to be raised above the ground, protected against rain and have enough air run through it for ventilation. Adequate detailing can significantly prolong the lifespan of the bamboo construction.

Cultural acceptance of Bamboo could be difficult. Therefore, it is recomended to introduce bamboo slowly. First, only the roof construction could be made out of bamboo. Later on, a mix of known materials with bamboo can be proposed. Bamboo could function as a construction, but it does not have to be visible from the outside. Finally, a bamboo house with a brick raincoat and metal roof sheets or ceramic roof tiles could be proposed. The upper walls, the windows, the doors and the floors can be made out of bamboo. When choosing the Delft wire lacing jointing technique the culturally acceptance is also taken into account. The metal wires give a more modern look than ropes and the technique is not difficult to learn.

When introducing bamboo as building material, the community based process as well as the development of a local economy can be stimulated. With the Delft wire lacing jointing technique, the local people learn a new method of construction. A small group of people can be taught to learn how to construct and spread the knowledge under the community. When the houses are constructed the families can not only easily extend their own houses, but also earn money by helping constructing houses for other families.

Bamboo can also be cut into stripes and woven into mats. These mats can be used to close the upper part of a wall, form a reinforcing layer in a prefabricated cement facade panel, or glued with a resin to each other and pressed into roofing sheets. The waving of bamboo stripes, prefabricating cement panels and fabricating roofing sheets are all opportunities for the development of employment. Additionally, these new building materials could lead to a diversification of the building material market.

Resumen

Los métodos y materiales de construcción que se usan actualmente para construir casas de bajos ingresos en Santa Cruz de la Sierra han sido analizados sobre su aceptación cultural, sus calidades de cuna a cuna (C2C), su asequibilidad y su adaptabilidad al clima. Esto resultó en una lista de materiales que se recomienda como material de construcción para las casas de bajos ingresos. El cemento y hormigón tienen una mala influencia en el medio ambiente, aunque son buenos materiales para realizar los cimientos y el piso bajo en el clima subtropical. Actualmente, no hay una alternativa mejor. Las paredes de adobito y tejados de tejas coloniales son un impermeable perfecto en este clima y culturalmente bienvenidos. De hecho, la gente construye adecuadamente con los materiales que actualmente son disponibles.

Además, materiales de construcción, que todavía no se usan, pero con un futuro potencial, también fueron estudiados. El motivo de buscar materiales de construcción alternativos es crear un mercado de materiales de construcción más diverso que puede bajar la tensión sobre los productos de arcilla. Esta investigación resultó en dos materiales potenciales, que podrían ser examinados más en profundo: Piedra-biológico y Matriz fortalecido con fibras vegetales. Desgraciadamente, estos dos materiales están todavía en desarrollo en los Países Bajos y no se pude encontrar la información local relevante de Santa Cruz. Por eso, se ha decidido no investigar estos materiales en esta tesina, pero puede ser que en el futuro sí pueden ser investigados. La aplicación de materiales de residuo no se recomienda. Quizá en el futuro se puede ejecutar una investigación en materiales de residuo de industria cuando se están buscando otros materiales de construcción para Santa Cruz de la Sierra.

Bambú, una planta que crece también en Santa Cruz de la Sierra, pero casi no usado como material de construcción, está explorado más en detalle. Bambú es una alternativa más asequible que la madera y una solución más sostenible que hormigón. Además, bambú como material de construcción tiene las ventajas de ser ligero y de manejar tensiones altas. El bambú crece muy rápido, que resulta en una producción de materiales de construcción relativamente rápida. Como material de construcción moderna, bambú es bastante nuevo y por eso están disponibles muchísimas oportunidades de investigaciones. Por ejemplo, una investigación hacia un conservante más sostenible y de bajos gastos que suministrará protección contra la degradación biológica y fuego, o una investigación hacia técnicas de juntar.

Se ha tomado la decisión de hacer una investigación hacia las técnicas de juntar de bambú. Esta investigación tiene más relación con la construcción de una casa, que permite una mejor integración con la tesina de arquitectura. Después del análisis de diferentes técnicas de juntar, la técnica de juntar del cordón de alambre de Delft ha sido elegida para investigar más en detalle. Esta técnica es fácil de aprender y el nexo se puede realizar rápidamente.

Se han hecho ciertos experimentos, usando un instrumento de presión para determinar cómo las fuerzas están trasladas desde un bambú hacia el otro. La construcción fue calculada para determinar qué fuerza los nexos necesitan para ser capaz de trasladar las fuerzas. De la calculación se concluye que la fuerza máxima traslada es de 26,7 kN.

El resultado del primer experimento no era muy agradable para la construcción de la casa. El nexo sólo podía manejar 6kN, lo que es demasiado bajo para la construcción calculada y además el nexo deslizó 15 centímetros. Por eso, era necesario mejorar el nexo. Se han probado dos nexos mejorados: un nexo con un intermedio de goma entre los bambús fue añadido para mejorar la traslación de las fuerzas y para prevenir que se puede desplazar, y un nexo con un alambre de acero adicional que se ha puesto perpendicularmente a los alambres de acero ya presentes, que tiene la función de tirar los alambres juntos.

De estos últimos experimentos se concluyó que con goma no se mejora el nexo. Es que el intermedio hace que los bambús se deslizan aún más que sin goma. Sin embargo, la goma amortigua las vibraciones pequeñas. La adición de un alambre de acero extra al nexo, al contrario, sí presenta un mejoramiento. Desafortunadamente, el nexo aún no es capaz de una traslación de las 26,7 kN calculadas. Por eso se recomienda usar el método chino en combinación con la técnica del cordón de alambre de Delft hasta que se encuentra una mejor solución. En el método chino un bambú extra está introducido para prevenir que los bambús se deslizan.

El objetivo de esta investigación era desarrollar un producto o detalle de construcción que apoya el desarrollo de una casa sostenible y asequible para las familias de bajos ingresos en Santa Cruz de la Sierra. El producto de construcción debe ser disponible localmente, no debería hacer daño al medio ambiente, debe manejar las condiciones locales, debe ser aceptado culturalmente, debe estimular un proceso de desarrollo que se basa en la comunidad y a lo mejor debe desarrollar una economía local.

Bambú pareció la mejor opción para estos criterios. El especie bambú Guadua Chachoensis es disponible localmente, aunque no se usa mucho como material de construcción. Por desgracia, hay que abrigar bambú contra el enmohecimiento. Por eso, líquidos químicos de conservación, como Borax, son necesarios. Preferiblemente, sería necesario hacer una investigación hacia conservaciones no-químicas para realizar un producto más amable por el medio ambiente. Cuando se usa bambú como material de construcción en un clima subtropical, el bambú necesita ser levantado por encima del suelo, debe ser protegido contra la lluvia y necesita suficiente aire recorriendo para la ventilación. Estos detalles adecuados pueden prolongar la vida de construcción de bambú significativamente.

La aceptación cultural del bambú puede ser difícil. Por eso, se recomienda introducir el bambú con despacio. Primero, solamente la construcción del tejado puede ser hecho de bambú. Después, se puede proponer una mezcla de materiales conocidos y bambú. El bambú puede funcionar como la construcción constructiva, pero no necesita ser visible de fuera. Por último, se puede proponer una casa de bambú con bajas paredes exteriores de adobito para la protección contra la lluvia y un tejado de chapas onduladas o tejas coloniales. Las partes arribas de paredes exteriores, las ventanas, las puertas y los pisos pueden ser hechos de bambú. Probablemente con la técnica de juntar del cordón de alambre de Delft no hay problemas con la aceptación cultural, porque los alambres de acero tienen aspecto de ser más moderno y la técnica no es difícil de aprender.

En introduciendo bambú como material de construcción, se puede estimular el proceso de desarrollo que se basa en la comunidad así como el desarrollo de la economía local. Con la técnica de juntar del cordón de alambre de Delft, la gente local aprende un nuevo método de construir. Un pequeño grupo de gente puede enseñar cómo construir y extender el conocimiento entre la comunidad. Cuando las casas están construidas, las familias no sólo pueden extender sus casas, sino también pueden ganarse la vida por ayudar en construir las casas de otras familias.

Además, se puede cortar bambú en tiras y tejerlo a una estera. Estas esteras se pueden usar para cerrar la parte arriba de las paredes exteriores, para formar una capa reforzada dentro de un panel de fachada de cemento prefabricado, o algunas esteras pegadas la una a la otra con una resina y comprimidas en chapas de cubierta. Tejer las tiras de bambú, la prefabricación de paneles de fachadas de cemento prefabricado y la manufacturación de chapas de cubierta, son todas oportunidades para el desarrollo de empleo. Además, estos nuevos materiales de construcción pueden dirigirse a un mercado de materiales de construcción más diverso.

Content

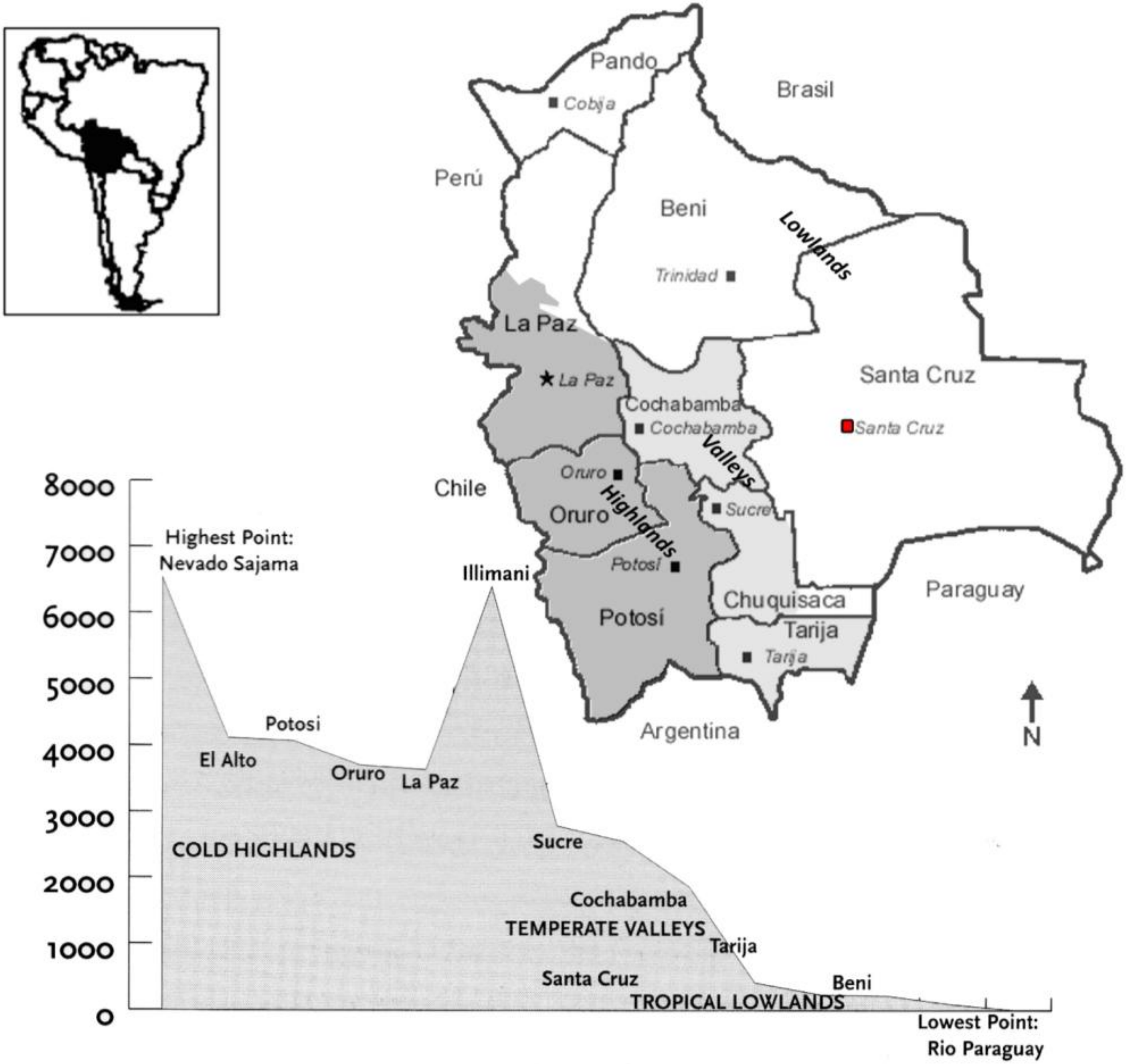


Fig. 1.1 Map of Latin America with the location of Bolivia. Map of Bolivia with its 9 departments, its capitals and location of the 3 climatically regions; highlands, valleys and lowlands Section of Bolivia with altitude above sea level. (1)

1 Introduction

In a course focused on sustainable development of Africa I got the opportunity to interview experts in the field of social housing in Africa. Among others, I interviewed Wim Stroecken, director of the Solid House Foundation. Solid House Foundation (SHF) is a Foundation, founded in November 2003, which has as goal sustainable development of housing for lower income groups in developing countries by means of housing. SHF works together with local lower income groups and prefers to have them participate in the projects by taking responsibility organisationally, financially, and in the form of labour. Next to constructing sustainable housing, community based development is very important. Subjects like housing, education, economical development, health care, safety and community development are integrated in the projects.

Berte Schoonman, a project manager for Bolivia at SHF, concludes in her visiting report: “In Bolivia there is a great need for development of social housing concepts. Housing organisations, NGO’s, different banks, as well as governments all conclude that a way of building that is quick, efficient, sustainable and relatively cheap is needed. The focus group is the lower and lowest income class in urban as well as rural context.” At this moment SHF is constructing domes of concrete. The domes are cost effective and of high quality, in a technical sense, but difficult to extend and not always desirable to live in. One of the locations to develop new housing in Bolivia is in the city Santa Cruz de la Sierra. (See Fig. 1.1) Some organisations in Santa Cruz de la Sierra are interested in the concept of SHF (building with the local people, community based development, making use of local materials and organisations), but not in their way of constructing: the dome. (2) A research in Santa Cruz de la Sierra on the current way of living and constructing was needed, resulting in a design proposal for social housing in this city. Together with Solid House Foundation I decided to make this my final thesis subject.

This thesis report will focus on the Building Technology aspects of social housing in Latin America. In the booklet “Social sustainable housing in Latin America’s semi-tropical zones; Case Study: Santa Cruz de la Sierra, Bolivia” the Architectural aspects will be expounded. More information about de historical urban development of Santa Cruz can be found in the booklet “Urban Development of Santa Cruz de la Sierra”. The three booklets together with the final design drawings and models are the end products of the master thesis in Building Technology as well as in Architecture with a sustainability annotation at the Delft University of Technology.

From 1950 Santa Cruz de la Sierra expanded enormously and is still continuing to grow. The rural groups in Bolivia have been forced to migrate to the cities, seeking means of survival, as the countryside has not been able to provide for the population surplus resulting from the higher growth rates. The migrants have appropriately assessed that life in the city offers them more hope for a better future than staying in the countryside where opportunities are scarce. (3) The migrants start constructing houses with materials and methods they use in the highlands and valleys, but in the tropical climate many houses are not adequate.

In this research the current and potential future building materials and methods for construction of low cost housing in Santa Cruz de la Sierra will be discussed. The central question in this thesis is:

What building product can support a community process, develop a local economy, is sustainable and deals with the local climate conditions and cultural acceptance?

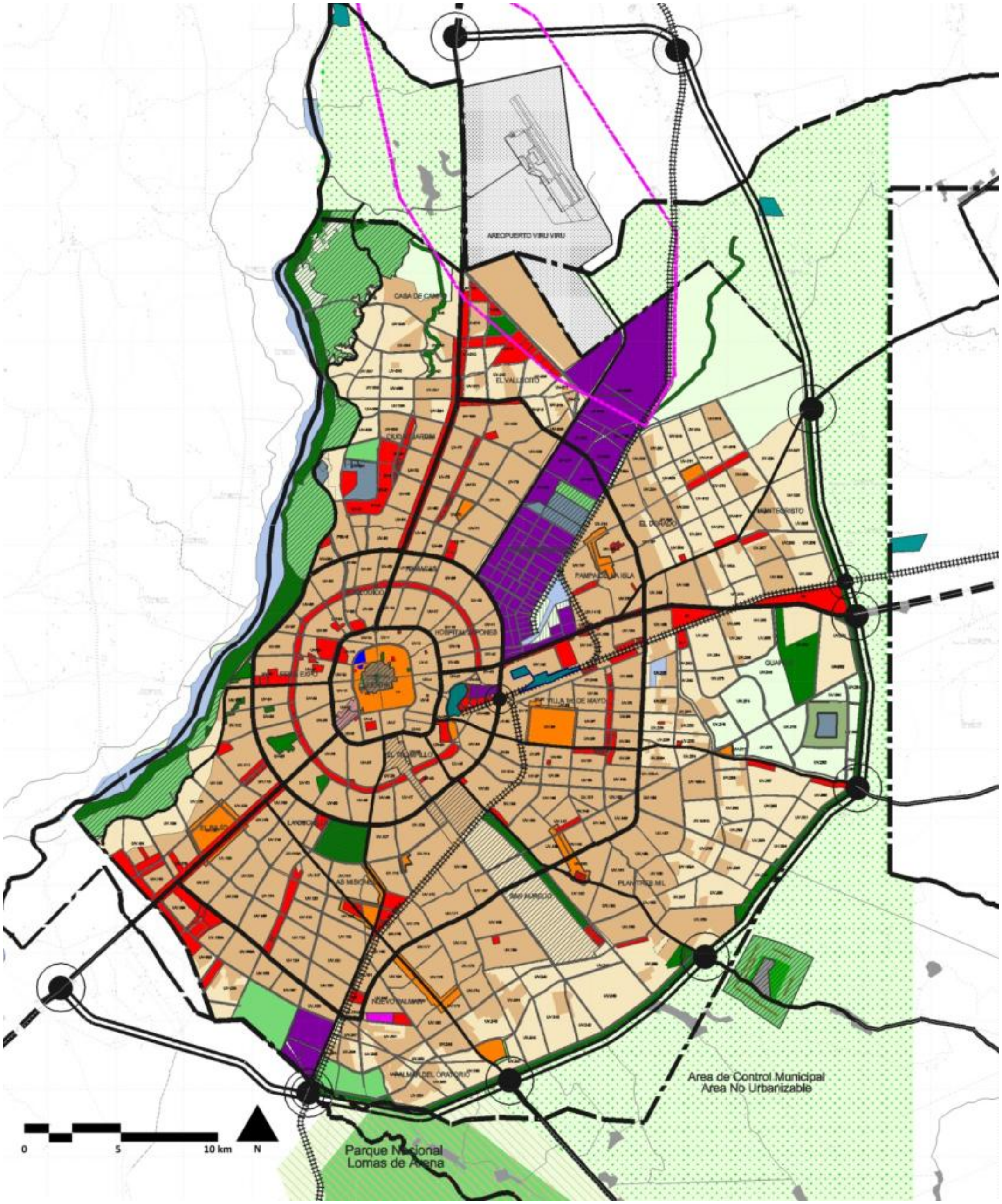


Fig. 1.2 Map of Santa Cruz 2004 (4)

The goal of this research is to develop a building product or detail that supports the development of a sustainable and affordable house for the lower income groups in Santa Cruz de la Sierra. The building product should be locally available, not harm the environment, deal with the local conditions, be culturally accepted, stimulate a community based process and maybe can even develop a local economy.

This thesis is structured as follows. In chapter two the current way the urban poor in Santa Cruz de la Sierra construct their houses, their preference in materialisation and the current available building materials will be described. In chapter three the potential building materials that can be developed in Santa Cruz will be discussed and one material for further exploration will be chosen. In chapter four the chosen material Bamboo will be analysed. In the chapters 5 and 6 the experiments done with bamboo jointing will be described and in chapter 7 the conclusion for the proposed building knot will be given and recommendations for implementations and further research and will be given.

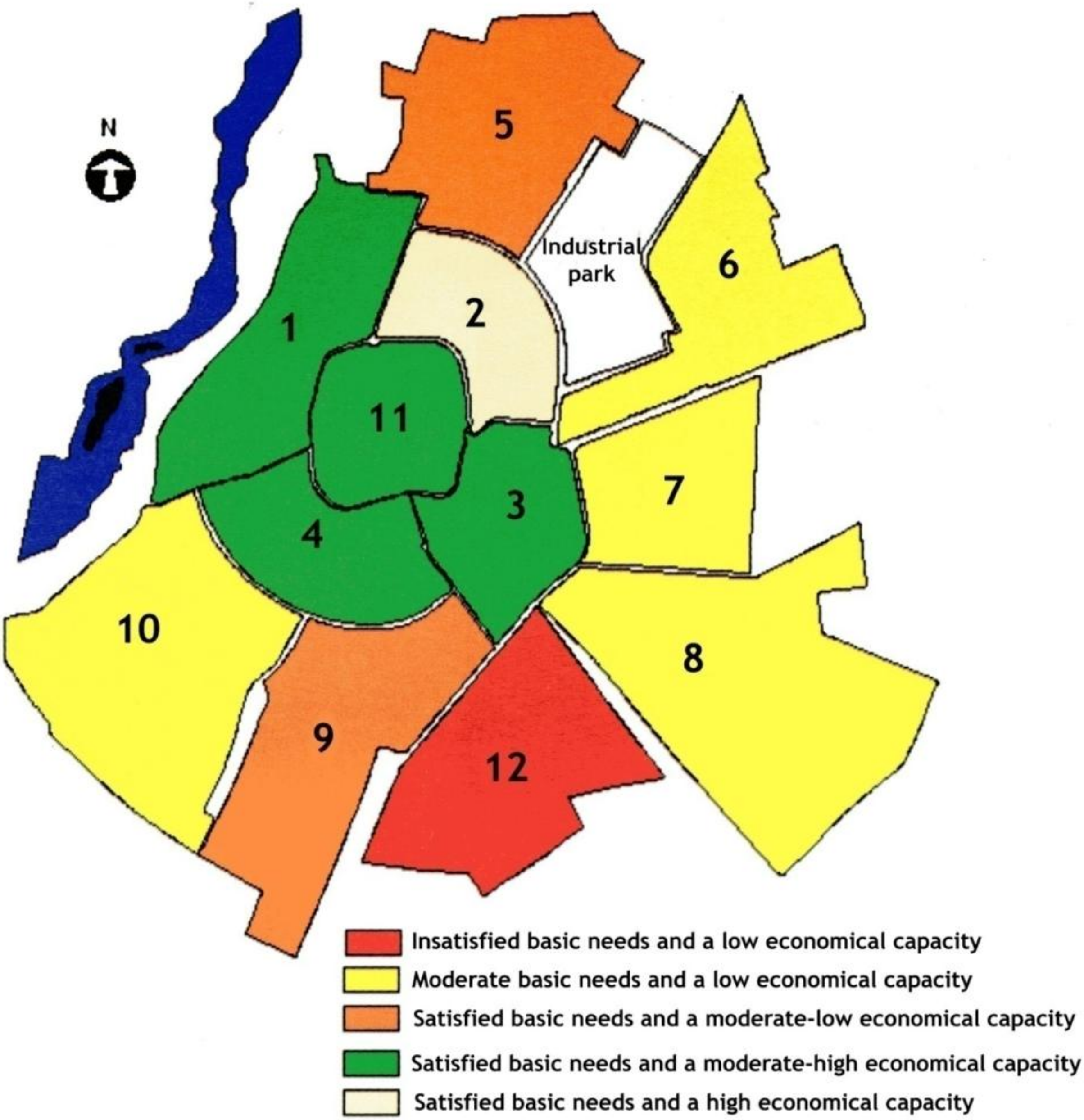


Fig. 2.1 Level of poverty in the districts of Santa Cruz de la Sierra (5)

2 Building materials in popular housing

During the stay in Santa Cruz de la Sierra a small research was done in cooperation with Cedure, a local NGO, about how the poorer families in these districts live by means of 12 in-depth interviews. We choose districts 8 and 12 as research areas, because of their difference in consolidation and because we could make use of an already existing network of neighbourhood chairmen. From the poorest districts, district 8 is the oldest as it already exists for 25 years. Close to the city centre, the district is well consolidated, while in the border of the city the new neighbourhoods start. District 12 is the newest district, which appeared from 1995 on. (See Fig. 2.1.) The level of consolidation was the first parameter for the choice of families. The second parameter was the differentiation between migrants from other departments and migrants from the department Santa Cruz called originals, resulting in 6 different groups.

Age of the Neighbourhood	Type of Family
New neighbourhood in new district. (D. 12)	Migrant family
	Original local family
New neighbourhood in consolidated district. (D. 8)	Migrant family
	Original local family
Consolidated neighbourhood in consolidated district. (D. 8)	Migrant family
	Original local family

When designing for the urban poor, you have to understand how people live nowadays and how they prefer to live. In this chapter you will be taken to two different districts in Santa Cruz de la Sierra in Bolivia where the setting of 12 families will be described. The financial and social situation, the available building materials and the cultural setting influence the quality and appearance of a house. However, the main reason to construct a house is to protect against climatically influences. In this chapter first the financial and social situation of the lower income groups will be described, followed by the climate in Santa Cruz and in which way it influences the way of constructing houses. In chapter 2.3 and 2.4 the used building materials and available building materials will be discussed. In the final paragraph a conclusion will be drawn.

2.1 Financial and Social situation

Most of the families that move to Santa Cruz first hire a room or move in with family that already has a house, before settling down themselves. De commercial housing organisations in Santa Cruz do not offer low priced houses for the lower income groups, only parcels far from the city centre are affordable. After earning some money the families buy a piece of land from a land broker mostly, paid in monthly terms during a couple of years, or occupy a parcel. Not all brokers are reliable and many families end up living on parcels without having official papers. From the twelve families we interviewed, only five said to have official papers of the parcel, while others were having their papers in transfer. In a research of 444 families done by CidCruz[1], 30 % had their official papers while 70% had their papers in transfer. (6) This is a general legal problem, and affects not only the poorer inhabitants, but also

[1] CidCruz is a local centre for research and documentation in Santa Cruz, who research the social and economical development of people in the poorer districts of Santa Cruz. In 2008 CidCruz worked together with 200 neediest families living in the district 8, to construct bathrooms, kitchens and rooms. For the election of the families they executed a research. The data from this research will be referred to in this thesis.

Fig. 2.2 Temporal shower and toilet

Fig. 2.3 Only planned vertical extension

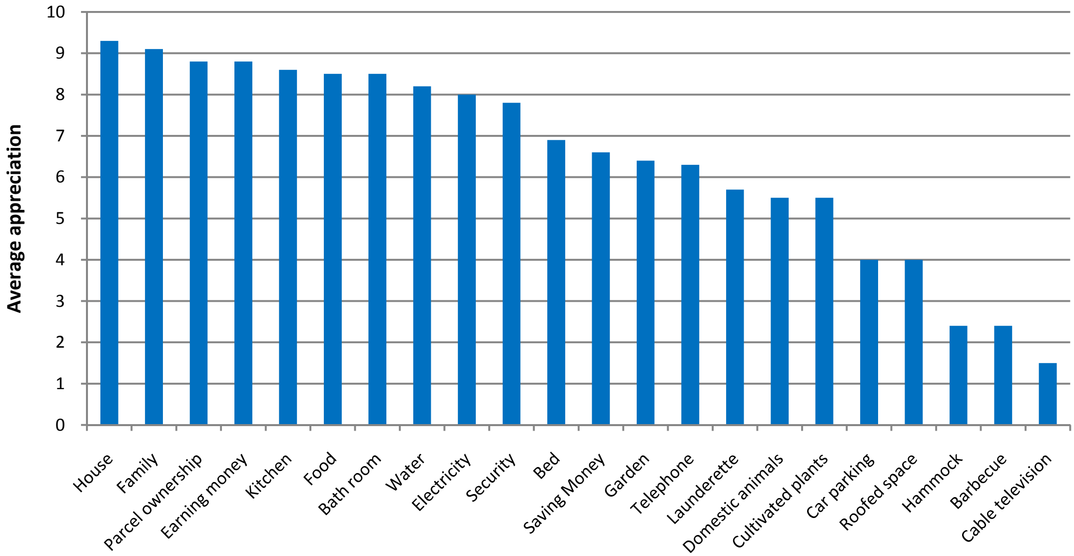


Fig. 2.4 Average appreciation of aspects in and around the house

the financial possibilities of a municipality. That is because every owner of a parcel with official papers has to pay taxes, which will be used for construction of urban facilities and infrastructure.

After buying a piece of land, some of the interviewed families started constructing directly, while others first finished paying off their loan. Those families that directly inhabited the parcels often constructed first a precarious simple construction. Three of the families we interviewed also asked for a loan to pay for their constructions, but most of them collect building materials over time, until there is enough for another extension to their homes. The constructions made out of bricks were mostly realised by bricklayers, but constructions made with other materials were done by the owners themselves. Only one family got help from a NGO, who constructed a bathroom with septic tank.

It is very striking that all families constructed their houses in stages. There is no clear line between the time the family owned the parcel and the level of consolidation, because financial possibilities and demand for space also influence this development. In general there is a certain characteristic development. The first construction is often a single roomed space with an outdoor gallery. This single roomed space is often used as a kitchen as well as a dormitory. In the beginning, a pit latrine serves as toilet and a garden hose as shower. Some extend their single roomed space with a more temporary space for the kitchen. Finally, at every parcel one could find a washbasin where laundry could be done.

In all the researched houses the construction of the living areas and the bathroom was separately. The bathroom was mostly located at the back or at one of the sides of the parcel, but never on the front, probably because of the bad smell of the pit latrine and waste water. Horizontal extensions where mostly made as a continuation to the first living area. These second constructions functioned as extra sleeping room for the children, a kitchen or sometimes a better bathroom with a septic tank. Vertical expansion was only taken into account by one family. This family constructed the first floor and a stair to the second level. The floor of the second level functioned as roof because this extension was not yet realised. The flat roof caused leakage during tropical rains; therefore most families had a pitched roof. Besides, until now vertical expansion does not seem to be very important in Santa Cruz, because of the low density.

While economical activity seems to be important in the lower income group neighbourhoods, only one of the families we interviewed had a workshop on its parcel. Three other families facilitated social neighbourhood functions. Although the families didn't have economical activities on their parcels, half of them would like to have or were planning to have an economical activity within their parcel boundaries. Economical activities can also be generated by cultivation of plants or keeping domestic animals. Many of the families cultivated plants or had chickens or geese. The fruits, vegetables, meat and eggs are mostly produced for personal usage; only three families sell these products in the neighbourhood or on markets.

The families were asked to order pictograms of different aspects in and around their houses so a better understanding of their priorities and appreciation could be given. In Fig. 2.4 one can see the end results. Having a roof above your head, a family, ownership of a parcel and earning money was perceived as very important. The basic facility spaces like a kitchen and a bath room together with the availability of food, water and electricity were perceived as important as well. Also having a feeling of security scored quite high, which was also perceived by the high amount of dogs and geese; Ten out of the 12 families kept at least one dog and a couple of geese.

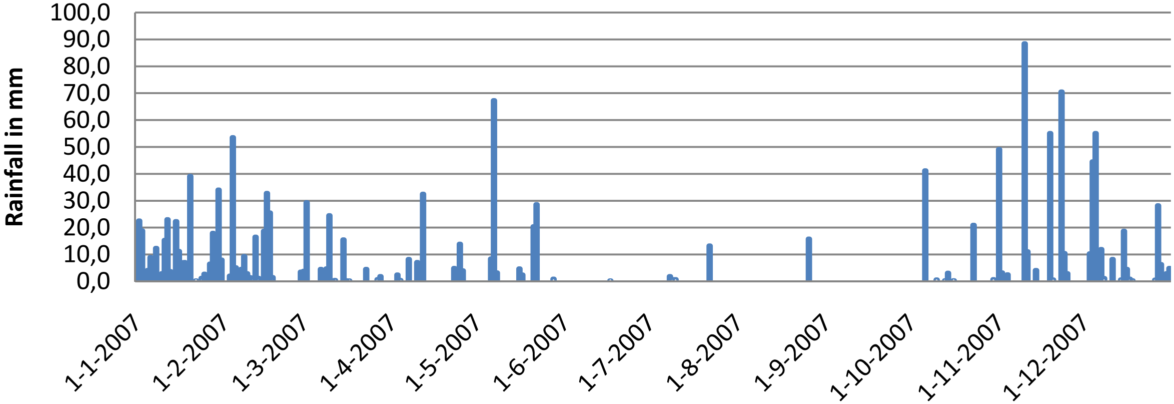


Fig. 2.5 Rainfall in Santa Cruz de la Sierra in 2007

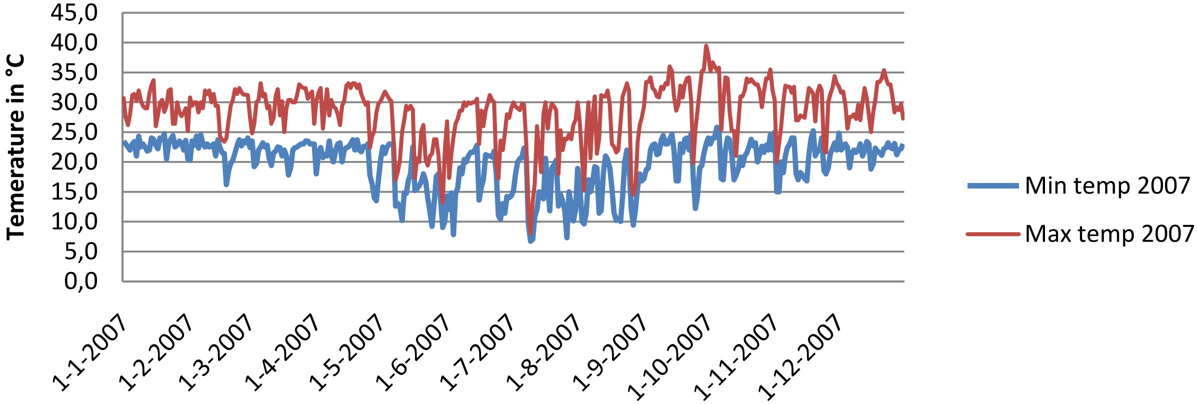


Fig. 2.6 Temperatures in Santa Cruz de la Sierra in 2007

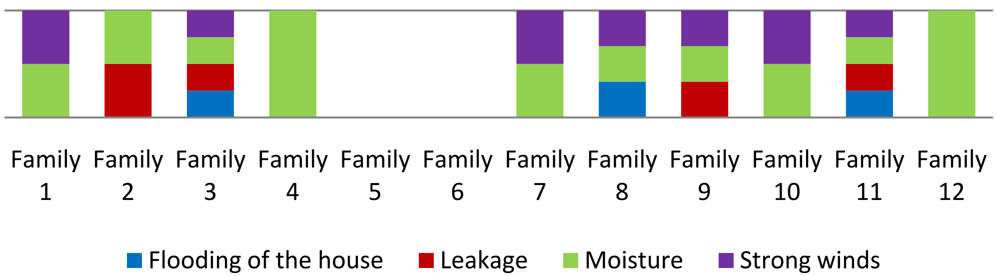


Fig. 2.7 Building physical problems

2.2 Climate and housing

Santa Cruz has a semi-tropical climate with annual temperatures around 21˚C and a relative humidity of 69%. Cold wind patterns, called “surazos”, can blow occasionally from the Argentine pampas making the temperature drop considerably. (See Fig. 2.6) January and February are months of great rainfall, but occasionally throughout the year tropic rainfalls surprise the cruceños. (See Fig. 2.5)

Many people living in the poorer districts come from the highlands or valleys. They bring their way of constructing with them, but this does not offer them any protection in this different ecological environment. Since the climate in Santa Cruz is hot, humid and rainy, the materials these people use are not suitable and the houses they build quickly get ruined, and uninhabitable. (1)

In the 12 in depth interviews the families where asked which problems do occur due to climatically impact. Ten of the twelve families had moisture problems. Especially after tropical rains combined with a high humidity, their walls staid wet, the floors humid and their cloths in the closets became clammy. If there was no sufficient ventilation the absorbed rainwater in the floors and walls caused mildew. Four of the 12 families interviewed had leakage problems at the roof, especially flat roofs were sensible for leakage in this climate.

Three out of the twelve families have their houses flooded during the rainy season. It seems that many houses in the poorer neighbourhoods of Santa Cruz remain flooded for a couple of days or sometimes weeks in the rainy season. The people have nowhere else to go, so are used to live with a couple of centimetres water in their houses.

Not only the rain and moisture, but also the southern wind causes problems. Seven out of the twelve families are bothered by the dust that enters the house or have to repair their houses after the “Surazo” passes. During the period the southern wind blows, many people in Santa Cruz do not work. They lay in bed covered with blankets, because of the cold. The wind causes a lot of damages to the more precarious constructions, like lifting roofs and blowing down walls. Besides a lot of dust enters the houses, which mostly do not have any windows.

The semi-tropical climate of Santa Cruz, with its heavy showers, a burning sun, and the southern winds which cause the temperature to drop with at least 10 degrees, influence the necessary building quality of the house. Besides, the high humidity level can degrade the used building materials. The house serves as a protective shelter against the hostile climate. To create a comfortable house, the climate should be used in a beneficial way. For example, the north-west wind can avoid the development of mould, and the sun can help heating up water for showering or cooking. Sun light heats up the house and preferably should be barred out, but the sunlight also helps the drying of materials after a heavy rain.

Fig. 2.8 Self constructed brick house in Santa Cruz de la Sierra.

Fig. 2.9 Self constructed wooden house in Santa Cruz de la Sierra.

Fig. 2.10 Construction made out of loam, sheets of corrugated iron and plastic cloths.

2.3 Used building materials and methods

In the in depth interviews we asked the families with which materials they build and what kind of building materials they preferred. CidCruz also analysed under the 444 families which building materials they used for constructing their kitchens, bathrooms and living rooms. In this way we can have a more general picture of the current used building materials and methods.

Floor

In a research done by CidCruz 36% of the 1746 rooms investigated had a cement floor, 31% of the spaces were covered with earth, 26% of the rooms had brick floors and only 9% of the spaces were covered with ceramic floor tiles. A preference for cement floors was also found in the 12 in depth interviews conducted for this thesis; ten out of the 12 families had cement floors. The preference of a cement floor is related to the climatically conditions. Preferably the floors are 20 till 30 centimetres above ground level to prevent entering water during tropical rains. Besides cement floors are relative cheap and keep the moisture level inside the house low. If possible financially many people would like to finish their floors with ceramic floor tiles.

Wall

Traditionally the Cruzeños constructed with small bamboo stalks and loam or adobe stones. You can still find these constructions in the old city centre and in the rural areas. Currently clay bricks or ceramic bricks are much more common wall materials. Sometimes the walls are plastered to protect them from soaking by rain water. (See Fig. 2.8) Also in the research of CidCruz 72% of the walls were found to be constructed of bricks, 13% of the constructions, mainly the kitchens and bathrooms, were constructed out of wood. Rarely people constructed with loam, sheet of corrugated iron, cardboard or plastic cloths; only one of the 12 families interviewed used these materials. (See Fig. 2.10). All the other families constructed with bricks. All windows frames were made of wood, not all windows had glass; they were mostly covered with textile or fine meshed nets to keep the mosquitoes out.

Roof

The most important element of a house in a semi-tropical is the roof. Preferably the houses have a Spanish colonial tiled roof laid in cement and supported with a wood structure. Traditionally, roofs were covered with palm tree leaves, but nowadays it is expensive and only used for luxury housing. Asbestos cement plates are often used as a cheaper solution, but the asbestos fibres are unhealthy. Many migrants from the high lands use sheets of corrugated iron, which is also a cheaper solution. Unfortunately, the iron heat up by the sun and functions like an oven instead of sun protection. In the research of CidCruz 41% of the researched roofs where made of sheets of corrugated iron, while 27% of the roofs where made of asbestos cement plates. Only 10% of the roofs were made of Spanish colonial roof tiles. Interestingly, a big amount of the toilets didn't have a roof. In the in depth interviews some combined the roof materials. The Spanish colonial roof tiles or asbestos cement plates were placed on top of the enclosed spaces and sheets of corrugated iron covered the galleries.

Parcel boundary

In big cities the construction of the parcel boundary is very important. Preferably the walls are made of clay bricks which provide protection against burglars and youth bands. The investment required for a brick wall is large so most families have a border with plants and iron wire. Some families have partly walled boundaries, because their neighbour constructed it. But all families preferred a brick wall in the end.

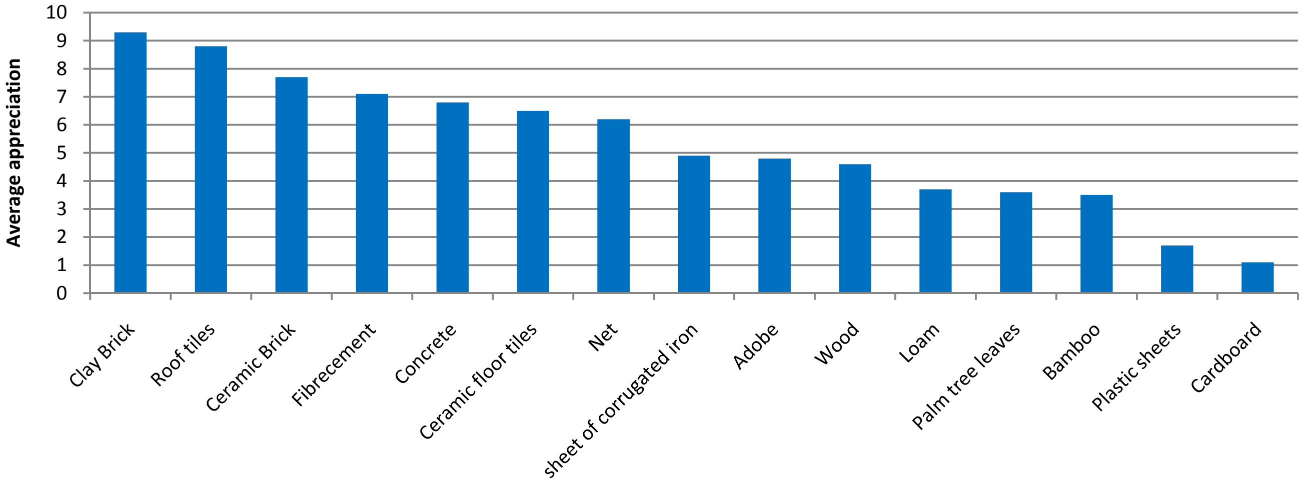


Fig. 2.11 Average appreciation of building material

Fig. 2.12 From linear product process to a life cycle product process (7)

Material Preferences

The visible building materials, especially the building products for the walls and roofs, are not only functional, but also give expression to a building. Therefore the election of building materials is not only depending on technical presentations, but also esthetical appearance and cultural acceptance. By means of pictograms the families were asked to order different building materials. (See Fig. 2.11)

The materials for walls and roof were the first to be discussed. The clay brick as wall material got the highest score for appreciation followed by ceramic bricks. In the interviews some said the ceramic brick is cheaper, but breaks up easier and soaks more water. A woman I interviewed talked really positive about her mother's house in a rural area, constructed out of loam walls. Unfortunately, she lives in the city, where loam is not a considerable building material. Loam or adobe can wash away during the rainy season, does not have the robustness that bricks have and loam has a rural image.

As roof material the colonial roof tile is preferable, but expensive. In contrast to the bricks, the colonial roof tile has two cheaper alternatives; the asbestos cement plates and the sheets of corrugated iron. The asbestos cement plates are technically a good alternative, but most people do not seem to know the negative health aspects. One of the elements in asbestos cement plates is asbestos, which is known to have toxicity and can cause lung cancer. The sheets of corrugated iron are often used as alternative roofing material, but due to the climate often not suitable.

Not many people know the possibilities of constructing with concrete. Most of them use cement for flooring and foundations. One family made a supporting construction for the window openings, but more advanced application was not found. Having a ceramic floor does not have the main priority, but is the dreamboat floor. Finally, an important material was a fine-meshed net in front of the windows and doors to keep the mosquitoes out of the house. The plastics and cardboard materials were not perceived as appropriate building materials. Remarkably, bamboo was not known as building material at all.

2.4 Sustainability of the used building materials

When choosing a building product we should not only look at the cultural preferences and simple method of application, but also to the environmental impact of materials on its surrounding. The sustainability of materials will be analysed as described in the theory Cradle to Cradle. (8) In this theory materials are divided into two cycles: the biological and technical cycle. The bio-degradable materials are part of the biological cycle. These materials can be used for human purposes and afterwards brought back into nature, which will feed the biological processes. The technical cycle is inspired by the biological cycle, but the synthetic and mineral materials make part of this cycle. These materials are part of a closed cycle from production till reproduction and will keep the same value during many lifecycles. (See Fig. 2.12) In this chapter we will look at which influence the materials have during their live cycles on the environment for the different building materials used by the lower income groups in Santa Cruz de la Sierra.

Clay Bricks

The clay bricks are still produced in a traditional way. Small families that live close to old river beds dug the clay, form them in wooden forms, and bake them outside in wood ovens. In tropical rainy season the ovens cannot burn, so the price of the bricks raises a lot. The demand for bricks raised a lot, because of the extreme expansion of the city. In 2001 Santa Cruz counted around 1 million inhabitants, nowadays it houses more than 1.5 million people.

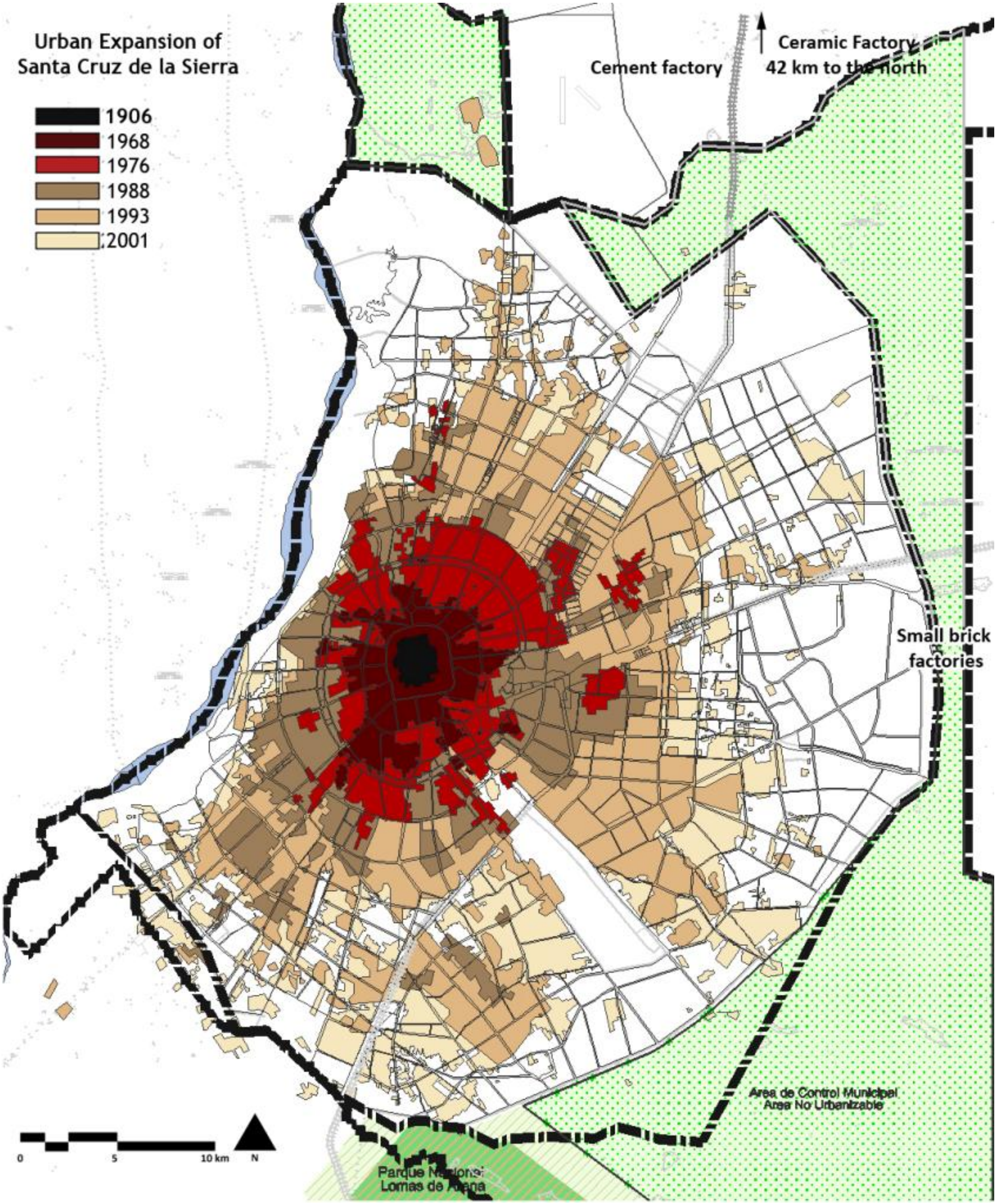


Fig. 2.13 Urban expansion of Santa Cruz de la Sierra between 1906 and 2001 and the location of the brick, cement and ceramic factories (4)

The rich as well as the poor construct with bricks, so more small brick factories arose in the surrounding of Santa Cruz. For one house of $44m^2$ constructed by Habited for humanity in Santa Cruz, 9800 bricks were used. A Dutch clay factory needs $130.000m^3$ clay a year to produce 100.000.000 bricks. This implicated that 1 brick uses $1,3dm^3$ clay and one small house $12,7m^3$ clay. Let's say the clay layer is 1 meter deep, so with 1 km2 surface of clay approximately 80 houses can be build. Many people do not live in brick houses yet and migration to this city is still 5-7% growth annually. So let's say in 5 years 100.000 new houses will be build, than $1250km^2$ clay is necessary for constructing these houses, which is one fourth of the surface of the province Andrez Ibañes where Santa Cruz is part of. For the production of bricks the clay of old river beds is used, which is a finite source. Additionally, clay is a fertile soil for the plantation of food products. So the production of bricks is not very sustainable and it should be wise to look for alternative building materials.

Ceramic Roof Tiles and bricks

In the north of Santa Cruz, 42 km from its city centre, lies the factory "Ceramica Norte" were ceramic roof tiles, ceramic bricks and ceramic floor tiles are produced. The ceramic bricks are formed, using an extruder, into a hollow brick, so less clay is used. However, this decreases the mechanical qualities of the brick, and makes is more fragile. For these products river clay is used. When the amount of used clay and the new clay deposited by the river stays in balance, these products are more sustainable than the regular clay bricks. The techniques used for producing these bricks, roof tiles and floor tiles are better developed, resulting in a more stable price. Although using wood for firing bricks is less environmentally friendly than firing the bricks with gas, still a lot of fuel are needed to reach the needed bake temperature. Furthermore, it is questionable whether the clay products are cradle to cradle, because baked bricks will never turn back to clay. Additionally, when building walls with the bricks using cement mortar, the bricks can also not be easily detached and reused.

Adobe or loam

Abode bricks and loam walls are also made out of clay, with the environmental advantage that they do not need to be fired. In Santa Cruz, these materials were traditionally used to construct houses. The material was found on the location of the parcel, or close to the river, and easily made. The adobe blocks were formed from clay, sometimes mixed with cow dung and straw, and dried in the sun. The loam walls were made out of the interweaving of thin bamboo or wood, plastered with clay or loam. The city expanded on the sandy soils where no clay is found, so this way of constructing became unused. Besides as was said before, culturally it became a material for rural areas, not for the city Santa Cruz.

Asbestos cement plates

The asbestos cement plates that are sold in Santa Cruz are produced in Cochabamba, a city 500 km to the west of Santa Cruz. A mix of asbestos fibres, cement and water is the basis of the asbestos cement plates. Technically this is the ideal material; it is durable, has good thermal and acoustic isolation properties, does not burn, corrode nor rot. The price of a plate is low, but the health impact of this material is high. The asbestos fibres are very small and can be breathed in easily. Asbestos exposure becomes a health concern when high concentrations of asbestos fibres are inhaled over a long time period. Therefore, in most western countries the production of this material is forbidden, but in Bolivia it is still an accepted building material.

Fig. 2.14 Bamboo constructed restaurant "Casa del Camba" in Santa Cruz de la Sierra

Fig. 2.15 Bamboo constructed funfair "Buffalo Park" in Santa Cruz de la Sierra

Cement and concrete

Cement for Santa Cruz is milled 23 km to the north of Santa Cruz, but the semi-finished products come from La Paz, the capital city of Bolivia, 900 km north-west of Santa Cruz. (9) For the production of cement, high temperatures are needed and therefore a lot of fuel is used, like with the production of ceramic products. The transportation of the semi-finished products from La Paz makes this product even less environmentally friendly. Concrete is a mixture of cement, water, sand, gravel and stones. Cement reacts with the water in the mixture and glues the sand, gravel and stones together into a stony material. The origin of cement in Santa Cruz was already explained. Sand, gravel and stones are available at the different material markets in the city. You can order a truck loaded with one of these materials. The location where these materials are extracted was not researched. Probably, most materials are mined in the neighbourhood of Santa Cruz, but it is not clear whether this happens in a sustainable way.

Sheets of corrugated iron

Metal products are all imported from Brazil and Argentine. The environmental impact of this building product is high during the extraction out of the iron ore, because high temperatures are necessary. When reusing iron, the temperatures can be less high, so less energy is necessary. For reusing iron, the product should not be glued to other materials; otherwise it cannot be brought back into the technical cycle. The use of iron in Santa Cruz implicates long transportation routes which negatively influences the environment through the burning of fuels by trucks or the use of electricity in the case of train transportation.

Palm tree leaves

The use of palm tree leaves is a perfect example of a material from the biological cycle. This traditional thatching material has no negative impact environmentally. It can be used as roofing material and after usage brought back into nature. Unfortunately, the material is very labour-intensive and therefore the prices of this type of roofing are very high. Additionally, palm tree leave roofing is a perfect location for many insects, which is not very desirable.

Wood

Wood is also a biodegradable material and often used in roof constructions of housing in Santa Cruz. Because of the tropical climate, only wood of high quality can be used in housing, because lower quality wood has a low durability. The life cycle of the lower quality wood is too short to be used for human purposes. The harvesting of trees which produce high quality wood has to happen in a sustainable way, so this type of wood can still be harvest in the future and also used for constructions of the next generations. The government and environmental organisations in Bolivia are working hard to protect the tropical rain forests from illegal deforestation.

Bamboo

Bamboo also belongs to the biodegradable materials, if it is not treated with a chemical product. Bamboo grows naturally in different areas around Santa Cruz, but is rarely used as building product in Santa Cruz. Therefore, cultivation of bamboo did not occur yet. Lately, two giant constructions with public functions, designed by the Colombian architect Jose Luis Camacho Mustaffá, arose in Santa Cruz. (See Fig. 2.14Fig. 2.15)

Material	Cultural Acceptance	Cradle to Cradle	Affordable	Appropriate in semi-tropical climate
Clay bricks	++	+/-	+/-	++
Ceramic bricks	+	+/-	+	+/-
Ceramic roof tiles	++	+/-	+/-	++
Adobe and Loam	--	+	+	+/-
Asbestos cement plates	+	--	++	+
Cement and Concrete	+	-	+/-	++
Sheets of corrugated iron	+/-	-	++	+/-
Palm tree leaves	-	++	--	+/-
Wood	+/-	++	+/-	+/-
Bamboo	+/-	++	++	+/-

Table 2.1 The analysed materials with the score on cultural acceptance, cradle to cradle, affordability and climate adaptively.

2.5 Conclusions

The houses constructed by the lower income groups develop gradually and the quality of these constructions varies. When the lower income groups use durable materials like bricks and roof tiles, often an expert is hired to construct that part. The expert mostly is a relative, friend or neighbour who knows how to lay bricks or construct a tiled roof. The temporal constructions made out of wood, sheet of corrugated iron, plastic sheets and adobe are self-built. The durable materials also have a higher cultural acceptance as shown in Fig. 2.11 .

The sustainability of a house is related to the value the owners give to the house. Therefore, when designing a house for lower income groups, one should look at the cultural acceptance of the proposed building materials. The more cultural accepted materials will have a higher value to them so will last longer. The design of the house could be a mix between self construction and hiring an expert, depending on the durability of the material. The self-construction parts of the house should be portable and applicable by unskilled manpower. Due to the self construction, the families will know better how their house is compiled, so reparations and improvements can be done easily by themselves. Their houses should be extendable according to their needs, desires and financial possibilities. The different possible phases should be visible in the proposed design of the house. Proposing a design with already clear possibilities for future extensions will result in a higher quality product.

During the selection of building materials de environmental impact should also be taken into account. Environmentally friendly, bio-degradable building materials are preferable, because in most cases they do not need complex processing and after usage these materials can be given back to nature. Unfortunately, many bio-degradable materials are not durable for many years in this semi-tropical climate. Therefore, they are habitually treated with a preservative, which are often toxic chemicals which poison the environment. The technical materials, on the other hand, perform much better in this semi-tropical climate, but in most cases their production requites a lot of energy and consequently, fuel.

The different materials analysed in this chapter are put together and were assigned scores based on cultural acceptance, cradle to cradle, affordability and climate adaptability. (See Table 2.1) The materials that are colored red have a really negative score on one of the four topics, and are excluded for further building material selection. Cement and concrete sheets of corrugated iron have a negative impact on the environment, but are quite affordable and are culturally quite well accepted. Ceramic bricks and wood score quite average and clay bricks, ceramic roof tiles and bamboo are the most preferable building materials.
From this we could give a recommendation which materials are best for use in the current situation. Cement and concrete do not score high, especially on the cradle to cradle topic, but these are perfect materials in this climate for making the foundations and the ground floor. It should be noted that a good alternative is not present. For construction, a research into bamboo could be done as a more affordable alternative to wood or a more sustainable solution than concrete. Walls of clay bricks and roofs of ceramic roof tiles are the perfect raincoat in this climate and also are culturally attractive. In fact, the local people construct quite well with the materials they have. The only building material that could be explored more is bamboo. However, as was explained in paragraph 4, if all people construct with clay bricks, no fertile soil for agriculture will be left. A more diverse building material market could take away the stress on the clay products. So it would be interesting to look at non present alternatives that could be introduced in Santa Cruz.

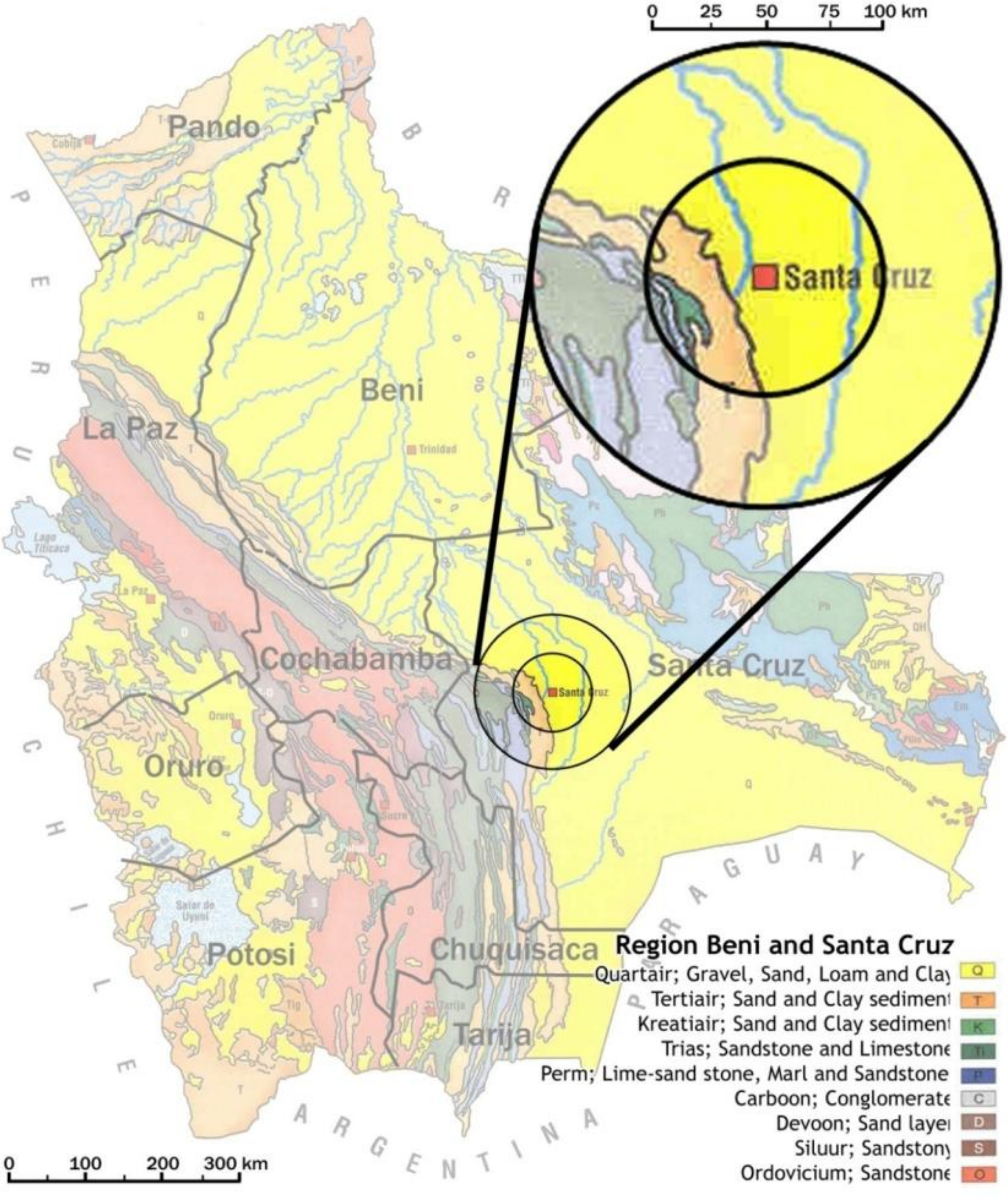


Fig. 3.1 Geological map of Bolivia with a zoom in on Santa Cruz de la Sierra (10)

3 Potential materials

In this chapter we will look at potential building materials that are not yet available in Santa Cruz. As we want to make use of locally available materials, we will look into the resources that can be found in Santa Cruz. From there on a search into still unused potential materials will be explored. Resources can be found in minerals that are available at the surface (paragraph 1), natural fibres that grow naturally in the surrounding (paragraph 2) and materials that are labelled as waste materials (paragraph 3).

3.1 Minerals

In Fig. 3.1 the geological map of Bolivia is presented with two circles around the city of Santa with a radius of 50km and 100km. In the zoomed in figure we see that there mainly is gravel, sand, loam and clay available and at a bit of sand and lime stone. Currently, clay is used in the form of bricks and ceramic building products as described in chapter 2. Loam is a traditional building material, nowadays often used in the rural areas. (See chapter 2) Gravel and sand are additions in concrete, which is a less used material.

Deltares[2] recently performed research into soil consolidation with bacteria, based on the natural process of sandstone creation. For sandstone you need carboxyl group ($CO3^{2-}$) that glues the grains of sand and forms a stone with the qualities you prefer. In the newly developed process at Deltaris, the carboxyl group ($CO3^{2-}$) is extracted from calcium chloride and urea. The bacteria consume the urea and release carboxyl group ($CO3^{2-}$) and ammonium. The bacteria functions as a catalyst and take care of a slow release of the carboxyl group ($CO3^{2-}$). Calcium chloride is a good dissoluble salt, which creates a good distribution of calcium-ions. The calcium-ions and carboxyl group ($CO3^{2-}$) react to calcium carbonate. The hardening time depended on the metabolism of the bacteria. Due to the slow release, crystal forming occurs, resulting in a good crystal structure. (11) IBR consult[3] extended the research to the building industry, because of the potential to develop an energetic low building stone.

The production of bricks can be characterised by the next process steps: Extracting of raw materials, measuring the raw materials into doses, mixing the materials, shaping them and finally the solidifying step. The raw materials are available, although it is questionable if it is preferable to produce urea in big quantities. Measuring the raw materials into doses and mixing them is possible, and pouring or pressing can be potential forming techniques for the developing of bricks. Unfortunately, the hardening process is quite difficult to control, because of the bacteria. Temperature, location and time can influence the productivity of the bacteria. Additionally, the released products from the chemical reaction should not kill the bacteria. The quality of sandstone is depending on the amount of limestone that develops. Therefore, the quality of the stone is not only dependent on the bacteria, but also on the amount of raw materials present for reaction. The measuring into doses and the generating of good conditions for the bacteria are important for creating a good product. (12)

From the research done by Deltaris and IBR consult can it be concluded that creating a bio-stone is technically possible. Unfortunately, there are also negative aspects to this product: the development of the by-products

[2] Deltaris is an independent institute for applied research and specialist advice in the field of water, soil and the subsurface in Delft, the Netherlands

[3] IBR consult, a Dutch engineering office established in Haelen (the Netherlands), is active in the fields of recycling, stony building materials and radiation in building materials.

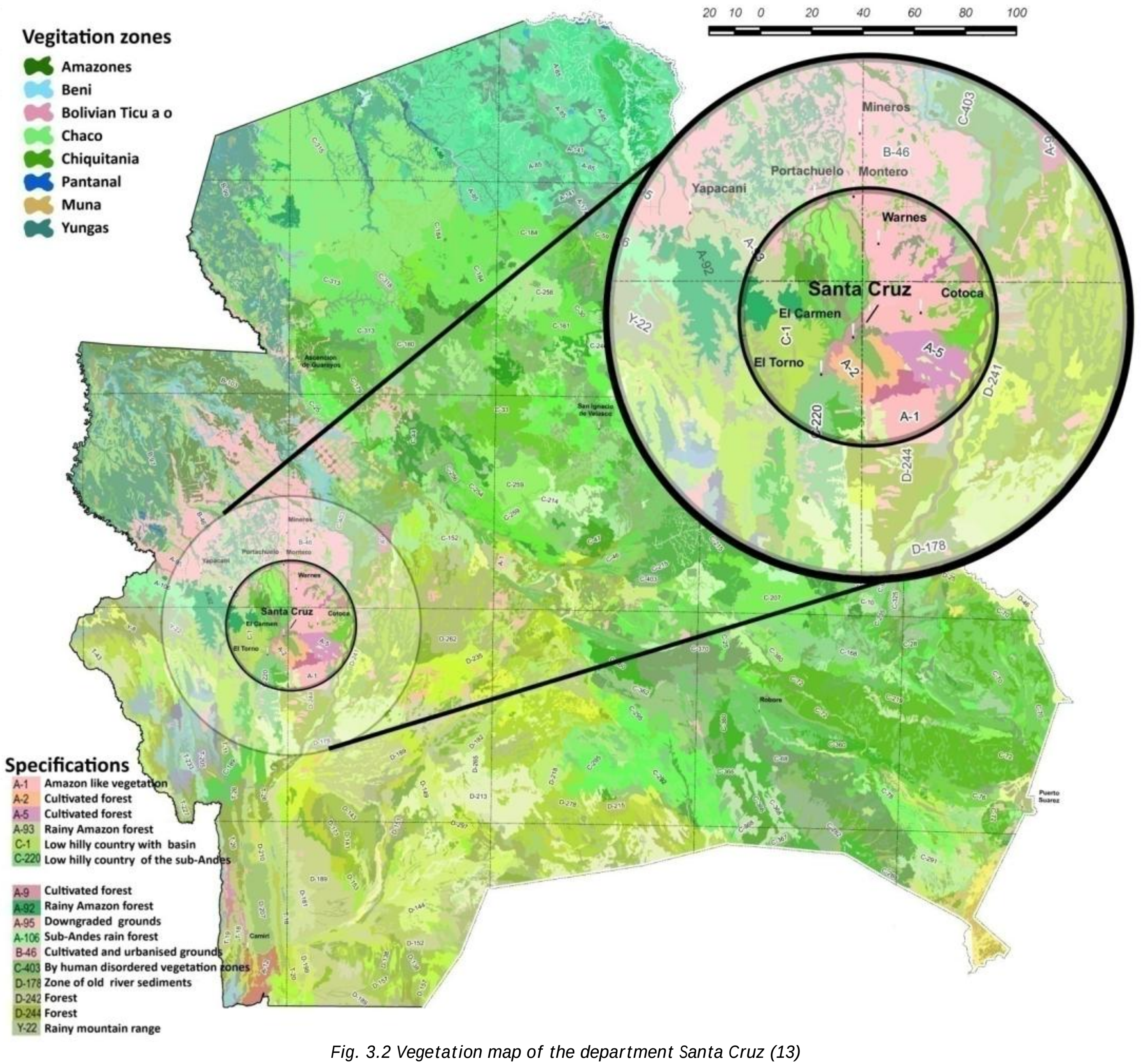


Fig. 3.2 Vegetation map of the department Santa Cruz (13)

chloride and ammonia. Too much ammonia released into nature causes acidification of soil and rainwater, which is a perfect environment for the development of algae. Additionally, the captured ammonia in the building material causes a nasty smell for at least the first years. Chloride causes a change of colour of the building product and is also not a pleasant product that is released into nature. Next to this, the costs of the current production process are too high to make it economical feasible.

Further research into the processing techniques has to be done to see if the complete stone process is feasible. Additionally, research into alternative raw materials which can also form calcium carbonate with a slow release has to be done. Maybe urine can be a substitution for urea. For an implementation in Bolivia, not only the raw materials have to be investigated, but also the availability of similar bacteria that are locally available as well as a financial feasibility study.

The development of a bio stone in Santa Cruz has a high potential, because there is no building product market with high technical standards such as in the Netherlands. The introduction of the bio-stone or pour techniques can be of lower quality. Next to this, the inhabitants of Santa Cruz de la Sierra prefer a stony house, which is also preferable in the sub-tropical climate. On sustainability level it also scores higher, because the production does not require energy. Unfortunately, the current production technique is not desirable for health, climate and financial reasons. Therefore, it is not a feasible research area for this moment, but maybe it can be researched into depth more in a couple of years when IBR consult find a better production technique or Deltaris finds better raw materials for production.

3.2 Natural fibres

Vegetation can grow naturally or can be cultivated. Preferably, the cultivated products are used for human purposes, so the naturally grown vegetation will not be extinguished. The cultivated lands are not only used for the growth of natural fibres for building purposes, but also for food production, and recently, bio fuel production. A balance should be made between the demand for food, fuel and building material and the amount of soil used for the cultivation of these products. Unfortunately, the consideration of which product will be cultivated depends more on the amount of profit one can made.

Santa Cruz de la Sierra is the capital of the department Santa Cruz and lies in a Semi tropical area. In Fig. 3.2 a vegetation map of Santa Cruz is presented. In the map two circles around the city of Santa Cruz are drawn; one with a radius of 50km and one of 100km. In the zoom in we see many different colours which can be understood that many different fibres grow naturally in the surroundings of Santa Cruz. The natural fibres that are used currently as building materials in Santa Cruz are wood and in a lesser extend bamboo.

Another way of using natural fibres is in composite materials, which combines the tensile strength of fibres and the pressure strength or stiffness of matrixes. Nebasco[4] found out how to produce composite products with natural fibres. They use mats with coco's fibres and hemp fibres pressed together or enlaced which are delivered on rolls. Nebasco places the mat with natural fibres in a mould and covers the natural fibres with a fluid synthetic material

4 Nebasco, part of NPSP composieten, is a company that researches and produces sustainable compost products for building industry, design industry, and automobile industry.

Fig. 3.3 Earthship, construction with car tires

Fig. 3.4 "Casa de boteillas", construction with plastic bottles

which protects the fibres. After hardening, a stiff product is produced. It is possible to make facade panels of curved roofs with this material. Currently Nebasco is doing research into the use of natural resins to make their products even more sustainable. Unfortunately, they were not able to share this information yet. (14)

However, it can be an interesting material to develop for Santa Cruz. There are many natural fibres available in Santa Cruz and finding a natural resin should also be achievable. For example, there is a large sugar industry in Santa Cruz, where a lot of sugar plant fibres are available which maybe can be processed into mats. A research can also be performed into the growth of hemp or jute which can be interweaved to mats. For resins one can look into natural resins from trees or natural available oils. Panels can be produced with a low tech technique: by hand laminating both sides with a natural resin. The production has to be done with great care, because when air inclusion happens the product becomes sensible to moisture.

Culturally, the product is very different from traditional ways of constructing. Therefore, it could get the same image as a ceramic brick: not very burglary proof, which gives it less priority for further research than the bio stone. Additionally, the production technique is quite sensitive for air inclusion and seems quite complex. If it is technically possible to produce a building product with these raw materials in Santa Cruz, it is culturally wiser to first offer the product to the high class inhabitants. As the middle class wants what the high class has, and the low class prefers the way the middle class lives, the building product will end up by the lower income groups. Additionally, in the beginning the price of the product will be high because the investment costs also have to be covered. By the time the low income groups want this product, the price will also be acceptable.

3.3 Waste materials

What if we could turn waste into a building product. We can differentiate between two types of waste; biological waste from agricultured plants and technological waste, which is not biodegradable. The use of biological waste from agriculture plants is already discussed in paragraph 3.2. Constructing with technological waste like car tires and bottles are already known.

In the east of the United stated a number of constructions with car tires can be found, constructed by Mike Reynhold from 1970 on which are called Earthships. The homes are primarily constructed to work autonomously and are generally made of earth-filled tires, utilising thermal mass construction to naturally regulate indoor temperature. Earthships are built to utilize the available local resources, especially energy from the sun. For example, windows on the sunny side admit light and heat, and the buildings are often horseshoe-shaped to maximize natural light and solar-gain during winter months. Likewise, the thick, dense outer walls provide effective insulation against summer heat. (15)

Ingrid Vaca Diez, the wife of a local factory owner in Santa Cruz, designed and constructed two houses out of plastic and glass bottles. The first house cost her 18.000$ and the second one 10.000$. She got the money for the constructions from friends, who support her ideas. The receiving family did not have a say in the houses she designs, but have to participate in the construction. The bottles were filled up with sand and laid in a loam and cow dung mix. The same mix was also used to plaster the houses. The way of constructing can help a couple of people, but not tackle the main housing problem. Additionally, the sustainability of constructing with bottles is to be questioned. (See Fig. 3.4)

Fig. 3.5 Bamboo forest in Hawaii

It may be possible to develop stony building materials from rest products of industry. The rest products has to comply with high amount of mineral elements, has to be chemical reactive in certain conditions and be available in big amounts. For example, the fly ashes of coal heated installations, slag of blast furnaces and ashes from burning biomass (like rice film) are suitable binders to form together with loam and/ or sand a building material.

Giving waste materials a new life is not an easy task. First of all there has to be a very good culture of waste separation. Secondly, the quality of the building material depends on the quality of the waste. In Santa Cruz there is no waste separation. Waste that comes from industries can have potential, but have to be researched locally. Making constructions out of car tires of plastic bottles can be a solution for a small group, but is not a structural solution. Thereby it is not an environmentally better solution; it only prolongs the life of the plastic bottles or tires. Finally, it is questionable if these materials are culturally acceptable.

3.4 Conclusion

It was an interesting excursion to search for alternative building materials that do not yet exist in Santa Cruz. It resulted in two potential materials that could be examined more in depth, Bio stone and Natural fibre reinforced natural materials. Unfortunately, it is so soon yet to continue doing research in one of the materials. The use of waste materials is not advice. Maybe, further research can be done in waste materials of industries, when searching for other potential building materials for Santa Cruz de la Sierra in the future.

As was said in the conclusion of chapter two, a further research into bamboo is interesting. Bamboo therefore is the material chosen and it will be analysed, discussed and tested in the next chapters.

Material	Cultural Acceptance	Cradle to Cradle	Affordable	Appropriate in semi-tropical climate
Clay bricks	++	+/-	+/-	++
Ceramic bricks	+	+/-	+	+/-
Ceramic roof tiles	++	+/-	+/-	++
Adobe and Loam	--	+	+	+/-
Asbestos cement plates	+	--	++	+
Cement and Concrete	+	-	+/-	++
Sheets of corrugated iron	+/-	-	++	+/-
Palm tree leaves	-	++	--	+/-
Wood	+/-	++	+/-	+/-
Bamboo	+/-	++	++	+/-
Bio-stone	+	+/-	-	++
Natural fibre strengthened natural material	-	++	-	+
Car tires of plastic bottles	-	-	+	+/-

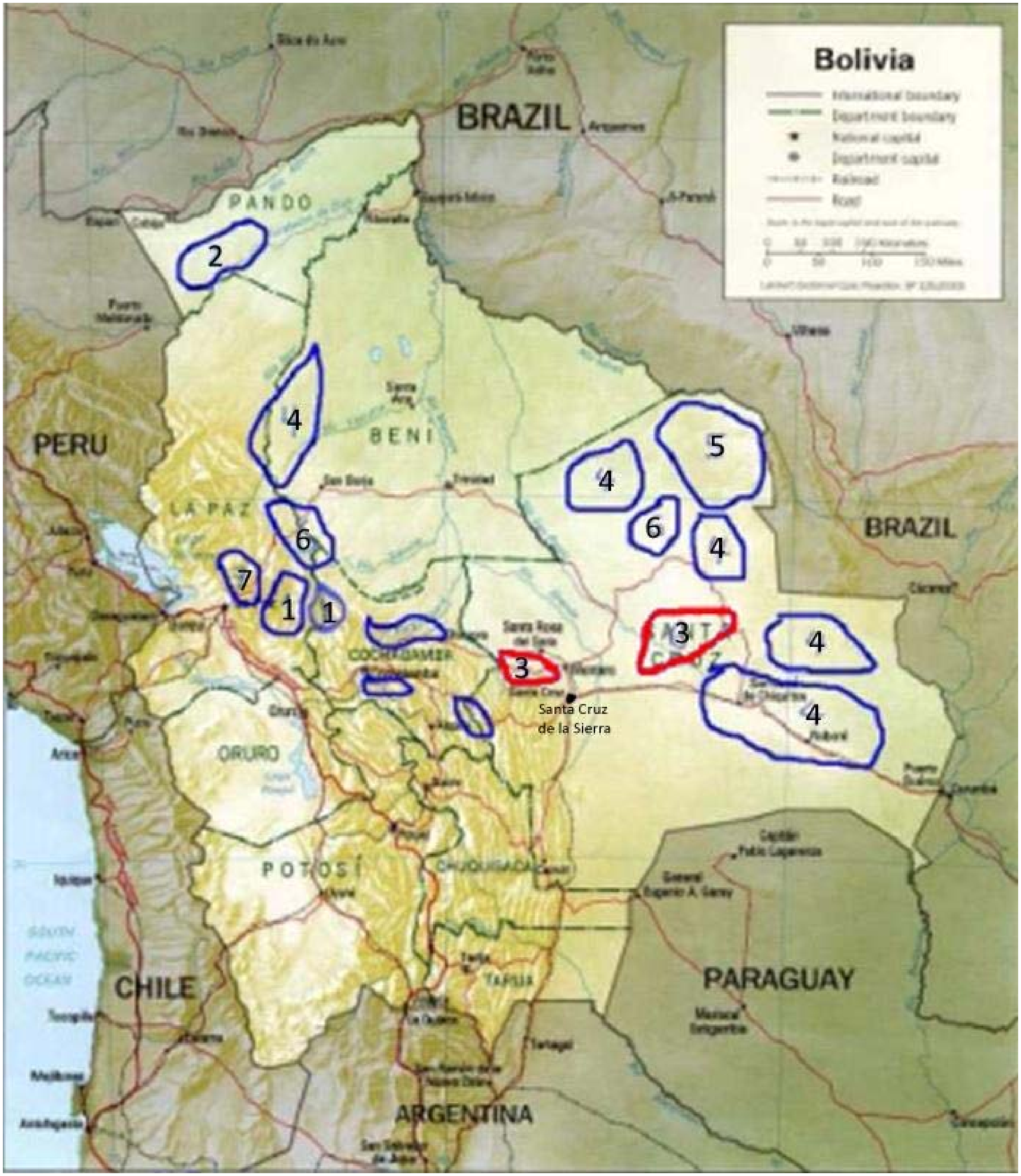


Fig. 4.1 Bolivia's main bamboo growing regions; 3 = Guadua chacoensis (16)

4 Bamboo

In this chapter a deeper analysis of bamboo as a building material will be given. In the first paragraph we will look at which species grow in Santa Cruz, the locations where they grow and how they grow and can be harvested. In the second paragraph the durability and flammability of bamboo will be described and different preservation methods will be discussed. In paragraph 3 the different existing jointing techniques will be analysed and in paragraph 4 the construction techniques will be discussed and a calculation for the construction will be made. In the last paragraph the conclusion from this chapter will be drawn and further research steps will be described.

4.1 Growth and Harvest

In Bolivia a number of bamboo species can be found, but the exact number of species is still uncertain. Additionally, there is much uncertainty of the area of bamboo forest in the highlands as well as in the lowland regions of the country. In Fig. 4.1 a map with an estimation of bamboo distribution is drawn. In the surroundings of Santa Cruz de la Sierra two areas are marked red. In these areas the bamboo species Guadua Chacoensis grows, which has been found suitable for construction. (16)

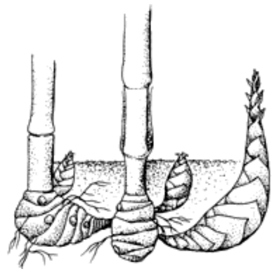


Fig. 4.2 Clumping bamboo root system

Bamboo reproduces through their root system, called rhizome, on a regular base and once in the approximately 15 years by flowering. Two types of root systems can be defined; the clumping rhizome and running rhizome. The clumping rhizome, also called sympodial rhizome, is non invasive, because each new rhizome turns upward and develops into a culm. (See Fig. 4.2) The running rhizome, also called monopodial rhizome, has a single, dominant subterranean stem, or axis, that develops secondary stems that either extend laterally or run upward to become culms and is invasive. (See Fig. 4.3)

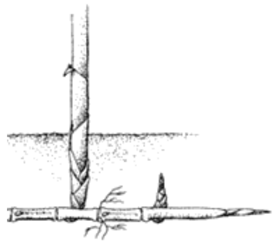


Fig. 4.3 Running bamboo root system

The Guadua Chacoensis has a clumping rhizome and is non invasive. Therefore it could be possible to introduce this plant in the gardens of the lower income families, so future extensions can be harvested by the families themselves. Thanks to the rhizome system that firmly anchors the plant; the bamboo helps to prevent erosion and keeps the soil loose, resulting in better rain water absorption.

The Guadua Chacoensis can be harvested after three to five years. Different harvesting techniques can be found in literature, but in general a couple of aspects are needed to be considered while harvesting bamboo:

- Before felling the culm, analyse its age to make sure it has became strong enough for construction.
- Make sure to leave enough mature culms to protect the smaller plants against wind and direct sunlight.
- Be careful with shots and small plants that surround the chosen culm.
- Preferably harvest the bamboo outside the rainy season and in winter, while insects hibernate.
- Cut the bamboo stem at a maximum height of 25-25 cm from ground level and always above the node. This avoids fluids gathering in the culm that would affect the rhizomes negatively.
- Leave the felled culm for 10-15 days in a vertical position, on top of the rhizome.
- Store the felled culms in a covered and protected place. (16) (17)

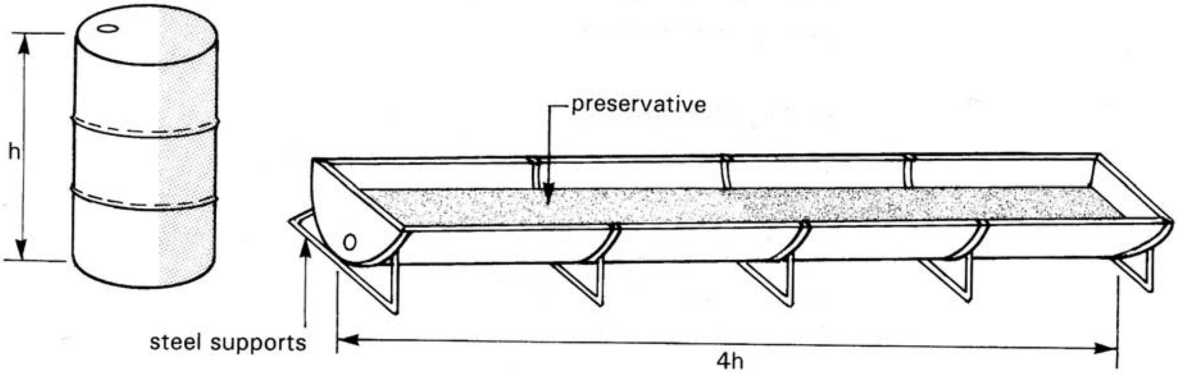
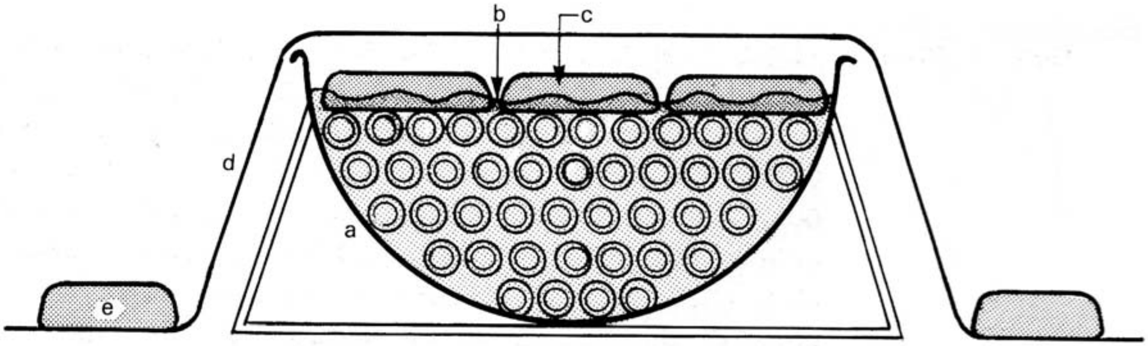


Fig. 4.4 Open tank method for cold soaking (18)



Key

a	Trough containing submerged bamboo.
b	Level of preservative.
c	Large stones to keep bamboo submerged.
d	Plastic cover to protect against rain.
e	Stones to keep plastic cover in place.

Fig. 4.5 Cross section of open tank (18)

4.2 Durability and Flammability

The main concern of any actual or potential user of a bamboo house or product is the short durability of the materials. Bamboo has less natural durability than most types of wood, so prolonging the usable life of Bamboo by preservation is necessary. After harvesting the bamboo different methods of preservation and fire protection are possible. In this paragraph some of the methods found in literature will be described.

4.2.1 Non chemical (traditional) methods of preservation

Smoking above fire places inside houses

Traditionally, bamboo culms are placed above fireplaces inside the house so that the smoke and heat rises up, and both dries and blackens the culms. It is possible that the process produces some toxic agents that provide a degree of protection. Alternatively, the heat generated by the fire could possibly destroy or reduce the starch content of the bamboo stem. (18)

Soaking method

Soaking involves immersing the culms in stagnant or running water for a few weeks to leach out the sugars. Afterwards, the wet bamboos are air-dried under shade. (17)

Whitewashing method

Painting with slaked lime, mainly for appearance, maybe prolongs the life of the bamboo structure by preventing moisture entering the culms, which will provide a higher resistance to fungal attack. However, there remains a question as to whether the bamboo can be weakened over time by such alkaline treatment. (18)

Elevated construction method

Preventing the bamboo from coming into direct contact with the ground by placing the bamboo posts on stones or pre-constructed cement walls. Good air circulation throughout the structure is also necessary. In addition, careful attention to construction detailing will help to enhance the service life of the building. (18)

These treatments result in an increased resistance to insect and fungal attack when compared to freshly cut bamboo culms. However, because of the low natural resistance of bamboo to biological deterioration, the methods do not provide durability in the long term and therefore offer no real cost saving benefits. (18) However, correct design of all building details is a must; no chemical treatment will be good enough to solve the problems caused by incorrect design. (17)

4.2.2 Chemical treatment methods

Bamboo has a number of important chemical and anatomical differences from wood. Bamboo has no linked radial transport system for liquids as wood has. The vessels of bamboo, which run axially between the internodes, are isolated from each other by parenchyma cells, and the vessels vary in vessel diameter. Finally, the outermost cells of the culm have a waxy coating, with makes penetration by liquids more difficult. Therefore, not the same preservative methods as for wood can be used. (18)

The anatomy and structure means that there is very little opportunity for the radial movement of liquids. Therefore, the penetration of liquids into the culm takes place through the vessels in the axial direction. The

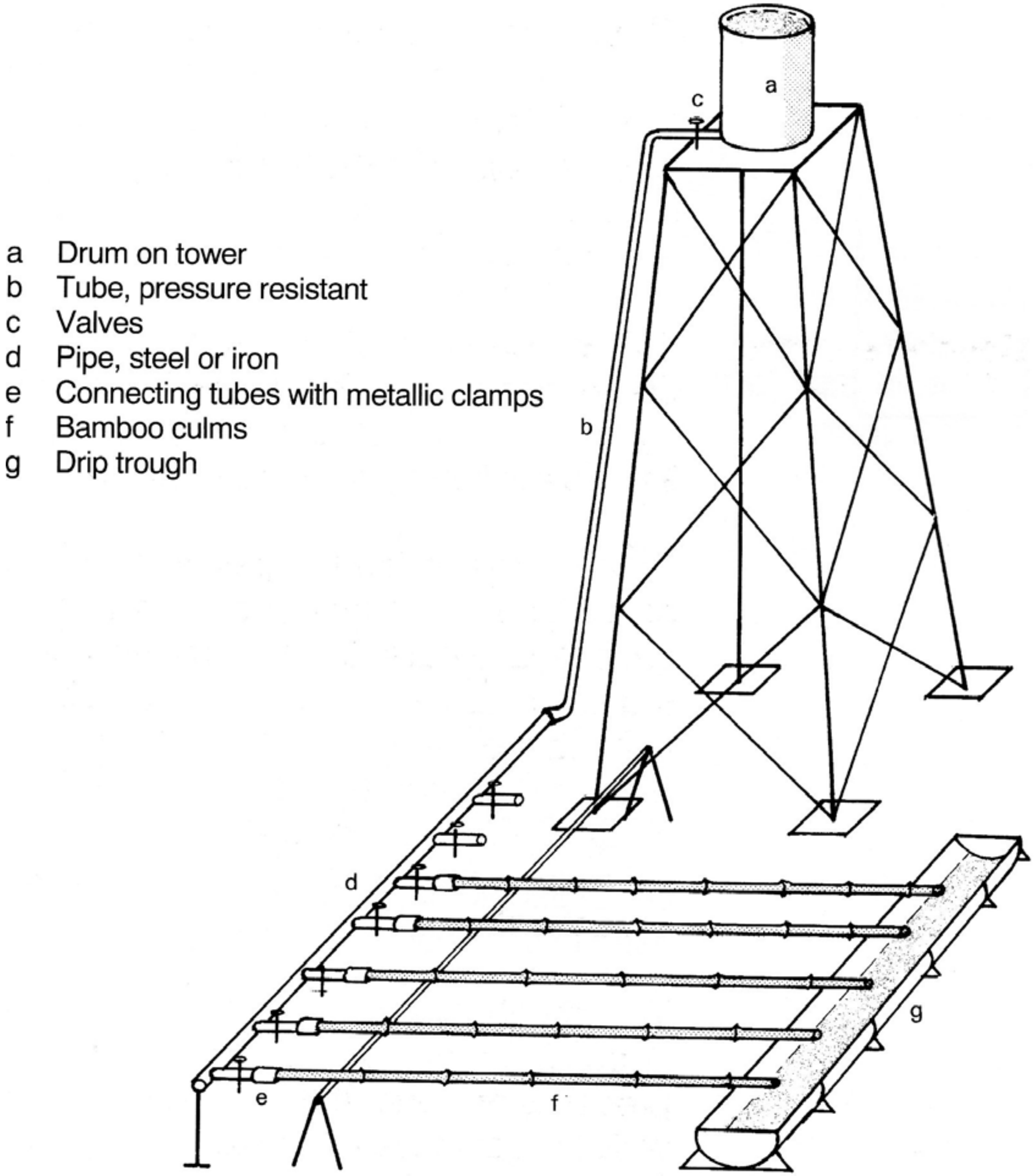


Fig. 4.6 The Boucherie method (18)

vessels only account for about 5-10% of the bamboo cross section. So even when the vessels are filled to saturation point, the bamboo can still be vulnerable to fungal or insect attack if the preservative does not diffuse sufficiently into the main tissue of the culm. There are several treatment techniques which can be used for bamboo culms as well as for split culms. The treatments will be described below for complete culms, but can be used for split culms as well. (18)

Butt treatment
The butt ends of freshly cut culms, with the branches and leaves intact are placed in a drum containing the preservative. The continued transpiration of the leaves draws the chemical solution into the vessels of the culm. This treatment process is very slow and it is uncertain whether enough diffusion has taken place to ensure a good preservation. (18)

Open tank method for cold soaking
Culms, which have been prepared to size, are submerged in a solution of a water-soluble preservative for a period of several days. The solution enters the culm through the ends and sides by means of diffusion. It is recommendable to use immature dried culms to have an effective protection. This treatment method is economical and simple. (18)

Boucherie method
Preservative is led by gravity from a container placed at a higher level than the culm through pipes into its base end. The culms are fastened to the tubes by rubber sheaths and clamps. It is also possible to held the culm vertically and to scratch the inner wall of the top internode in order to use it as a reservoir for treatment. The treatment is terminated when the solution at the dripping end shows a sufficient high concentration of chemicals. The best results are obtained during or shortly after the rainy season, using younger culms with higher moisture content. Allowing the bamboo to dry slowly in the shade for a period of at least two weeks after treatment ensures that the solution diffuses into all of the tissue surrounding the vessels. (See Fig. 4.6) The boucherie method can be improved by the introduction of pneumatic pressure over the preservative fluid, for example by using an air pump or electric pump. The preservative is forced axially through the culm by the air pressure in the reservoir. In this way the time of treatment is reduced from several days to 3-8 hours. (18)

Pressure treatment method
Pressure treatment, using either creosote or waterborne preservatives, offers the best method of preservation for bamboo culms. The applied pressure ranges from around 0,5-1,5 N/mm2 (5-15 bar) and as such requires special factory and equipment. Accordingly, costs are high, but a service life of up to 15 years can be expected from adequately treated bamboo when used in the open and in contact with the ground. Air dried culms are preferable for this method. (18)

Hot and cold bath process
The bamboo is submerged in a tank of preservative, which is then heated to a temperature of 90°C for 20 minutes and then allowed to cool. When using preservatives which can precipitate when heated, it is best to pre-heat the bamboo in a suitable liquid, such as water and then transfer the bamboo into a separate tank containing cold preservative. When the treatment process has been completed, the bamboo should be allowed to dry slowly to allow further diffusion of the preservative to take place. This process is an acceptable alternative to the previous explained methods. (18)

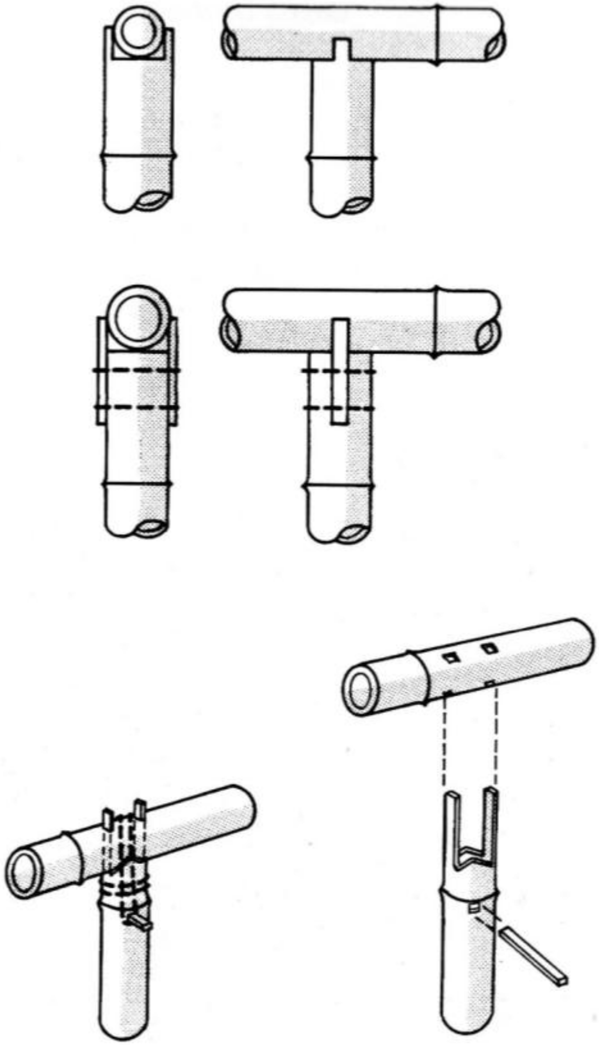


Fig. 4.7 Variations on the saddle joint (18)

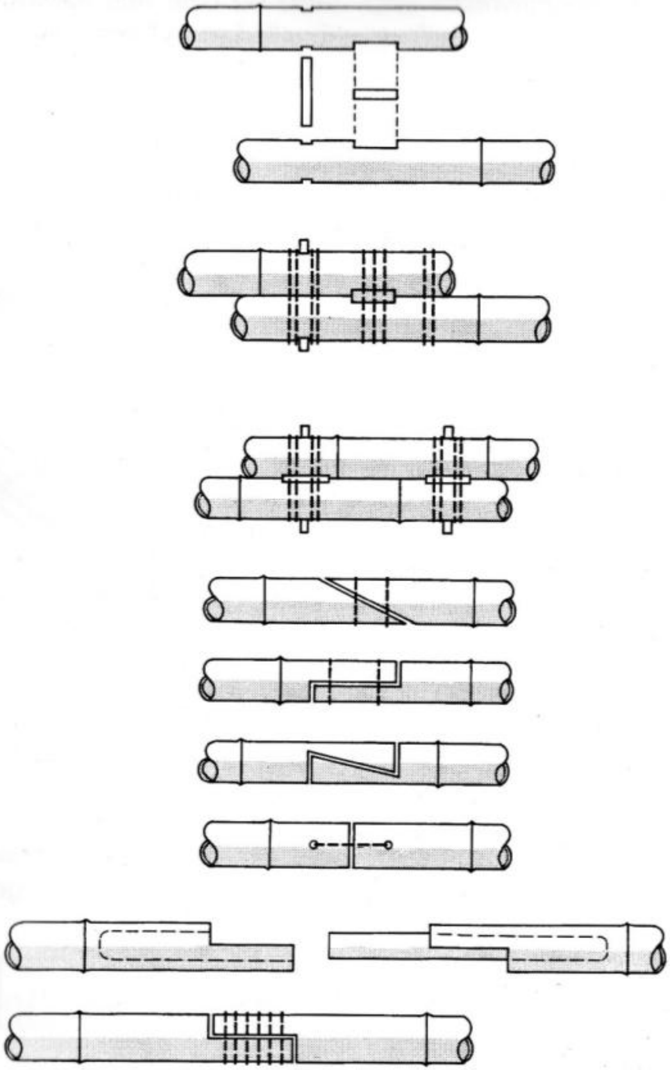


Fig. 4.8 Variations on splice joints (18)

When compared to traditional methods, the use of chemicals for the preservative treatment of bamboo is more effective in providing protection against biological deterioration. However, chemical preservatives are invariably toxic and care and attention should be exercised whenever they are used. (18)

4.2.3 Fire retardant treatment

Fire presents a potential hazard in any form of construction, but the risk is especially high in bamboo buildings. The combination of bamboo and matting, and the tendency of the internodes to burst causes rapid fire spread. The danger is increased when the joint lashings are destroyed, which can cause catastrophic collapse of the building. (18)

It is, however, possible to treat bamboo with a combination of preservative and fire retardant chemicals; the process is normally carried out by pressure treatment. Unfortunately, the cost of fire retardant treatment is generally high and is therefore often considered inappropriate. The importance of finding a suitable and cost effective treatment, which will provide combined protection against bio-degrade, and fire is a necessary area for further research. (18)

4.2.4 Conclusion

Chemical preservation of the bamboo culms is unavoidable. Within the available preservation chemicals, boron based chemicals, like Borax, are the most effective and safe preservatives. The preservation methods, the boucherie and bath process, are already known techniques for the preservation of guadua chacoensis in San Pablo, a village ±300km north of Santa Cruz. The inhabitants of San Pablo use borax as preservation liquid and additionally the bamboo stem will be sprayed with oil or diesel to prolong the durability even more.

In the ideal situation less toxic and better bio degradable preservation liquids can be found to develop an even more sustainable building product. Because of the preservation of the bamboo culms, the bamboo becomes dangerous for the environment when biodegrading in nature.

4.3 Jointing

After preservation of the bamboo stems, a structure can be made with the stems. A structure can only become a structure when the stems are joined together in an appropriate way. Different jointing techniques are found in literature and analysed in this thesis. The fastening of bamboo stems can be with bamboo itself, vegetal ropes, wood, steel and concrete. The stems can be positioned in the same construction line, passing each other or joined by an intermediary. The different joints found are presented in a matrix in appendix B. In this paragraph the different joints will be discussed by the jointing materials.

Bamboo

By cutting bamboo stems in a certain way joints can be realised perpendicular as well as parallel to each other. (See Fig. 4.7 and Fig. 4.8) Moreover, some rope is added to fix the node. In general, these nodes are integrated into each other and the stems are positioned in the same construction line. Most of these jointing techniques require special tools for making the holes and cuts. Additionally, the people have to learn how to make the nodes and become skilled in it.

Fig. 4.9 Different ways of jointing with rope and steel wire

Rope
Wood can be easily joined with nails. In the case of bamboo this is not possible, because of its hollow structure. Additionally, cracks will appear where the nails penetrate the bamboo and make the joint more vulnerable for fungal attack. Therefore, many constructions made with bamboo are joined with ropes from nylon or vegetal ropes. In Fig. 4.9 some examples of wire jointing are presented. The left three images are a combination of special bamboo cutting, mortise and tenon jointing and rope. The middle three images show some lashing techniques when the bamboo stems pass each other. The centre image is a technique of making a corner using 2 bamboos stems and realising three construction directions. By carving out one of the two stems and bending it 90°, the other stem can be clamped. Together with some rope a node can be made.

Wood
Bamboo stems can also be jointed with wooden inserts, see Fig. 4.10. Bamboo is a adequate construction material, because of its hollow stem, its lightness and its ability to handle high tension load. Unfortunately, in the joints the hollow tube has some disadvantages when it has to transfer forces. By inserting wood the bamboo will be locally strengthened by the massive wood, without losing its construction advantages. However, it takes a lot of effort, special tools and knowledge to produce the inserts. Therefore, the wooden insert joint does not seem to be a solution for the situation in Santa Cruz de la Sierra.

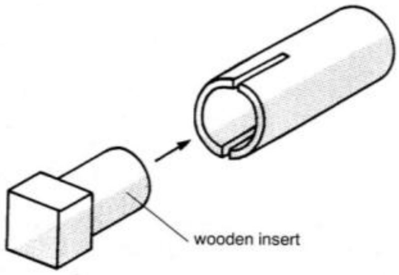


Fig. 4.10 Wooden insert joint


Fig. 4.11 Consolidation of the round wood joint

Steel
Many joints of steel have been developed in the last decades, especially for modern buildings. From connections with steel plates, external clamps up to steel intermediates. For social housing in Santa Cruz de la Sierra most of these proposals are far too expensive. In the eighties and nineties of the last century the building technology group of the faculty civil engineering of the Delft University of Technology worked on a wire lacing tool which could be used to consolidate the joints of round wooden constructions, see Fig. 4.11. The tool was further developed and possibilities were analysed to use the tool for bamboo constructions in developing countries. In Fig. 4.9 the right three images show what type of nodes can be made with this technique. The technique of jointing is rather simple and no complex elements are necessary. Therefore, it can be an interesting way for constructing in Santa Cruz de la Sierra.

Concrete
Besides steel, joints with concrete have been developed in combination with bolts. In general the joints are first bolted together and then the bolted segment is filled with concrete. Unfortunately, this technique makes dismantlement very difficult and replacement of a rotten bamboo stem almost impossible.

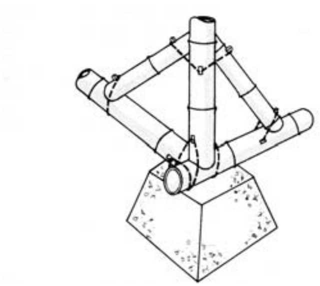


Fig. 4.12 Preformed concrete footings (18)

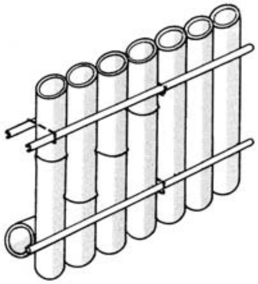


Fig. 4.13 Wall of whole bamboo culms (18)

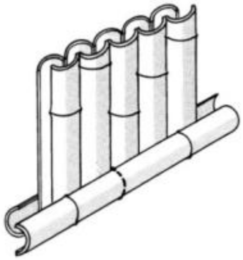


Fig. 4.14 Wall of vertical halved culms (18)

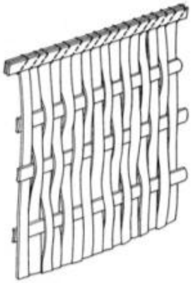


Fig. 4.15 Woven bamboo wall (18)

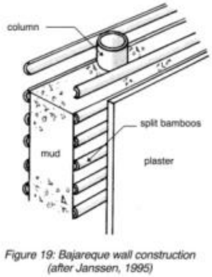


Fig. 4.16 Bajareque wall (18)

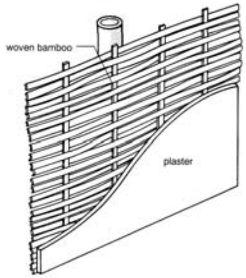


Fig. 4.17 Plastered woven wall

Bamboos are split into thin slivers

Slivers are woven into mats

Mats are soaked in adhesive resin

Mats are allowed to drain and dry

Mats are pressed together under high temperature and pressure to form roofing sheets

Sheets are trimmed to shape and may then be painted

Fig. 4.18 Production of roofing sheets (19)

4.4 Constructing

Not only the jointing of bamboo culms with each other, but also the detailing with other used building materials has to be analysed. Additionally, bamboo can also be used for the compleation of the house. The foundation, floor, walls and roof in relation with the bamboo construction will be discussed.

Foundations

Preferably,bamboo is never placed in direct ground contact, because it will become more sensitive to fungal attack. Therefore, rock or preformed concrete footings are advisable. The bamboo can be incorporated into a concrete footing. A disadvantage of integrating bamboo with concrete is that the bamboo can never be replaced. Alternatively, an integral, durable foundation can be realised by casting a concrete extension to a bamboo post using a plastic tube of the same diameter. Furthermore, the bamboo construction can also be joint by metal wires, which are integrated in the foundation.

Floors

The floors of the house can be made out of bamboo stems, half a stem or bamboo strips. Preferably, the floor is raised from the ground and air can pass easily.

Walls

Different ways of using bamboo as a wall material are known. Whole or halved bamboo culms can be used to make a wall. Split or flattened bamboo is mostly covered with wall plaster on both sides. Bamboo stripes can be woven into mats, which can become a protecting layer against rain, but leave enough opportunity to let air through. Traditionally, Latin American way of constructing walls is tying up horizontal bamboo strips to both sides of the bamboo or wooden posts, called Bajareque. The cavity is then filled with mud or mud and stones, producing a relative massive form of construction. In the rural areas of Santa Cruz the traditional houses have a thin bamboo stem woven structure wall which is plastered on both sides with adobe.

Roofs

The roof structures can be realised perfectly by a bamboo truss. In Appendix C a structural calculation of the proposed bamboo structure is made. From the calculation the conclusion can be made that a structure with bamboo is possible, even when using ceramic roof tiles as roofing material. Bamboo can also be used as roof covering in the form of bamboo tiles, which is susceptible to leakage, or in the form of bamboo shingles, which is labour intensive. Bamboo stripes, woven into mats, combined with bitumen and finished with a weatherproof coating can also form a roofing system, although this is not very desirable from a sustainability point of view. In Asia corrugated bamboo roofing sheets are developed as new cheap roofing material. Bamboo roofing sheets are formed by pressing together bamboo mats which have been stuck together with a glue resin. The corrugations are shaped by pressing them between plates in the pressing machine. The production of corrugated bamboo roofing sheets could be an interesting addition to develop new types of employment. (20)

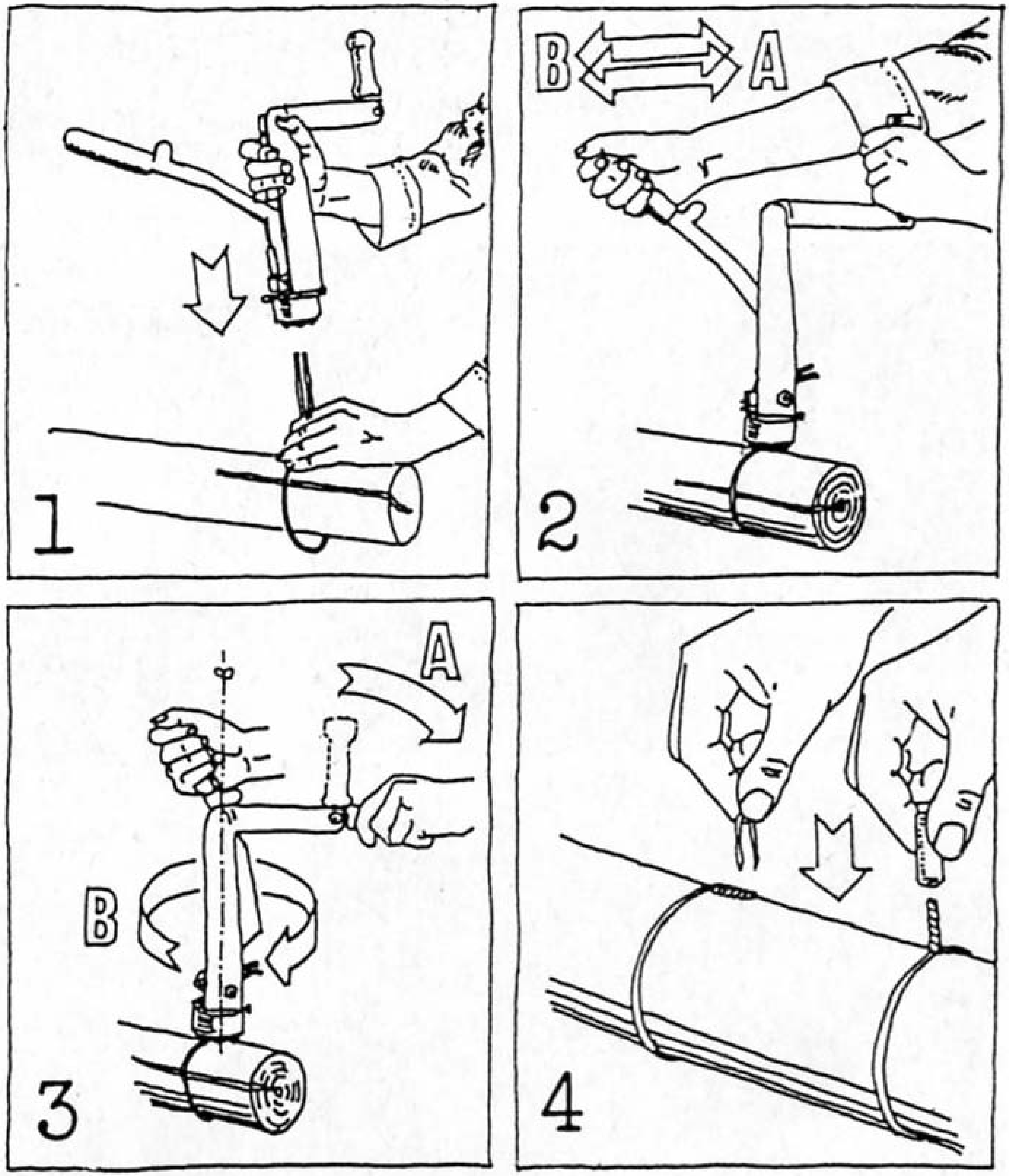


Fig. 4.19 Method of use of the wire lacing tool

4.5 Conclusion

Bamboo as a construction material has the advantages of being light and having the ability to handle high tensions. Additionally, the plant grows very quickly, which results in relative quick production of construction material. As a building material, bamboo is relatively new and therefore a lot of research opportunities are available. For further research two topics can be dealt with. Firstly, as concluded in section 4.2, a research into a more sustainable and cost effective preservative, which will provide combined protection against bio-degrade and fire is necessary. Secondly, a research into jointing techniques as concluded in section 4.3 is required.

The decision was made to conduct a further research into the jointing technique of bamboo stems. The reason for this decision was that this is a more building related research and allowing for a better integration with the architecture thesis. As already became clear from section 4.3 the Delft wire lacing jointing technique will be used for further research. In Fig. 4.19 the instruction of the use of the tool is explained for round wood. For bamboo only the nailing of the iron spiral in step 4 is adviced against. For further research a joint with this technique will be made and put under a pressure bench to determine how forces are translated from one bamboo stem into another. In the next chapter the experiments will be described.

The construction has to carry the covering materials and lead the forces to the foundation. The nodes of the bamboo construction will transfer the forces; therefore the joints need to have a certain strength. In appendix C a calculation of the construction is made from which it follows that the maximum force that has to be transferred is 26,7 kN. By executing some experiments the quality of the joint will be analysed.

Fig. 5.1 Test line up

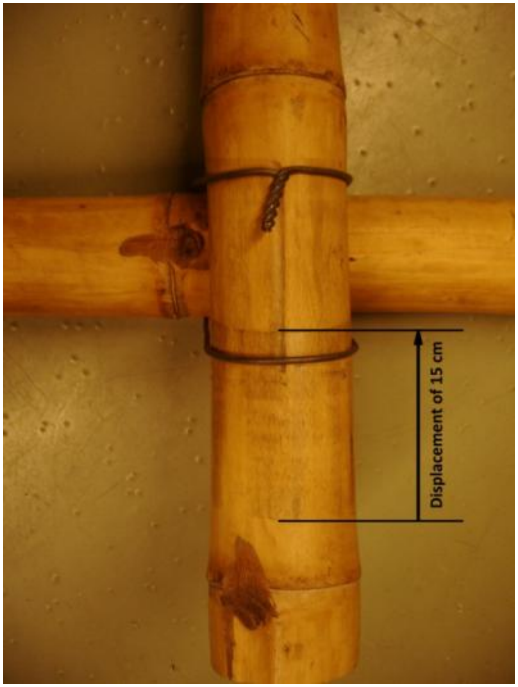


Fig. 5.2 Visual result of node 1

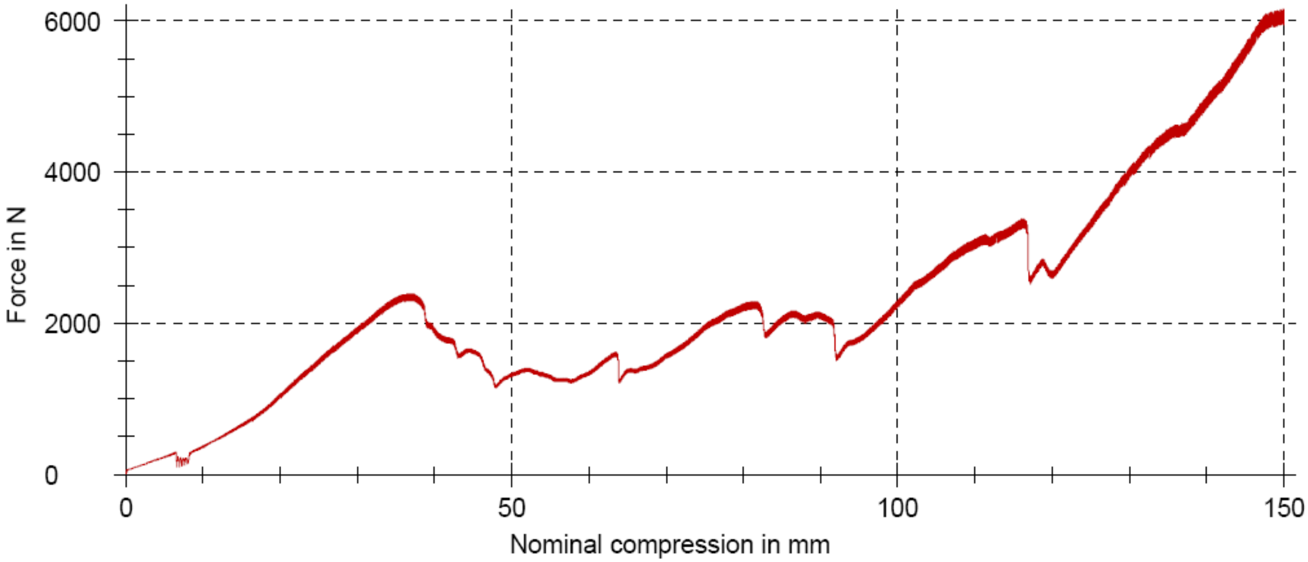


Fig. 5.3 Displacement - absorbed force result of node 1

5 Bamboo junction 1

In this chapter the first proposed bamboo joint test will be explained. In the first paragraph the method of testing will be explained. In the second paragraph the results will be presented. These results will be discussed in the conclusion. The complete test results can be found in Appendix D.

5.1 Method

The node tests were performed at the faculty of mechanical engineering of the Delft University of Technology. The local available bamboo species in Santa Cruz, Guadua Chacoensis, was not available in the Netherlands. Therefore, a similar species was found, the Guadua Angustifolia. The bamboo stem which was used for the pressure tests came from the bamboo area Cali in Colombia. The stem was between 4 and 6 years old and was treated with Borax and Hydrogen peroxide in a bath process. The partitions were perforated to improve the treatment.

As was already mentioned in chapter 4, the quality of the construction is not only dependent on the quality of the material, but also of the quality of the joints. Therefore, two tests were performed. Firstly, two bamboo stems are placed perpendicular to each other and jointed together with the Delft wire lacing tool. One bamboo stem functions as beam and is supported by a metal framework. The stem that is placed vertically will receive a constant pressure load until the node is displaced by 15 centimetres, as shown in Fig. 5.1. Secondly, a second node is made with the Delft wire lacing tool and placed in the same framework. This time the stem that is placed vertically will be subjected to an alternating load of 100 cycles followed by a constant load until the node is displaced by 15 centimetres.

With the first test, the absorption of forces in relation to displacement of the horizontal beam to the vertical culm can be analysed. The behaviour of the node can be observed. In the second test the behaviour of the node over time can be deduced. Additionally, four metal wires which are also used for jointing the bamboo stems are tested in a tension bench.

5.2 Results

The bamboo node of the first test was able to absorb 6 kN, but with a displacement of 15 cm, as can be seen in Fig. 5.3. The graph shows that displacement already occurs at small forces. Additionally, the graph becomes quite curvy after a displacement of 30 mm. This curvy pattern is also found on a small scale. The red line changes in thickness, because in fact the load oscillates with a high frequenty. The curvy pattern is a result of the fact that the forces have to be transferred through the surface where the two bamboo stems are touching. The bamboo surface is very hard and slippery; therefore, the vertical stem is sliding over the horizontal stem. The iron wires stretch and also slide over the smooth bamboo stems.

The bamboo node of the second test was able to absorb 7 kN, but also with a displacement of 15 cm. During the alternating load a constant load of 1 kN was absorbed, as shown in Fig. 5.4. Already after the first load cycle the bamboo stem sagged one or two centimetre and the metal wires stretched a bit. This test was executed much quicker than the first test. Therefore, the small scale movements as described in the first test were not noticed, probably because the joint did not get the time to recover.

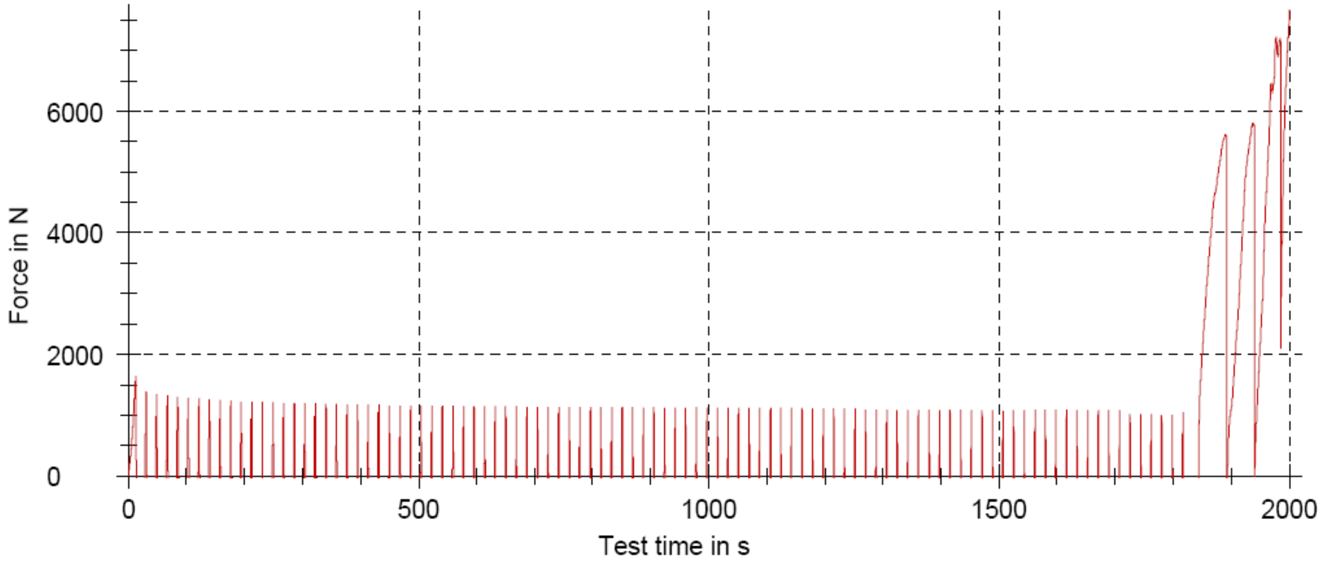


Fig. 5.4 Time - absorbed force result of node 2

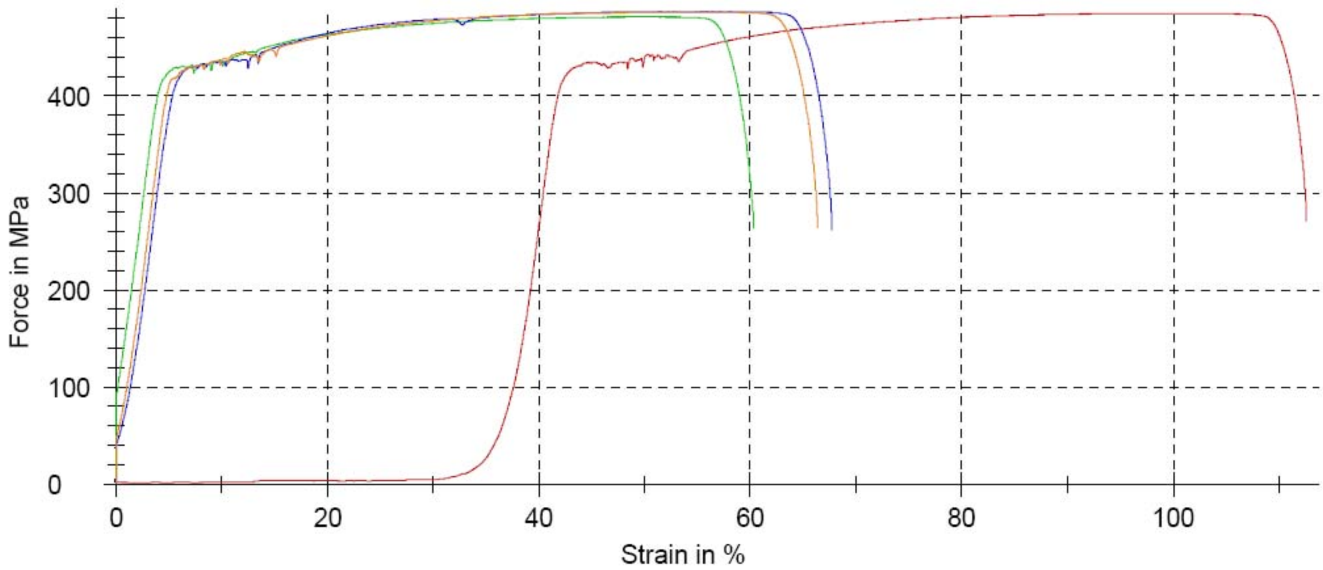


Fig. 5.5 Tensile tests with 4 iron wires

Next to the bamboo nodes four metal wires were also tested on the magnitude of tension they could handle, as Fig. 5.5 shows. The maximum tension before deformation is 400 MPa. The metal wires have a diameter of 3.4mm, therefore one wire can handle 3,6 kN. Although the node is produced with one wire, the force will be divided over 4 pieces of the wire. In the ideal situation the wires should be able to transfer 4*3,6 = 14,4 kN, but because the wires slide over the bamboo and rotate, less force will be adapted.

5.3 Conclusion

The results of the first test is not very pleasant for the construction of the house. Therefore an improvement of the joint is necessary. There are a couple of ways of improving the joint: the surface where the bamboo stems are touching each other can be improved by carving out a part of the stem. This will bring about a higher sensitivity to fungal attack and weaken the bamboo stem itself. Alternatively, an intermediate between the bamboo stems could be introduced to improve the force transmission and prevent sliding, like rubber from an old car tire (see Fig. 5.6) or a plastic casted element. A third option is that the iron wires can be pulled together with an extra iron wire, placed perpendicular on the four wires. Next to improving the joints, an extra bamboo stem could be introduced to prevent the bamboo stems from sliding. This method of constructing is inspired by the Chinese way of constructing, as shown in Fig. 5.7. However, quite a lot of sliding occurred with the first two nodes tested without reaching a very high force level. Therefore, the proposed improved nodes with rubber and an extra wire will be tested and described in the next chapter.

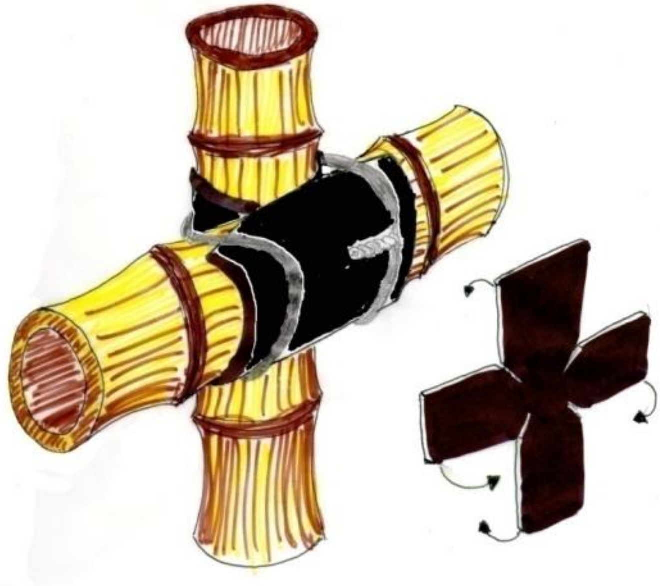


Fig. 5.6 Bamboo joint with metal wire and rubber intermediate.

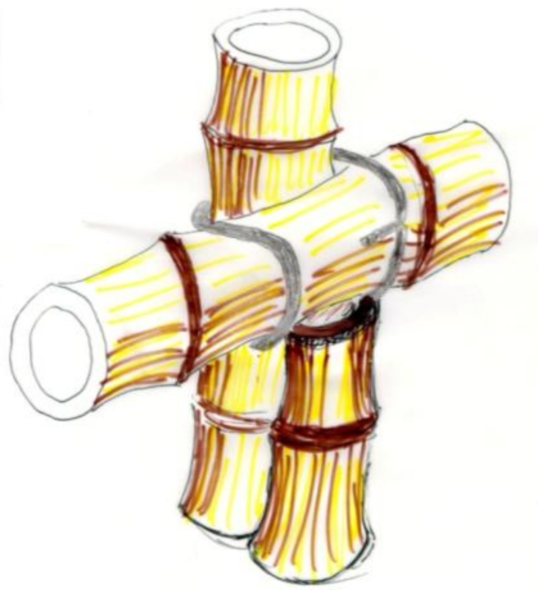


Fig. 5.7 Chinese method of constructing, extra support for the bamboo joint is added

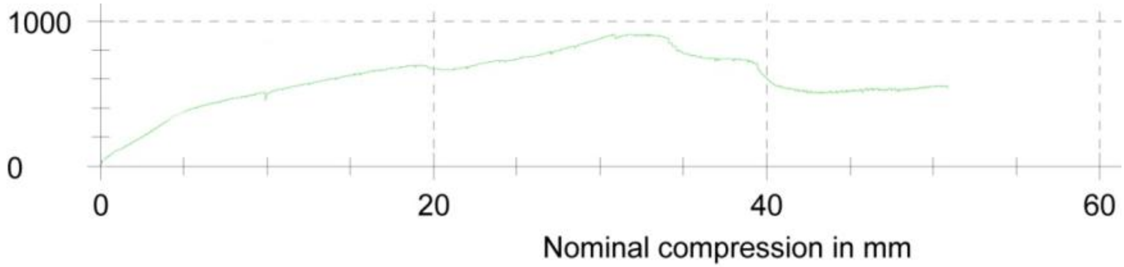


Fig. 6.1 Displacement - absorbed force result of the rubber - metal wire node

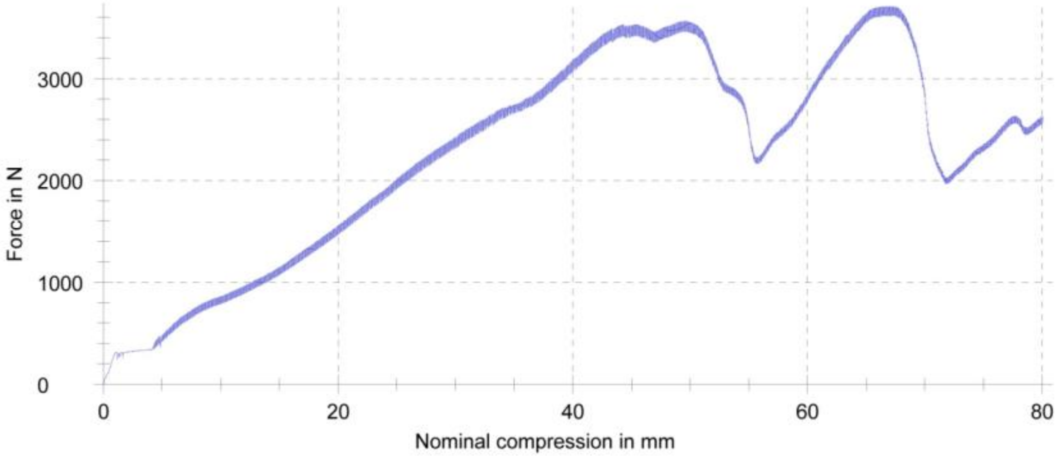


Fig. 6.2 Displacement - absorbed force result of the added metal wire node

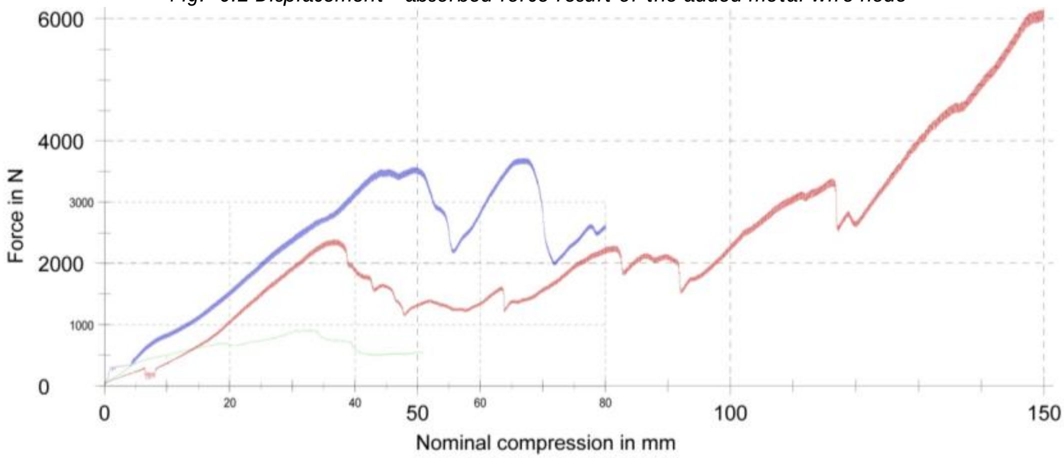


Fig. 6.3 Displacement - absorbed force combined result of the 3 tested nodes

6 Bamboo junction 2

In this chapter the tests of the improved bamboo joints will be explained. In the first paragraph the method of testing will be explained. In the second paragraph the results will be presented. These results will be discussed in the conclusion. The complete test results can be found in Appendix D.

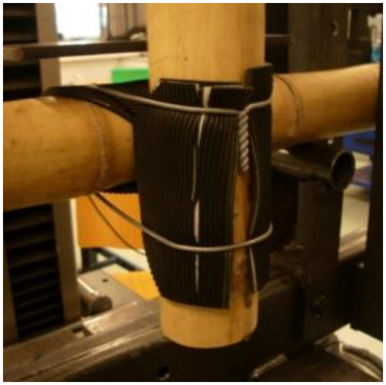


Fig. 6.4 Bamboo joint with rubber intermediate

6.1 Method

The bamboo stems from the first test did not fail, therefore these were reused for the improved bamboo joints tests. The method of testing was the same as that described in chapter 5.1 for test 1. The bamboo joint with a rubber intermediate was supposed to be made from a car tire. During the production of this joint we discovered that an old car tire in the Netherlands is not worn down enough and therefore, to stiff for this purpose. Therefore a more flexible rubber with ridges is used as shown inFig. 6.4. The joint with extra metal wire is shown in Fig. 6.5**Fout! Verwijzingsbron niet gevonden.**.

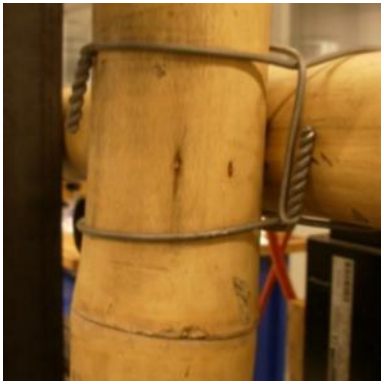


Fig. 6.5 Bamboo joint with extra metal wire

6.2 Results

First the joint with a rubber intermediate was tested. In Fig. 6.1 the result of this test are presented. After a displacement of five centimetres the test was put on hold. The maximum absorbed force did not reached the 1 kN. Due to the intermediate the bamboo stems were sliding even more than without the rubber, see Fig. 6.7. However, the green line in Fig. 6.1 is much thinner, because the rubber is damping these small scale movements.

The second joint tested had an extra wire in the perpendicular direction. The result is shown in Fig. 6.2. The maximum force absorbed within the eight centimetres displacement is 3,5 kN. The sliding of the bamboo stems occurred in the same way as in the first test as described in chapter 5.2, see Fig. 6.6. Additionally, the sliding made a tapping noise.

6.3 Conclusion

In Fig. 6.3 the result of the first test described in chapter 5 and the results of the two improved nodes are combined in one graph. From this graph we can conclude that adding rubber to the joint will not improve the joint. The addition of an extra metal wire on the other hand indeed shows an improvement. Unfortunately, the joint is still not capable of transmitting the calculated 26,7 kN. Therefore, it is advisable to make use of the Chinese method until a better solution is found.

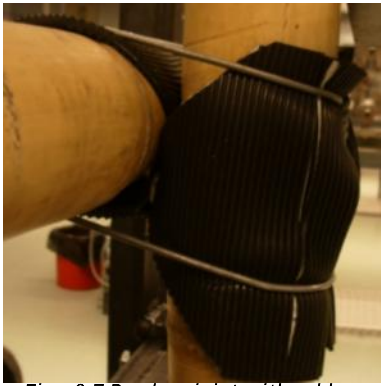


Fig. 6.7 Bamboo joint with rubber intermediate ater the pressure test

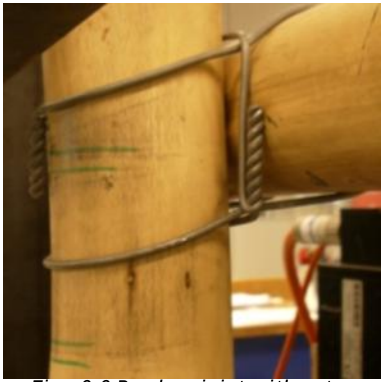


Fig. 6.6 Bamboo joint with extra metal wire after the pressure test

7 Conclusions and Recommendations

The goal of this research was to develop a building product or detail that supports the development of a sustainable and affordable house for the lower income groups in Santa Cruz de la Sierra. The building product should be locally available, not harm the environment, deal with the local conditions, be culturally accepted, stimulate a community based process and maybe even develop a local economy.

Bamboo was found to be the best option for these criteria. The bamboo species Guadua Chachoensis is locally available, although it is not often used as a building material. Unfortunately, bamboo has to be protected against fungal attack. Therefore, chemical preservation liquids, like Borax, are necessary. Preferably, research into non-chemical preservatives should be done, so a more environmental friendly product can be realised. When using bamboo as a building material in a semi-tropical climate, the bamboo has to be raised above the ground, protected against rain and have enough air run through it for ventilation. Adequate detailing can significantly prolong the lifespan of the bamboo construction.

Cultural acceptance of Bamboo could be difficult. Therefore, it is recomended to introduce bamboo slowly. First, only the roof construction could be made out of bamboo. Later on, a mix of known materials with bamboo can be proposed. Bamboo could function as a construction, but it does not have to be visible from the outside. Finally, a bamboo house with a brick raincoat and metal roof sheets or ceramic roof tiles could be proposed. The upper walls, the windows, the doors and the floors can be made out of bamboo. When choosing the Delft wire lacing jointing technique the culturally acceptance is also taken into account. The metal wires give a more modern look than ropes and the technique is not difficult to learn.

When introducing bamboo as building material, the community based process as well as the development of a local economy can be stimulated. With the Delft wire lacing jointing technique, the local people learn a new method of construction. A small group of people can be taught to learn how to construct and spread the knowledge under the community. When the houses are constructed the families can not only easily extend their own houses, but also earn money by helping constructing houses for other families.

Bamboo can also be cut into stripes and woven into mats. These mats can be used to close the upper part of a wall, form a reinforcing layer in a prefabricated cement facade panel, or glued with a resin to each other and pressed into roofing sheets. The waving of bamboo stripes, prefabricating cement panels and fabricating roofing sheets are all opportunities for the development of employment. Additionally, these new building materials could lead to a diversification of the building material market.

The bamboo species Guadua Chacoensis does not have an invasive root system and therefore it could be possible to plant the bamboo in the gardens of the families who work with and live in bamboo structures. This will provide the families with their own building materials which grow in their back yards. However, it is recommendable to consult a specialist to investigate whether the planting of bamboo on the parcels is feasible and realistic.

Bamboo is an interesting building material, but needs more research, especially in jointing techniques. As concluded in chapter six the proposed node in this thesis needs to be further developed. Further research with this technique could be done by testing different types of metal wires or adding more wires to one joint. Additionally, different people could be asked to construct this type of node, to research if the builder of the node influences the quality of the node. Next to research into this type of jointing alternative joints could also be developed. Jules Janssen stated in his book designing and building with Bamboo, that bamboo can only become a proper building material when the problems of jointing is satisfactorily addressed. (17)

Before realising a construction with the proposed jointing technique and Chinese construction method, prototyping tests are advisable. Preferably, the prototype can be constructed in Santa Cruz to not only test whether the construction is constructible, but also to know if the knowledge of constructing can be transferred easily. Additionally, the construction can be tested on stability during strong winds.

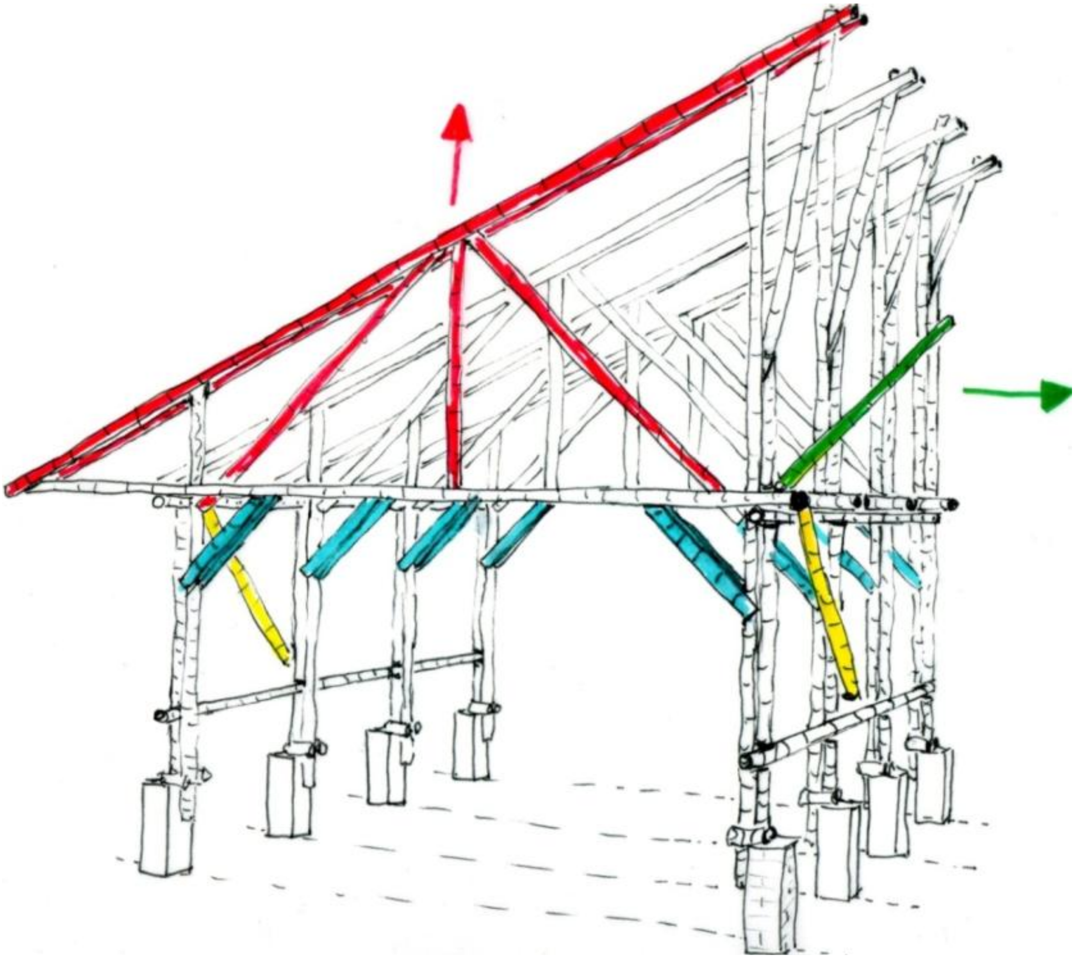


Fig. 7.1 possible construction made with the proposed jointing technique and the Chinese construction method

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Appendix A Visualisation of the 12 family interviews

Family 1

Original local family in a new neighbourhood
Family members: 5
Period of occupation: 6 years
% Built up area: 11,3

On the left the old kitchen which is located behind the first construction. This kitchen is no longer in use, because of the large number of holes in the roof.

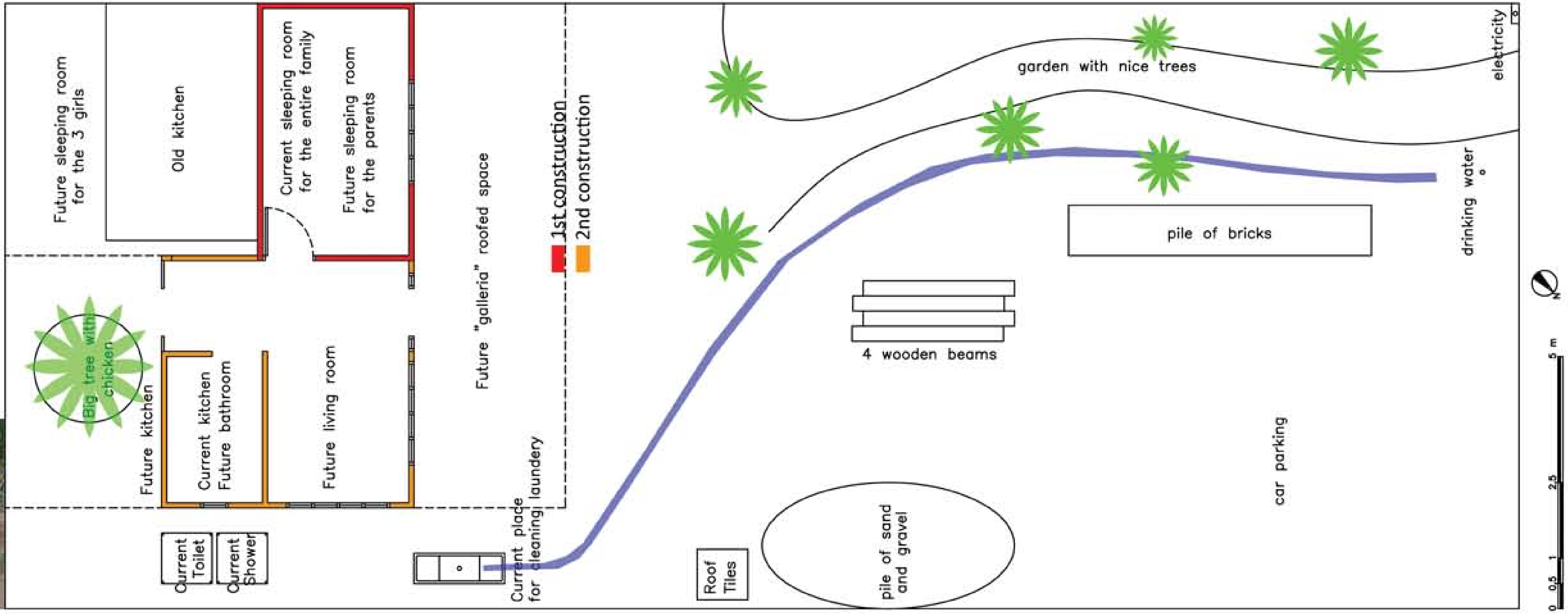
On the right the current kitchen, which will be used as bathroom in future.

Living room from inside

The uncovered brick structure is the second construction, which is still not finished. It contains a living room and a future bathroom which is used as kitchen nowadays.

The white structure is the first construction, which was made directly with bricks and tiles and has a multifunctional usage.

The building materials which are already bought for future constructions.



Family 2

Migrant family in a new neighbourhood
Family members: 7
Period of occupation: 9 years
% Built up area: 21,2

The bathroom is still not finished, but it is already in use.
In front is the cleaning place for laundry

A picture taken from the entrance

The temporary construction made of wood, metalsheets and plastic. These materials once served as materials for the family's first construction.

The "galleria" with a cement floor.

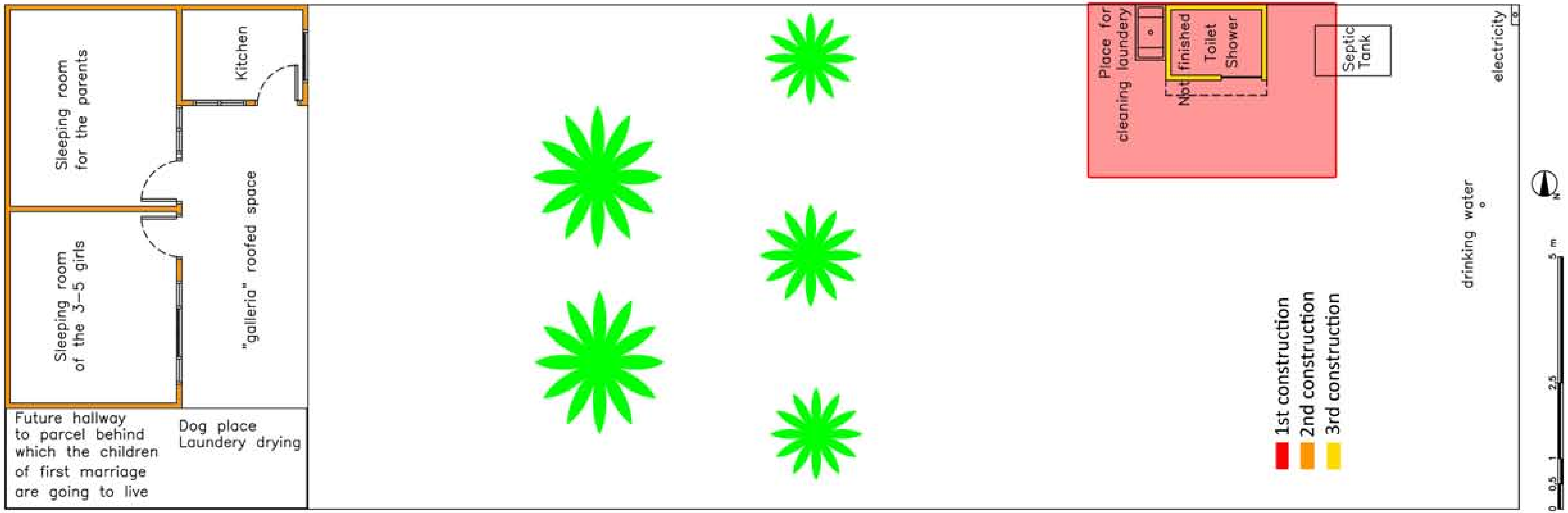
Living room

One construction consisting of two rooms and a kitchen. In front of the rooms is a roofed space "galleria" is constructed to provide shadow.

At the left, fibre cement plates which are used as roof material for the kitchen and steel plates are used as roof material for the "galleria".

The windows have no glass, because of a lack of funding.

The water tap



Family 3

Migrant family in a new neighbourhood
Family members: 1
Period of occupation: 7 years
% Built up area: 7,8

The back facade. Exterior view

The back facade. Interior view

The interior of room 1

Interior of room 2.
Electricity comes from the neighbours.

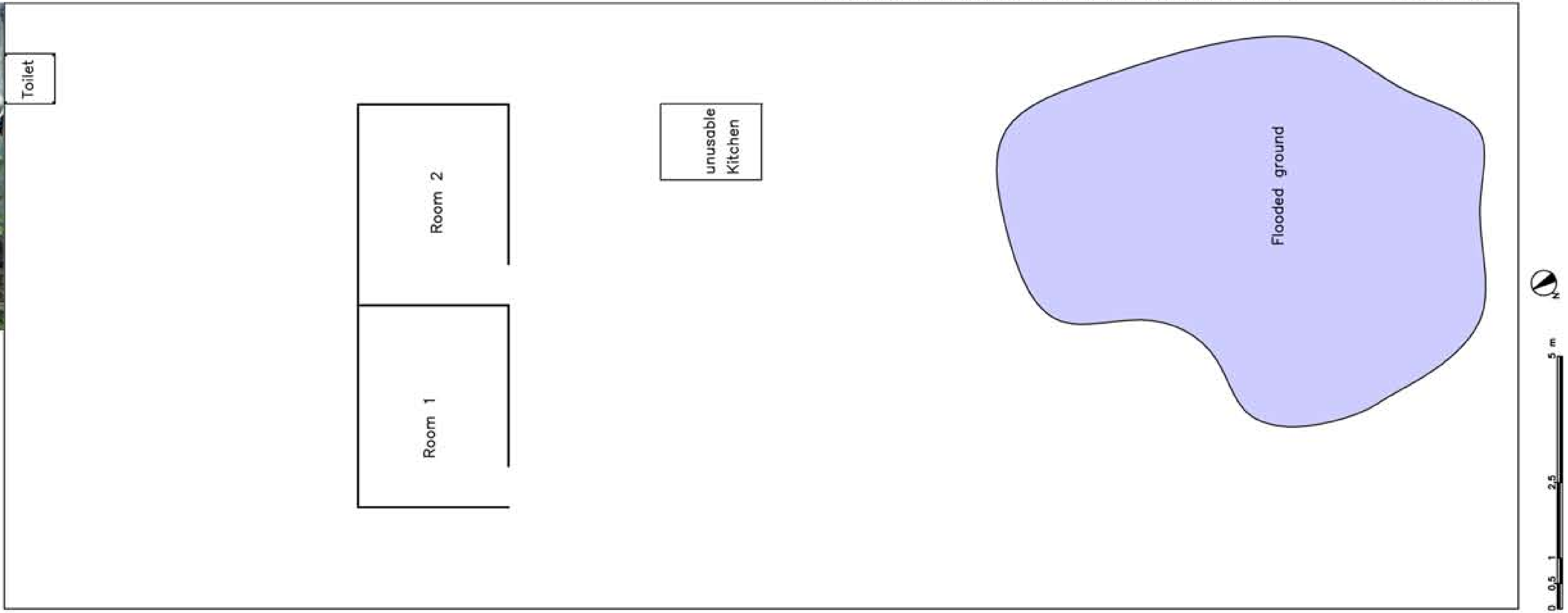
One of the two rooms made of plywood, plastic and steel sheets

The flooded garden

A fallen adobe wall

The toilet

The fallen kitchen, the owner gets food from his neighbour or buys it on the street.



Family 4

Migrant family in a new neighbourhood
Family members: 5
Period of occupation: 12 years
% Built up area: 15,0

The shower and toilet. A gift from an NGO

The second construction is still unfinished.
In the back a plastic roofed space for recycled bottles

The first construction made with
bricks and plaster. It has a multifunctional usage.
Cooking takes also place here

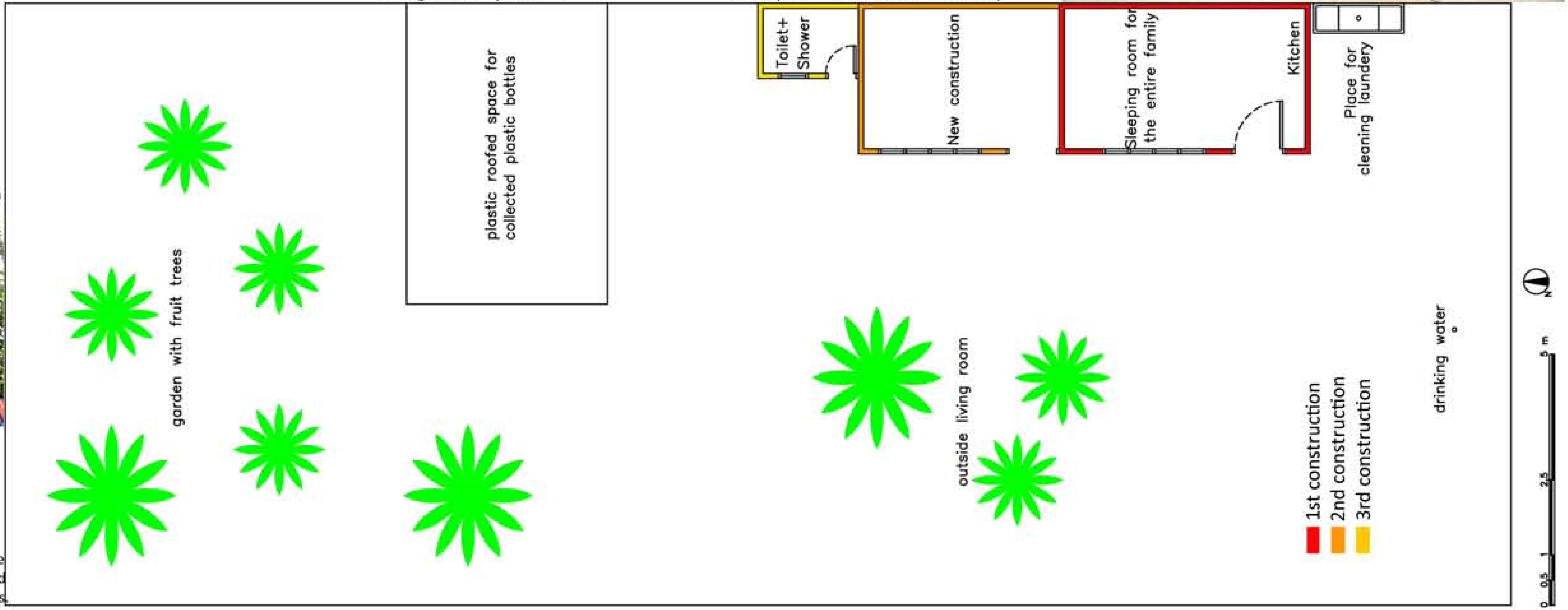
Laundry place. At the left a disconnected
wire from the electricity can be seen.
The bicycle is from the father of the family

Outside living room

water tap

Natural products from own garden

The materials that have
already been purchased
for future constructions



Family 5

Original local family in a consolidated neighbourhood
Family members: 4
Period of occupation: 16 years
% Built up area: 16,1


2nd construction made of bricks and metal roof sheets. First construction does not exist anymore


Kitchen, the third construction; on the same spot as where the first construction was.


A paved patio for neighbourhood reunions.


An altar

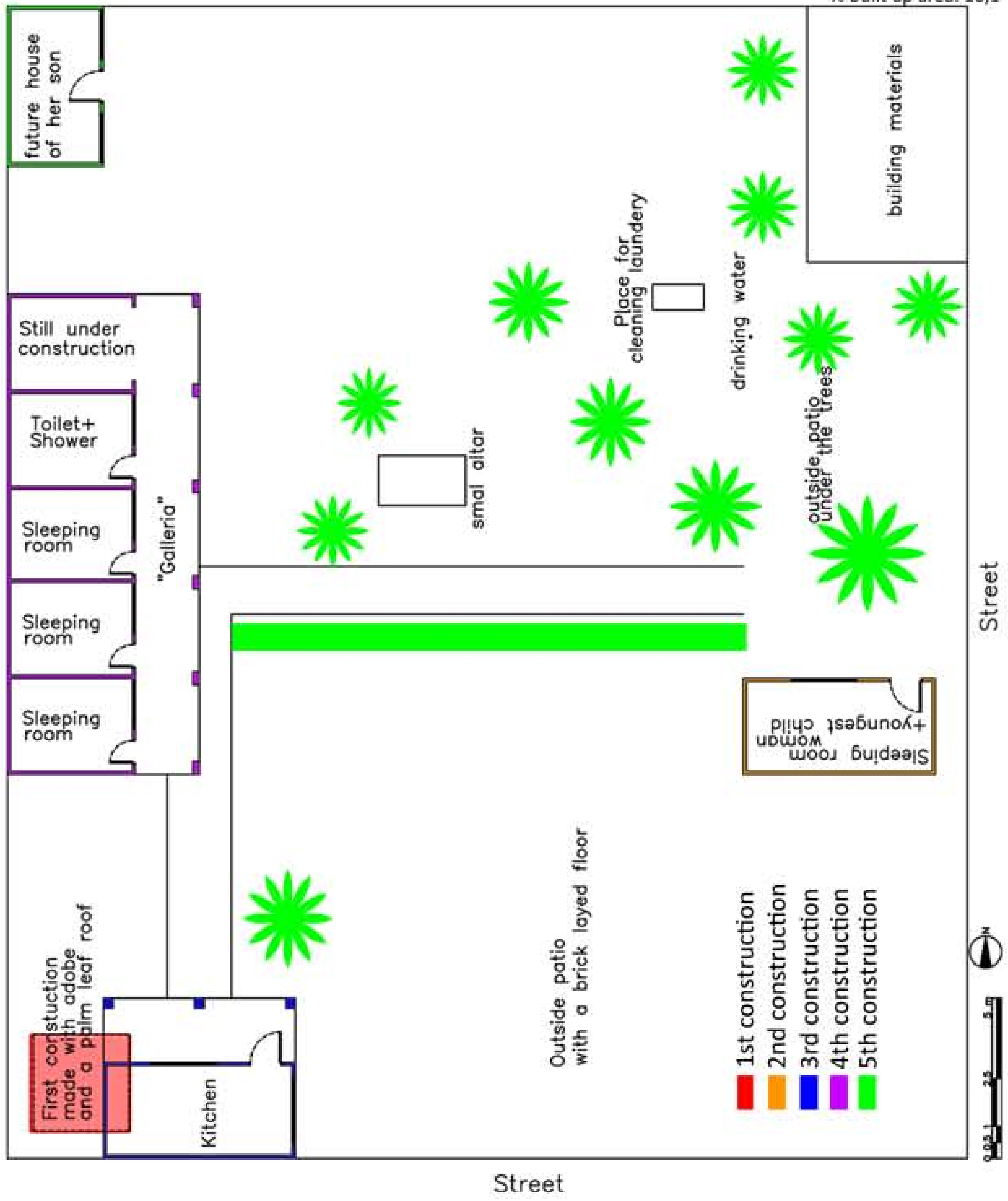

The newest construction for the son of the owner.


Three rooms, a bathroom and a "galleria" in front.


A water tap with a laundry spot


Different trees and in the back building materials.


Meeting place in the shadow



Family 6

Original local family in a consolidated neighbourhood
Family members: 10
Period of occupation: 18 years
% Built up area: 19,6


The owner working in his workshop.


In front the outside living room and at the back the workshop


The big tree provides a lot of shade and creates living space.

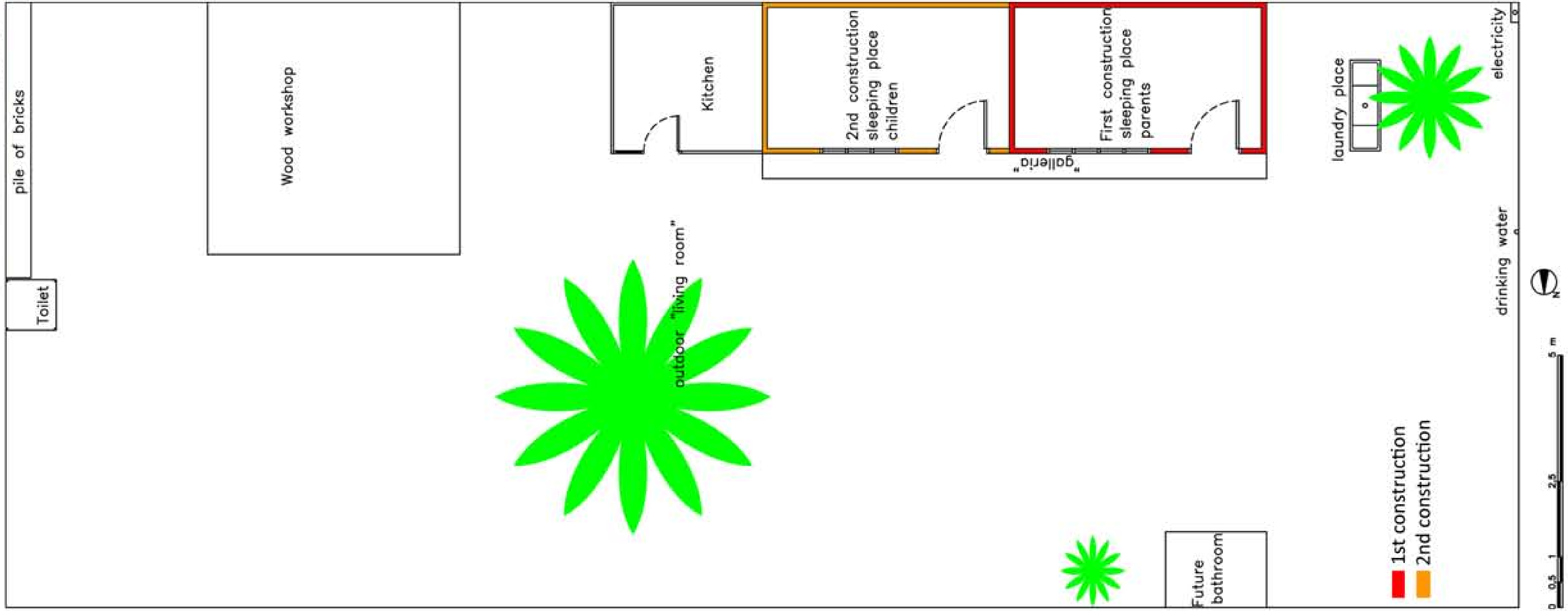

Temporary kitchen


The first two constructions made with bricks and steel plates. They are used as bed rooms.


The current toilet


The domestic animal


Future bathroom will be constructed here



Family 7

Migrant family in a new neighbourhood
Family members: 5
Period of occupation: 15 years
% Built up area: 25,3

The water tap, in front of the kitchen

The old Kitchen

The laundry place in front of the bathroom

The Toilet and Shower

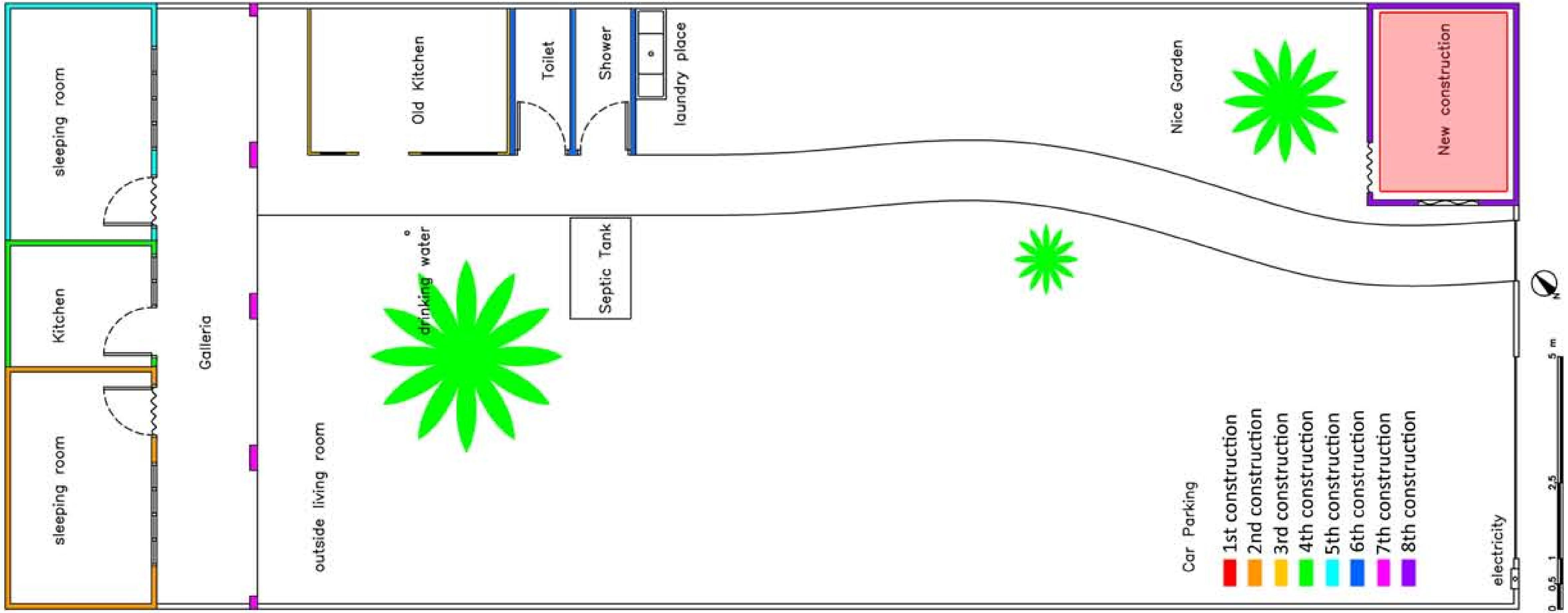
The newest construction

The owner in front of her house

The entrance path with nice garden

Drying of the Laundry

The car parking



Family 8

Original local family in a new neighbourhood
Family members: 6
Period of occupation: 1 year
% Built up area: 8,9


The 'garden' north-west of the house


The laundry place next to the toilet and shower

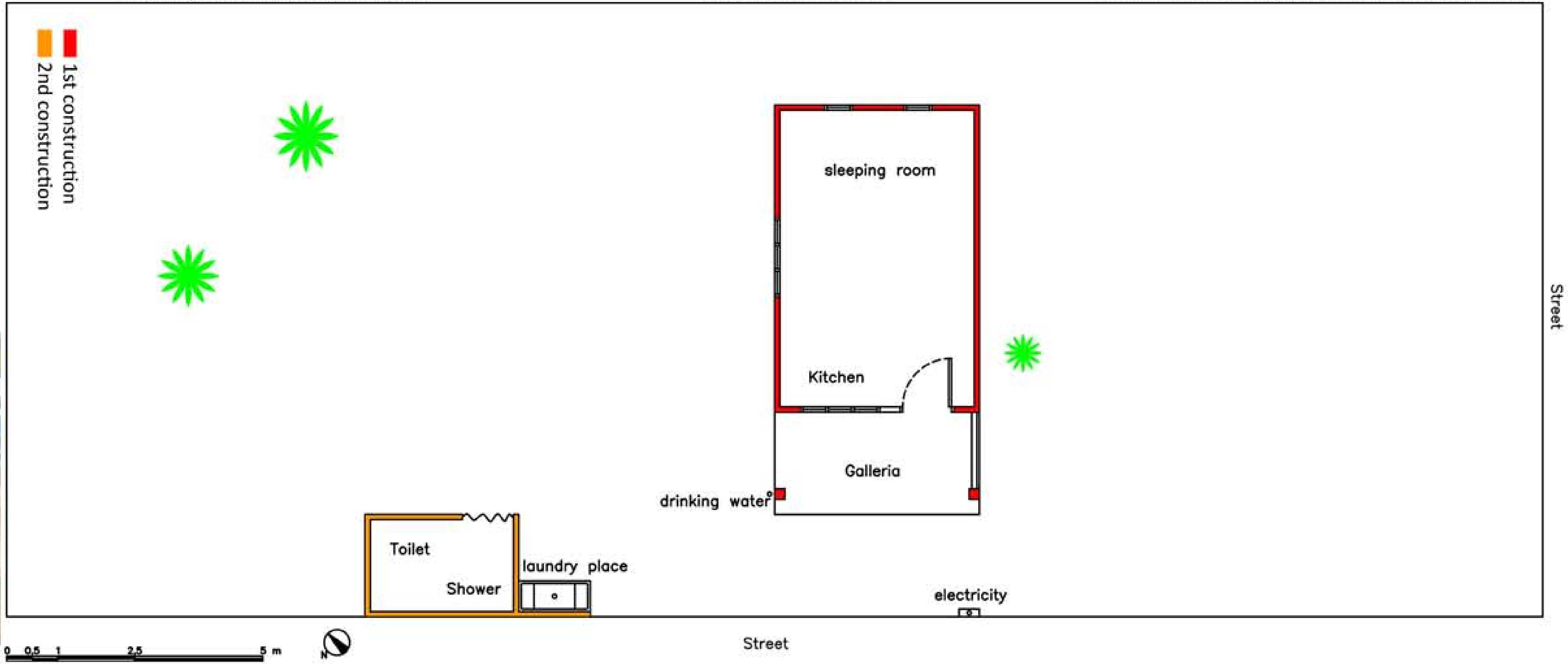

The renter under her galleria


The owner rents his house to this family untill the house is finished


The 'garden' south-east of the house


Behind the house


The water tap



Family 9

Migrant family in a consolidated neighbourhood
Family members: 3
Period of occupation: 7 years
% Built up area: 31,0

The Youth centre/living room

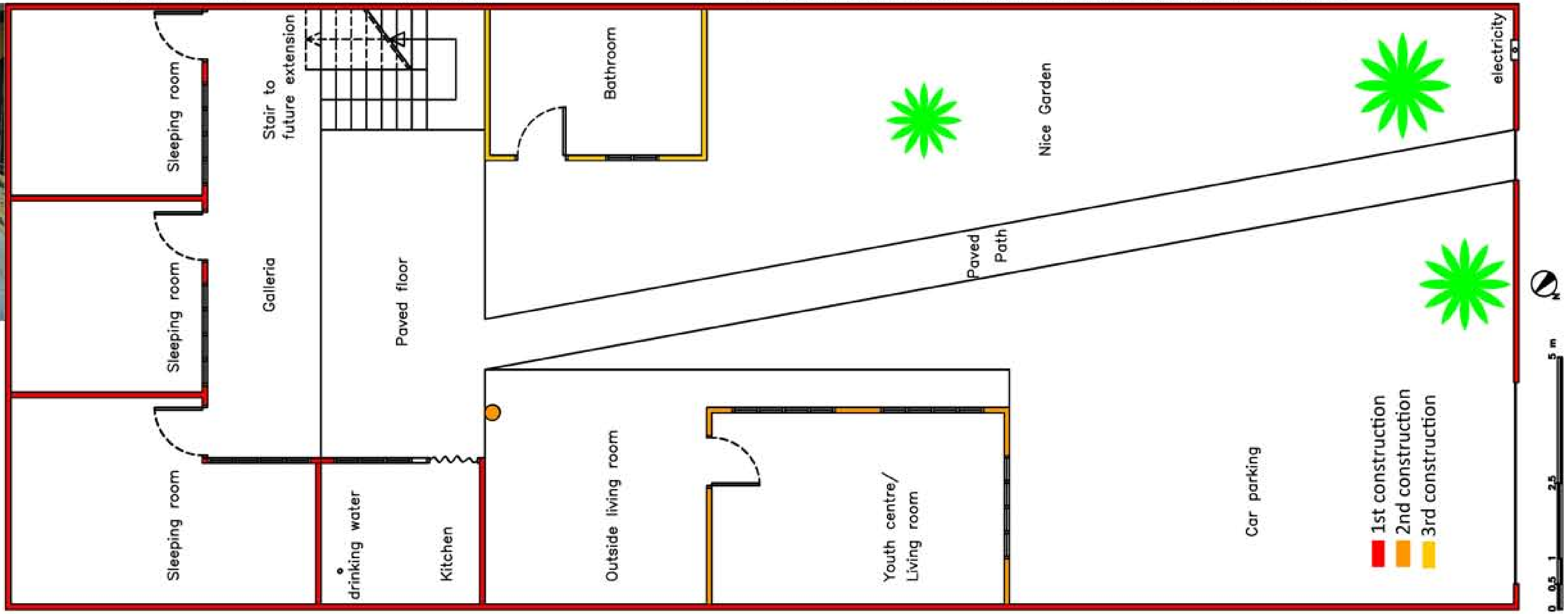
The outside living room

The kitchen

The first construction with 3 rooms and a kitchen a stair already leads to a future second floor

The paved path

The nice garden



Family 10

Migrant family in a consolidated neighbourhood
Family members: 7
Period of occupation: 20 years
% Built up area: 23,3

The interior of the kitchen

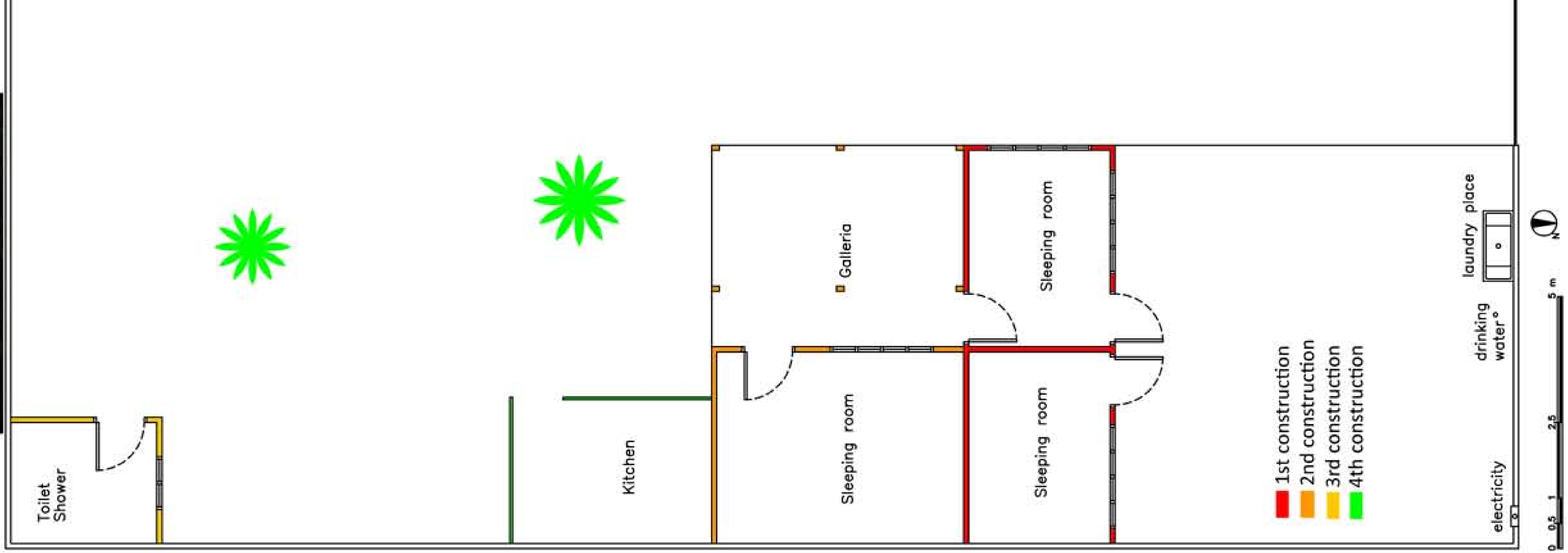
The kitchen

On the right the kitchen, on the left the gallery

The first construction with 2 rooms

The Gallery or outside living room

The toilet and shower in the back



Family 11

Original local family in a new neighbourhood
Family members: 4
Period of occupation: 1 year
% Built up area: 11,4

Water problem to the right of the house

The shower

The facade of the kitchen

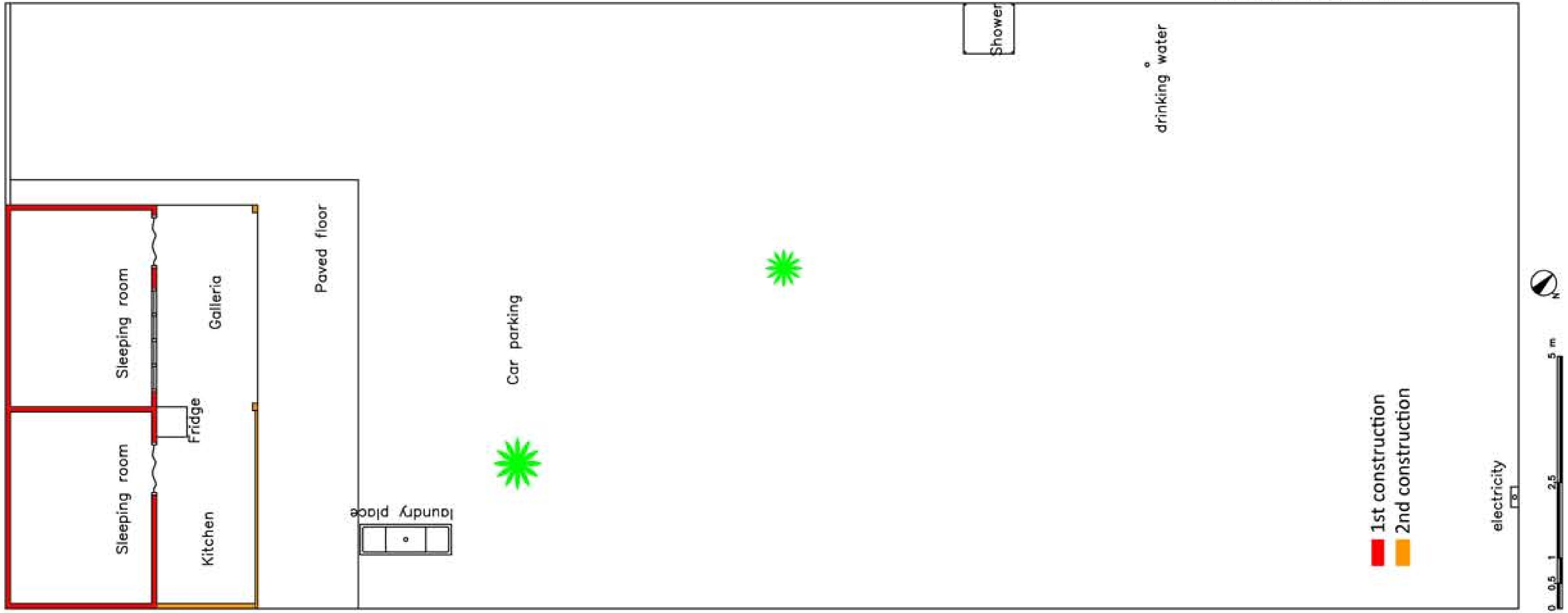
The kitchen

The entrance to the right room

The owner in front of her house

The laundry place

A view from the house towards the street



Family 12

Original local family in a new neighbourhood
Family members: 5
Period of occupation: 4 years
% Built up area: 8,9

The toilet and shower

The laundry place behind the house

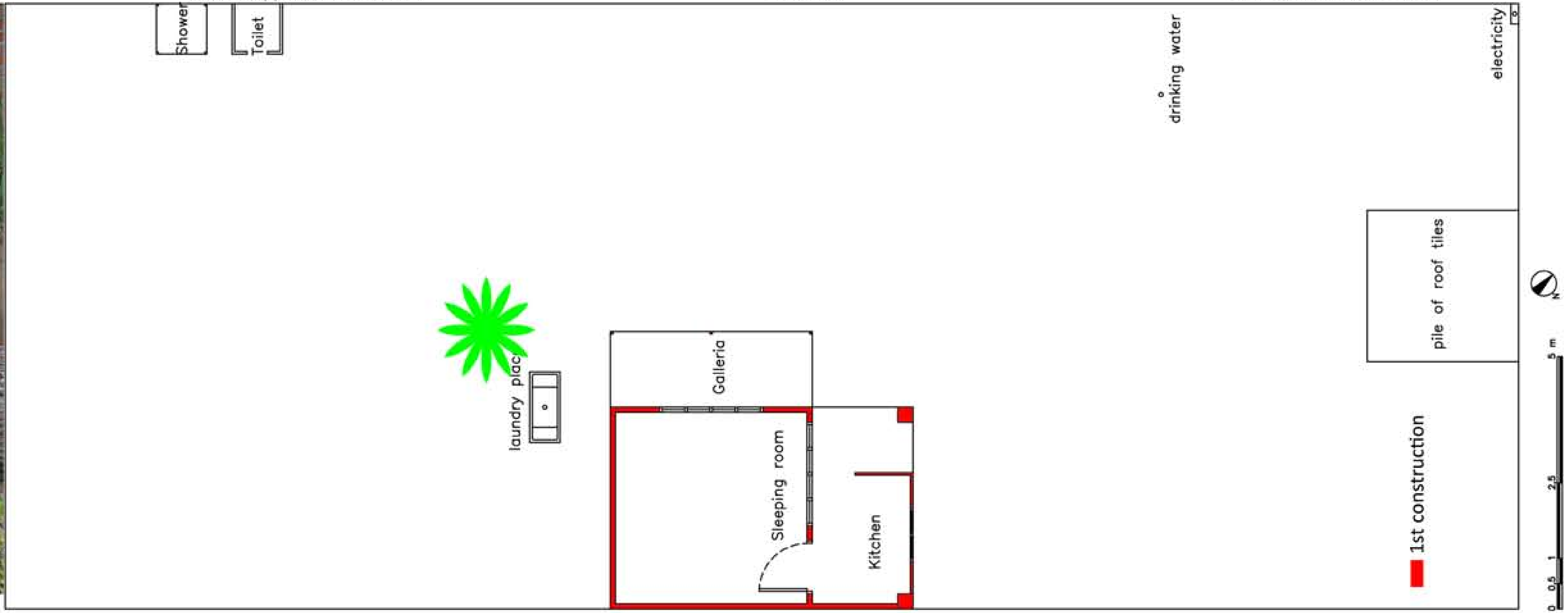
The kitchen

The owner in front of her house

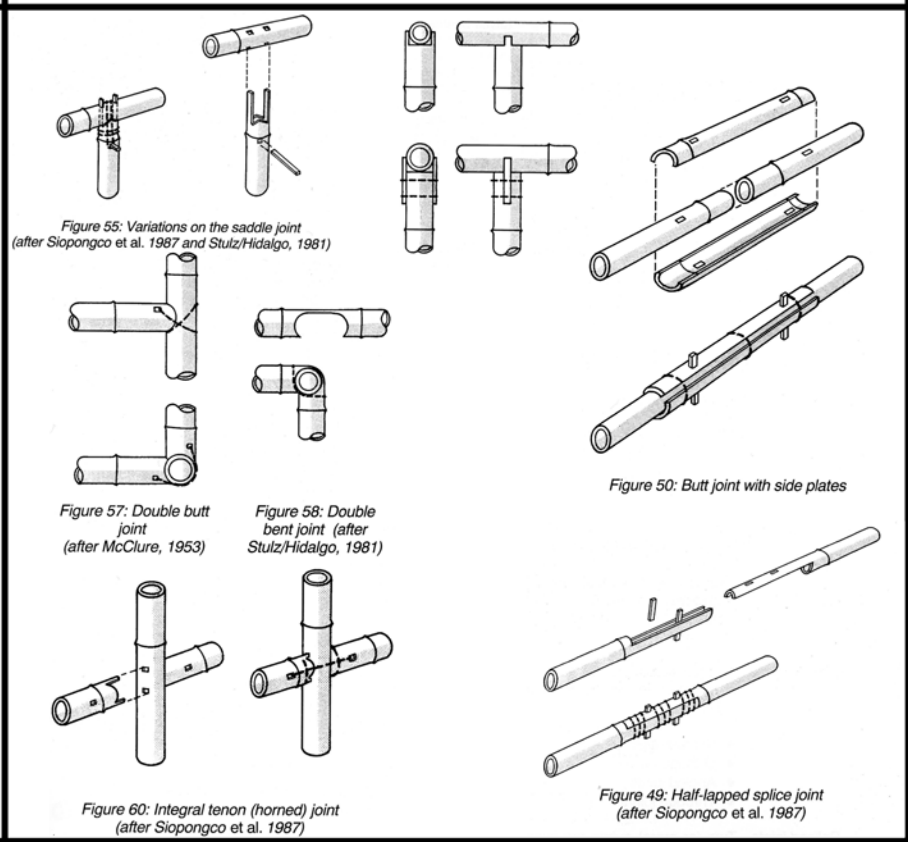
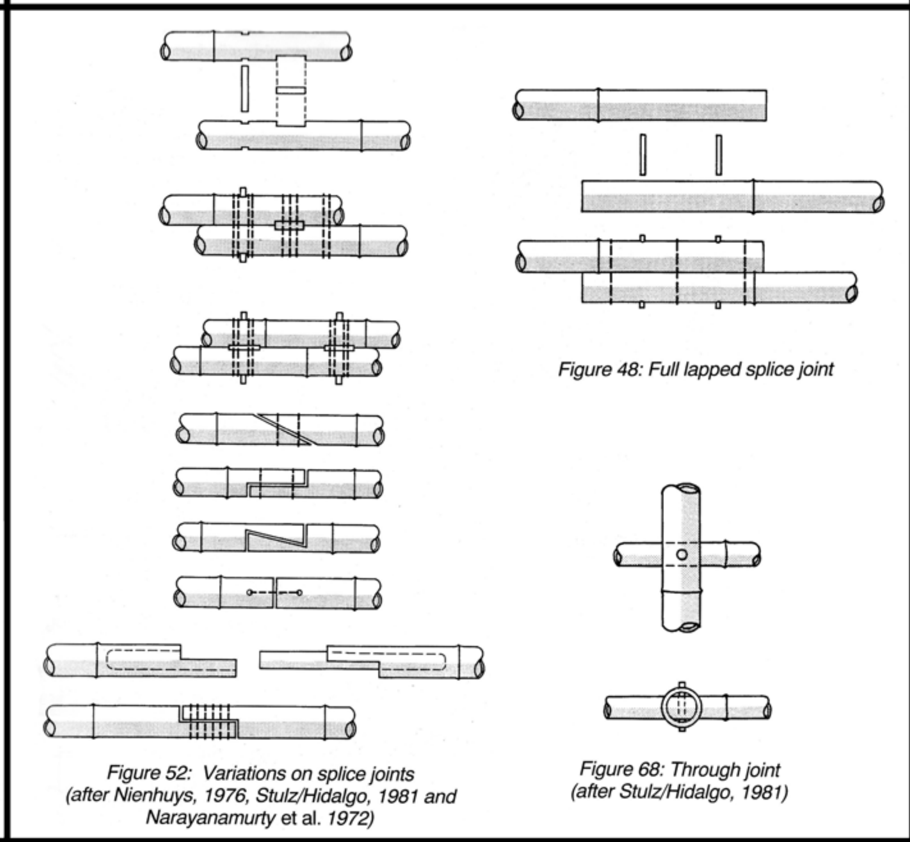
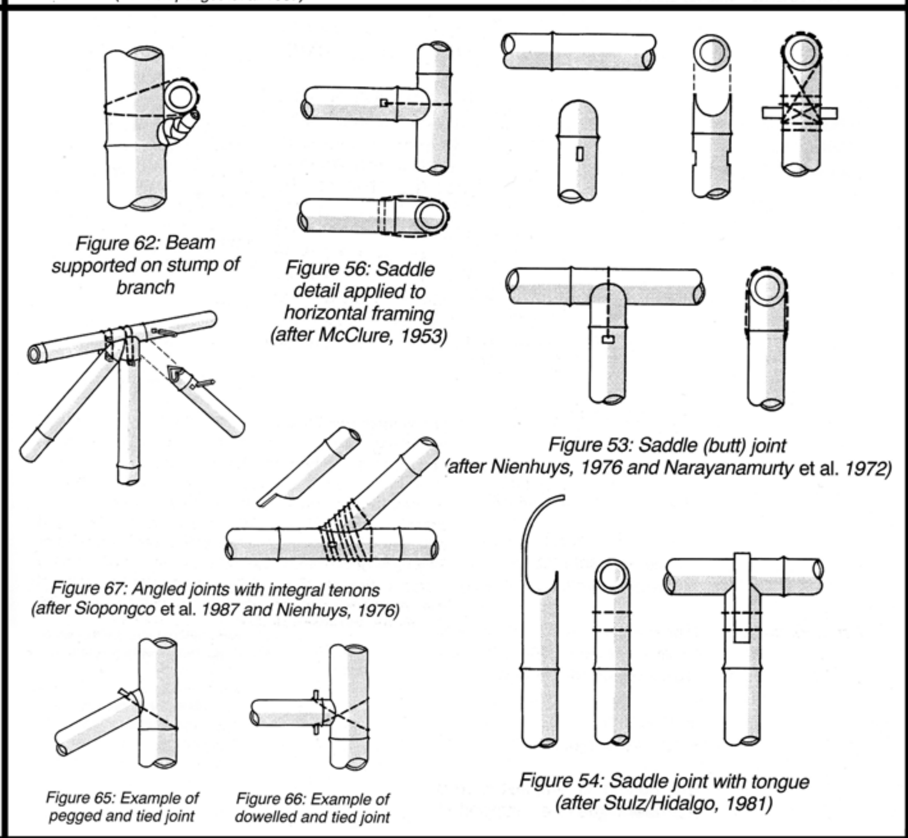
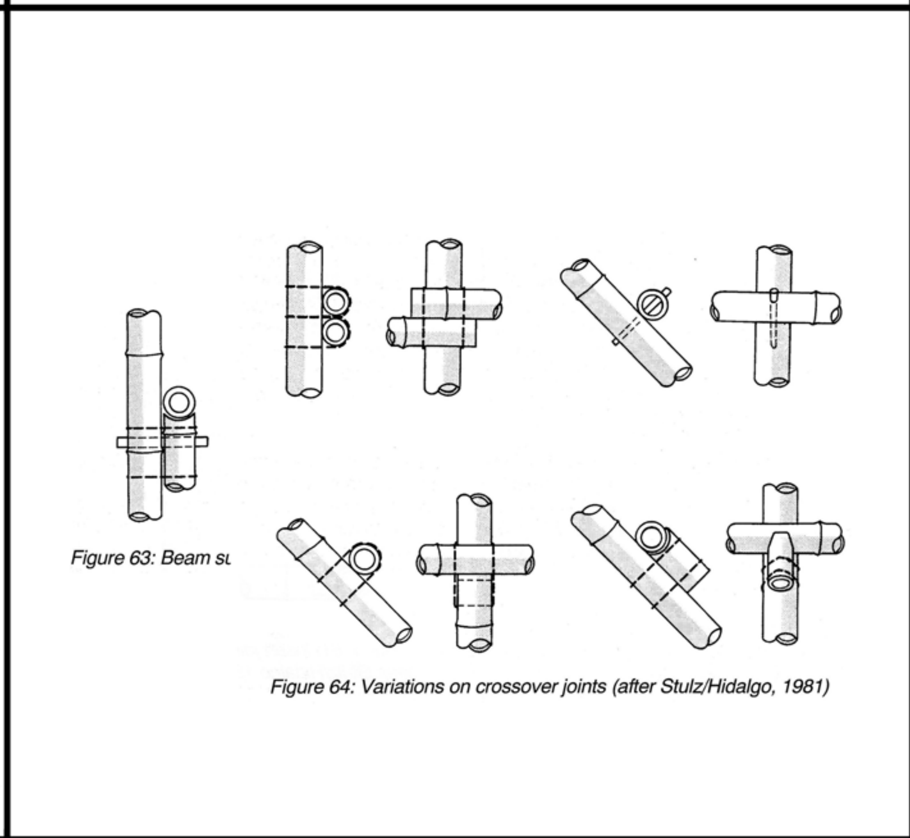
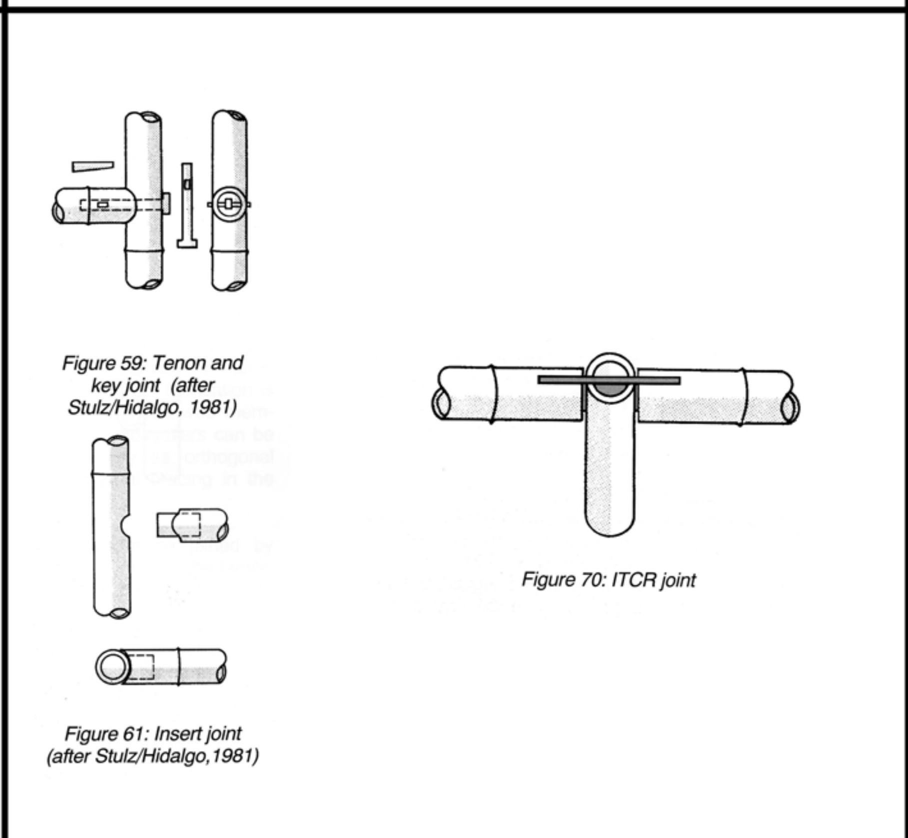
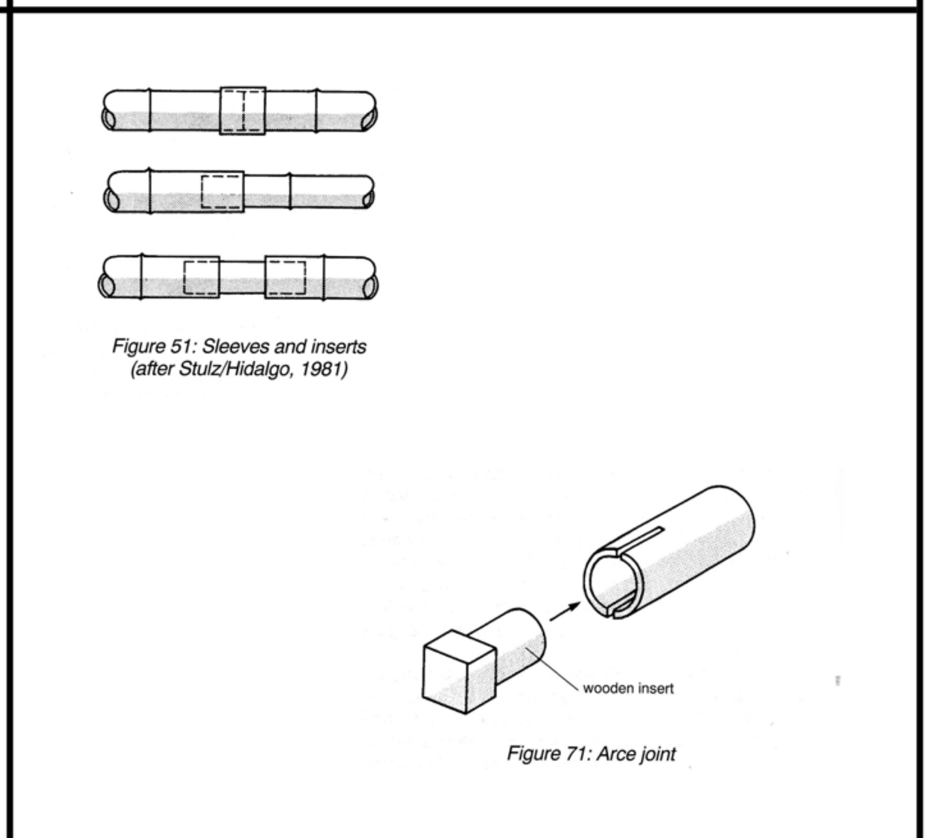
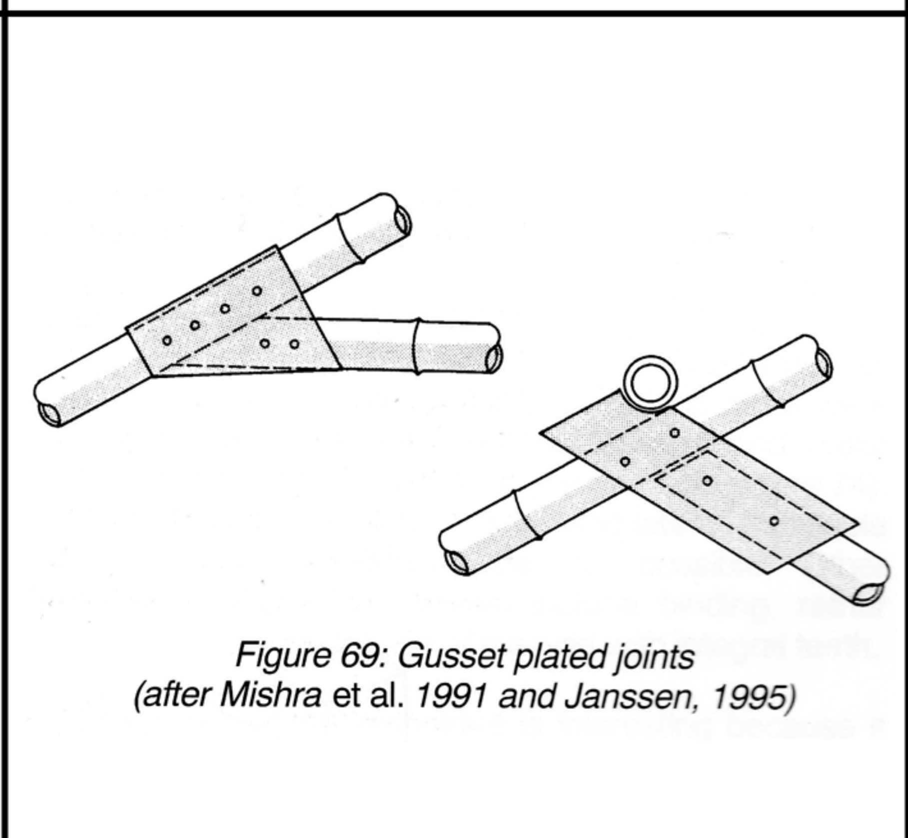
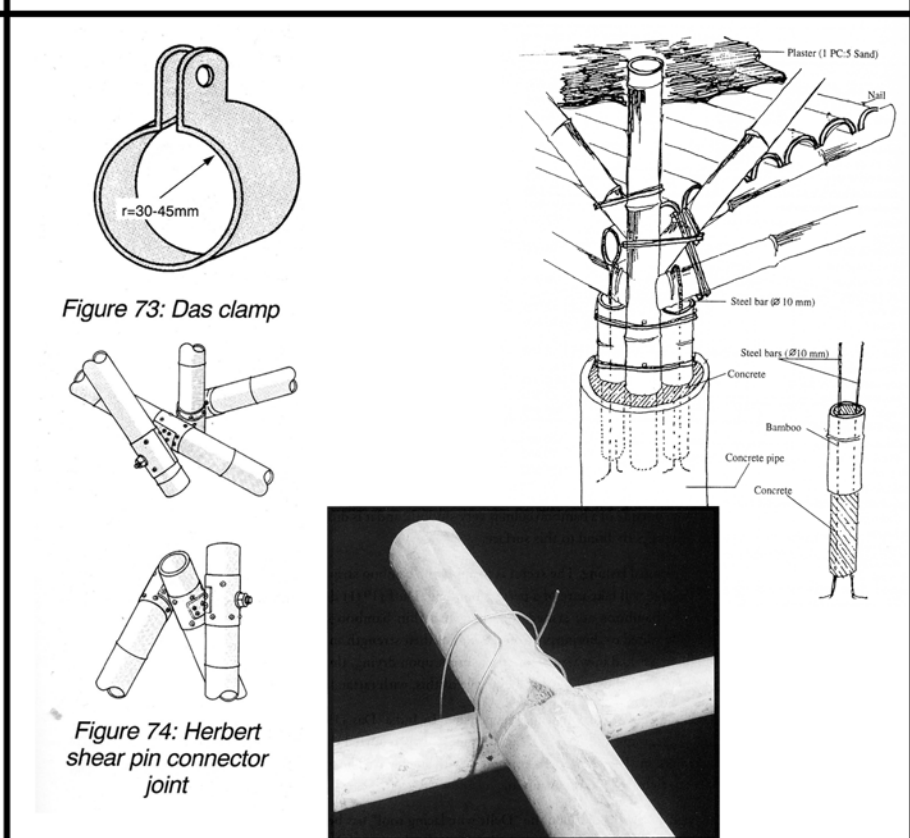
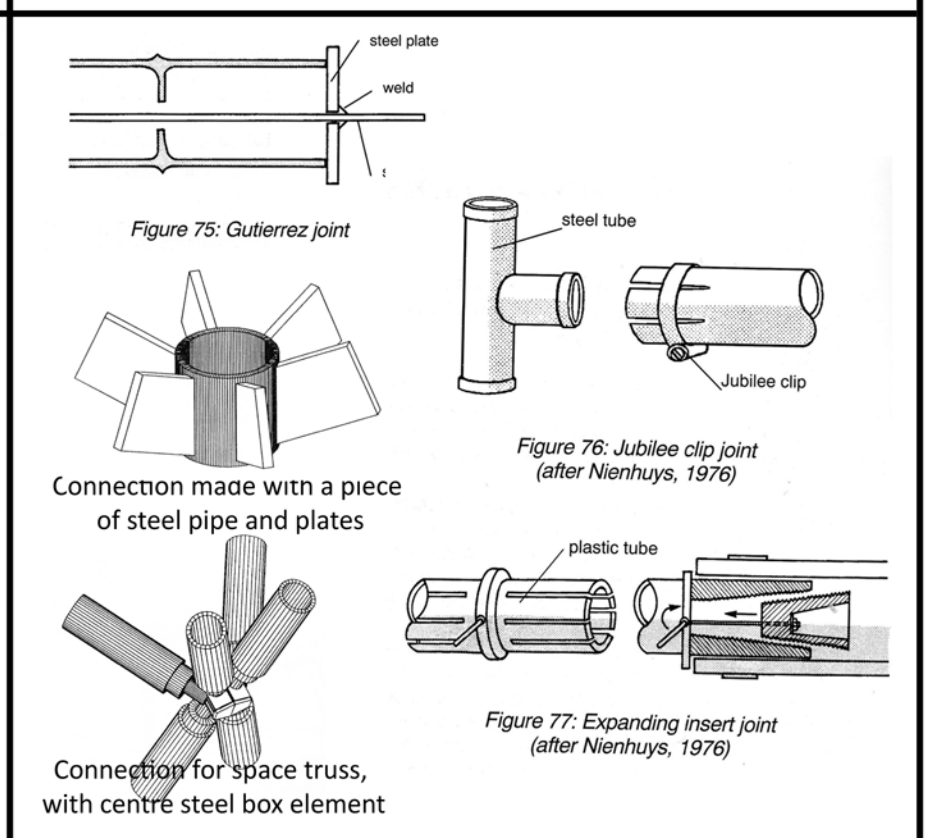
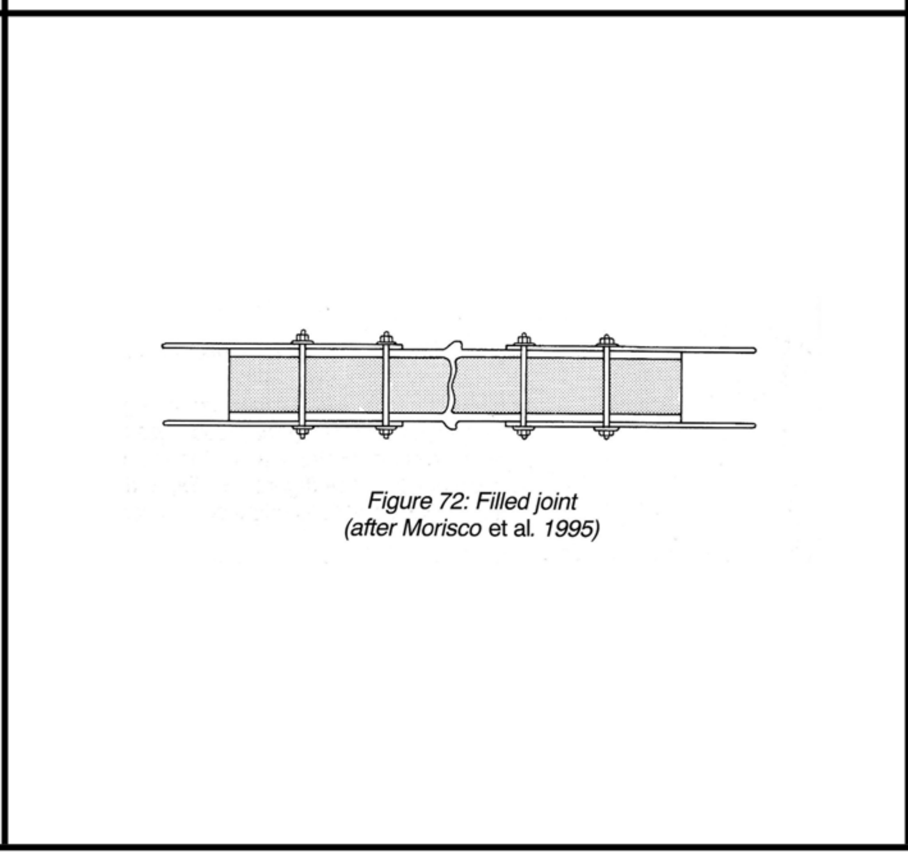
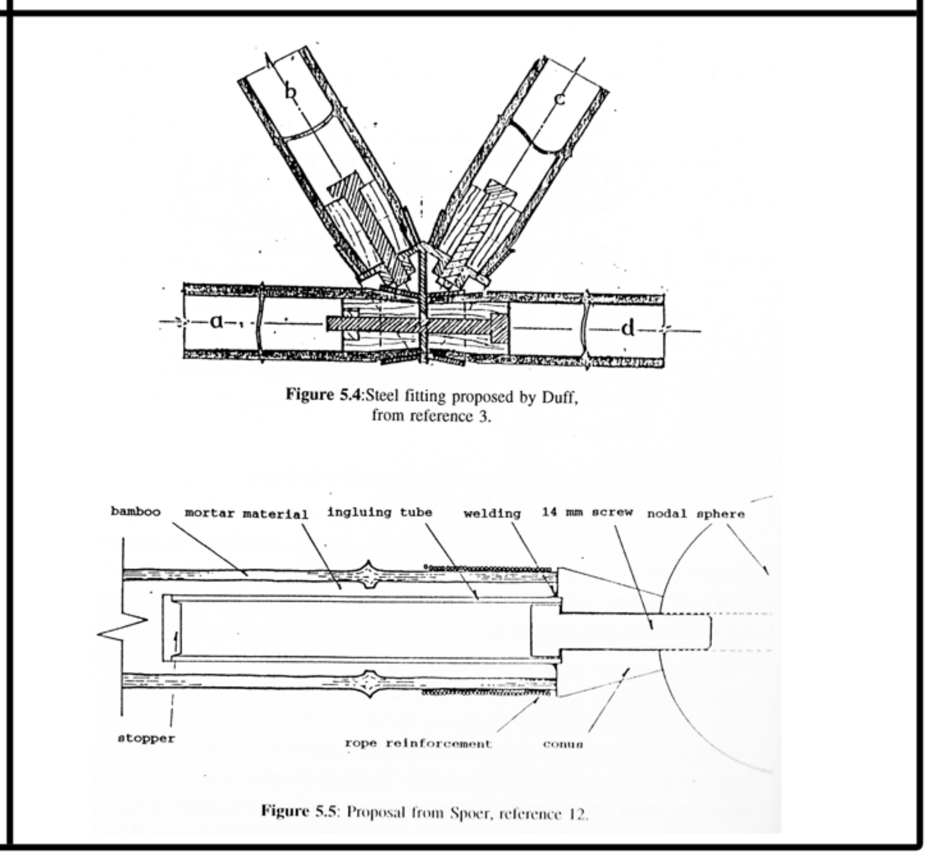
Water problem behind the house

Pile of roof tiles

Water tap



Appendix B Bamboo jointing techniques

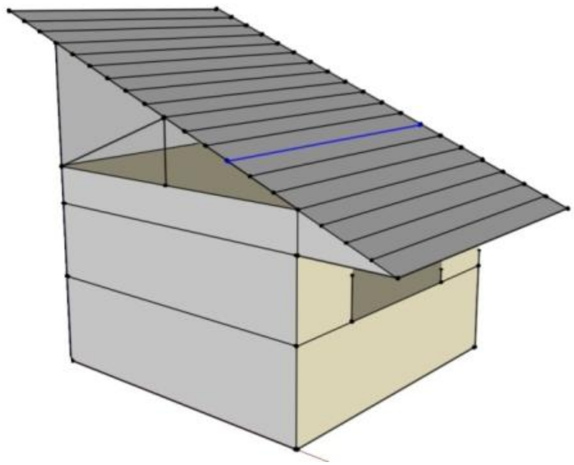
	In/op elkaar	Langs elkaar	Los van elkaar
Bamboe	 Figure 55: Variations on the saddle joint (after Sipongco et al. 1987 and Stulz/Hidalgo, 1981) Figure 57: Double butt joint (after McClure, 1953) Figure 58: Double bent joint (after Stulz/Hidalgo, 1981) Figure 50: Butt joint with side plates Figure 60: Integral tenon (horned) joint (after Sipongco et al. 1987) Figure 49: Half-lapped splice joint (after Sipongco et al. 1987)	 Figure 48: Full lapped splice joint Figure 52: Variations on splice joints (after Nienhuys, 1976, Stulz/Hidalgo, 1981 and Narayanamurty et al. 1972) Figure 68: Through joint (after Stulz/Hidalgo, 1981)	
Touw	 Figure 62: Beam supported on stump of branch Figure 56: Saddle detail applied to horizontal framing (after McClure, 1953) Figure 53: Saddle (butt) joint (after Nienhuys, 1976 and Narayanamurty et al. 1972) Figure 67: Angled joints with integral tenons (after Sipongco et al. 1987 and Nienhuys, 1976) Figure 65: Example of pegged and tied joint Figure 66: Example of dowelled and tied joint Figure 54: Saddle joint with tongue (after Stulz/Hidalgo, 1981)	 Figure 63: Beam su Figure 64: Variations on crossover joints (after Stulz/Hidalgo, 1981)	
Hout	 Figure 59: Tenon and key joint (after Stulz/Hidalgo, 1981) Figure 70: ITCR joint Figure 61: Insert joint (after Stulz/Hidalgo,1981)		 Figure 51: Sleeves and inserts (after Stulz/Hidalgo, 1981) Figure 71: Arce joint
Staal	 Figure 69: Gusset plated joints (after Mishra et al. 1991 and Janssen, 1995)	 Figure 73: Das clamp Figure 74: Herbert shear pin connector joint	 Figure 75: Gutierrez joint Connection made with a piece of steel pipe and plates Figure 76: Jubilee clip joint (after Nienhuys, 1976) Connection for space truss, with centre steel box element Figure 77: Expanding insert joint (after Nienhuys, 1976)
Beton	 Figure 72: Filled joint (after Morisco et al. 1995)		 Figure 5.4: Steel fitting proposed by Duff, from reference 3. Figure 5.5: Proposal from Spoer, reference 12.

Appendix C Calculation of the construction

To be sure the constructions of the houses proposed for Santa Cruz de la Sierra will have a suitable construction three parts of the construction will be calculated. First a roof beam will be calculated, which now has to span 4 meters. Secondly the truss will be calculated. Thirdly the column that leads all forces to the foundation will be calculated and the number of bamboo culms needed for one column. Additionally, a calculation of one node will be made, to know the forces passing through the nodes. In this way the node tests can be better analysed.

Part 1 Roof beam

The roof beams are supported by two trusses and joined with the steel wire lashing method. (In the drawing on the right the blue line represents one roof beam.) The roof beams have to carry a permanent load of the colonial tiled roof placed in cement.



Beam properties; Guadua Chancoensis

Length L = 4000 mm

Own assumptions:

Diameter ø = 80mm

Wall thickness d = 15 mm (thickness bamboo stem from joint experiments)

$A = 3{,}1 * 10^3\ mm^2$

$= 3{,}1 * 10^{-3}\ m^2$

$I = 1{,}70 * 10^{-6}\ m^4$

$W = 38 * 10^{-6}\ m^3$

$\rho = 700\ kg/m^3$

From an investigation done by two students of the Linköping's University in Sweden the Young's modulus, tensile strength are deducted and the standard deviation within the tested bamboo. (16)

$E = 11185\ MPa$

$\sigma_{pull} = 94\ MPa = 94 * 10^6\ N/m^2$

From here the allowable stress in the beam can be calculated with the calculation defined by Jules Janssen in his technical reports No. 20 of the INBAR (17):

$\sigma_{all} = (\sigma_{pull} - 2{,}33\ s) * G * D / S$

$s = 0{,}15 * 94 * 10^6\ N/m^2 : 14 * 10^6\ N/m^2$

G = practice – laboratory factor : 0,5

D = modification value for duration of load for the permanent, temporary and wind loads : 1,5

S = safety factor: 2,25

$\sigma_{all} = (94 * 10^6 - 2{,}33 * 14 * 10^6) * 0{,}5 * 1{,}5 / 2{,}25 = 20 * 10^6\ N/m^2$

$\tau_{all} = 0{,}003 * \rho = 2{,}1\ N/mm^2$

From this data we can calculate the maximum moment, shear stress and movement:

$M_{all} = \sigma_{all} * W = 0{,}76\ kNm$

$V_{all} = \tau_{all} * A / 2 = 3{,}2\ kN$

$d_{all} = L / 250 = 6\ mm$

Permanent load on the roof slat

Own weight

Massa/m = A * ρ = 2,2 kg/m

F = m * g = 1,5 * 10 = 22 N/m = 0,022 kN/m

Extern

Per meter around 10 roof tiles lie on a roof slat. One roof tile weights 2,8 kg, so a distributed load of 0,28 kN/m is given by the roof tiles. Besides the roof tiles are laid in cement. Let say the roof will be covered with 3 cm cement. The roof slat will carry 0,42 m of the cement layer. Cement ρ = 2000 kg/m^3. Resulting in a equal distributed weight of 0,17 kN/m.

Roof tiles	0,28 kN/m
Cement	0,25 kN/m +
	0,53 kN/m

Permanent load: q_{perm} = 0,55 kN/m

Wind load

For the calculation of wind loads the Dutch regulations are used, because no Bolivian restrictions could be found

$p_{rep} = C_{dim} * C_{index} * C_{eq} * \Phi_1 * p_w$

C_{dim} = factor for the dimensions of the building: 0,96

C_{index} = wind factor divided in :

C_{pe} = external wind pressure: 0,70

C_{pi} = internal wind pressure: 0,3

C_f = surface is not smooth: 0,02

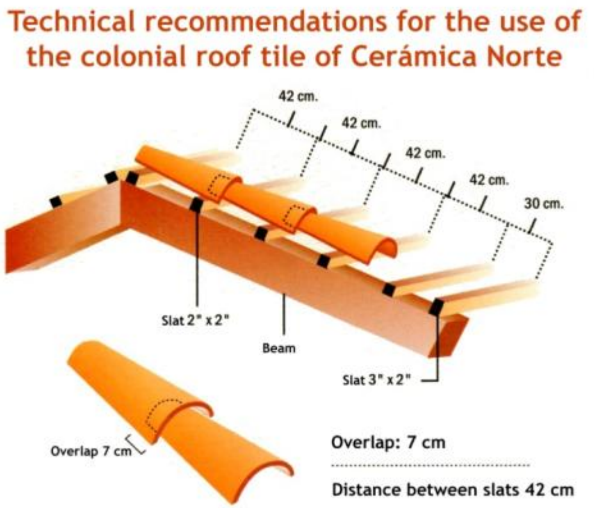
$C_{pe;loc}$ and C_t : are in this case not relevant

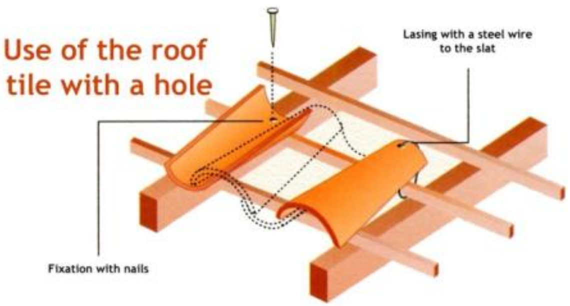
h < 50 meter and h/b < 5, so C_{eq} = 1,0 and Φ_1 = 1,0

p_w: extreme value of push pressure: 1 kN/m^2

So p_{rep} = 0,96 * 1,02 * 1,0 * 1,0 * 1,0 = 0,98 kN/m^2

q_{wind} = 0,98 * 0,42 = 0,41 kN/m





Service load
During the construction a person should be able to stand on the construction and also afterwards it should be possible to do some reparations. Therefore one roof beam should also be able to hold the weight of one person with reparation tools.
Service load Q_{rep} = 0,8 kN

Load Combinations
Ultimate limitation
Only permanent loads
UL 1 $\gamma_{fg} * q_{perm}$
γ_{fg} = 1,35 (21)
1,35 * 0,55 = 0,74 kN/m

Permanent and wind load
UL2 $\gamma_{fg} * q_{perm} + \gamma_{fq} * q_{wind}$
γ_{fg} = 1,35
γ_{fq} = 1,5
1,35 * 0,55 + 1,5 * 0,41 = 1,35 kN/m

Permanent and variable loads
UL3 $\gamma_{fg} * q_{perm}$ and $\gamma_{fq}\ Q_{rep}$
γ_{fg} = 1,35
γ_{fq} = 1,5
1,35 * 0,55 = 0,74 kN/m and 1,5 * 0,8 = 1,2 kN

Service limit
Only permanent loads
SL1 $\gamma_{fg} * q_{perm}$
γ_{fg} = 1,0
1,0 * 0,55 = 0,55 kN/m

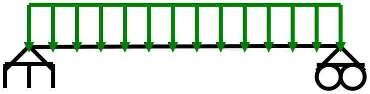
Permanent and wind load
SL2 $\gamma_{fg} * q_{perm} + \gamma_{fq} * q_{wind}$
γ_{fg} = 1,0
γ_{fq} = 1,0
1,0 * 0,55 + 1,0 * 0,41 = 0,96 kN/m

Permanent and variable loads
SL3 $\gamma_{fg} * q_{perm}$ and $\gamma_{fq}\ Q_{rep}$
γ_{fg} = 1,0
γ_{fq} = 1,0
1,0 * 0,55 = 0,55 and 1,0 * 0,8 = 0,8 kN

Calculation of the roof slat

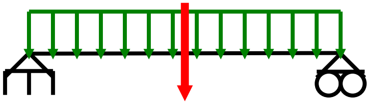
Only UL2 and UL3 will be calculated because these are the heaviest loads.

UL2



M_{act} = 1/8 ql^2 = 1/8 * 1,35 * 4^2 = 2,7 kNm
V_{act} = 0,6 ql = 0,6 * 1,35 * 4 = 3,24 kN
d_{act} = 5/384 * ql^4/EI = 5/384 * (1,35 * 4^4)/(11185 * 1,7 * 10^{-6}) = 237 mm

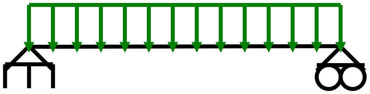
UL3



M_{act} = (1/8 ql^2) + (¼ Ql) = (1/8 * 0,74 * 4^2) + (¼ * 1,2 * 4) = 2,7 kNm
V_{act} = (0,6 ql) + (0,5 Q) = (0,6 * 0,74 * 4) + (0,5 * 1,2) = 2,4 kN
d_{act} = (5/384 * ql^4/EI) + (1/48 Ql^3 / EI) = (5/384 * (0,74 * 4^4)/
(11185 * 1,7 * 10-6)) + (1/48 (1,2 * 43)/(11185 * 1,7 * 10-6)) = 214 mm

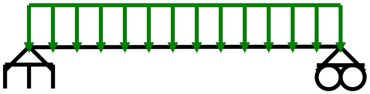
In both cases the construction will fail. Therefore a new calculation is made with a the trust supports closer together L will be 1,5 meters

UL2



M_{act} = 1/8 ql^2 = 1/8 * 1,35 * $1,5^2$ = 0,38 kNm
V_{act} = 0,6 ql = 0,6 * 1,35 * 1,5 = 1,2 kN
d_{act} = 5/384 * ql^4/EI = 5/384 * (1,35 * $1,5^4$)/(11185 * 1,7 * 10^{-6}) = 5 mm
R_{trust} = 2 * ½ ql = 1,35 * 1,5 = 2,0 kN

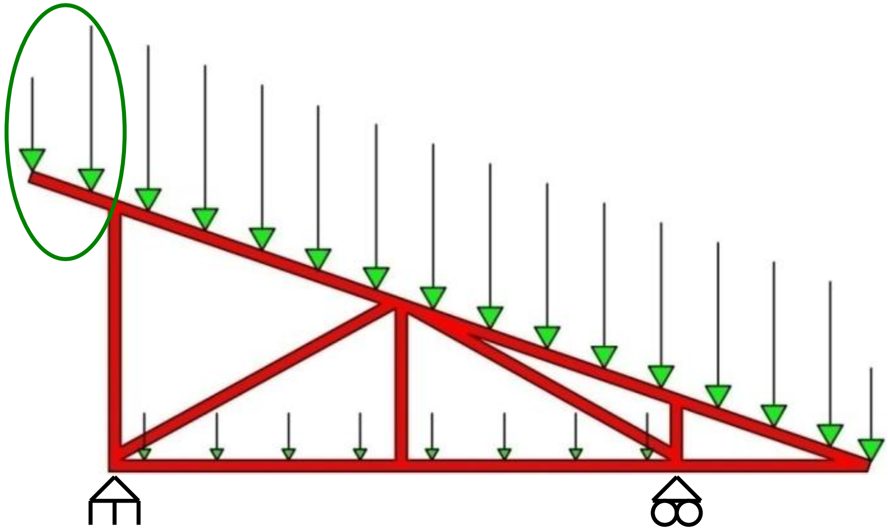
UL3



M_{act} = (1/8 ql^2) + (¼ Ql) = (1/8 * 0,74 * $1,5^2$) + (¼ * 1,2 * 1,5) = 0,66 kNm
V_{act} = (0,6 ql) + (0,5 Q) = (0,6 * 0,74 * 1,5) + (0,5 * 1,2) = 1,3 kN
d_{act} = (5/384 * ql^4/EI) + (1/48 Ql^3 / EI) = (5/384 * (0,74 * $1,5^4$)/
(11185 * 1,7 * 10^{-6})) + (1/48 (1,2 * $1,5^3$)/(11185 * 1,7 * 10^{-6})) = 7 mm
R_{trust} = ql + ½ Q = 0,74 * 1,5 + ½ * 1,2 = 1,7 kN

So the design should be changed to a denser support grid of 1,5 m. In this case the beam does not fail, only when a person goes to the roof will bend one mm more than preferable. The roof slats will not have a length of 1,5 meter, but probably 4,5 meter so in fact one roof slat is supported by 4 trusses. Thereby, bending will be lesser than calculated.

Part 2 Truss



Beam properties; Guadua Chancoensis

Diameter ø = 80mm

Wall thickness d = 15 mm

$A = 3,1 * 10^3\ mm^2 = 3,1 * 10^{-3}\ m^2$

$I = 1,70 * 10^{-6}\ m^4$

$W = 38 * 10^{-6}\ m^3$

$\rho = 700\ kg/m^3$

$E = 11185\ MPa$

$\sigma_{pull} = 94\ MPa = 94 * 10^6\ N/m^2$

$\sigma_{all} = 20 * 10^6\ N/m^2$

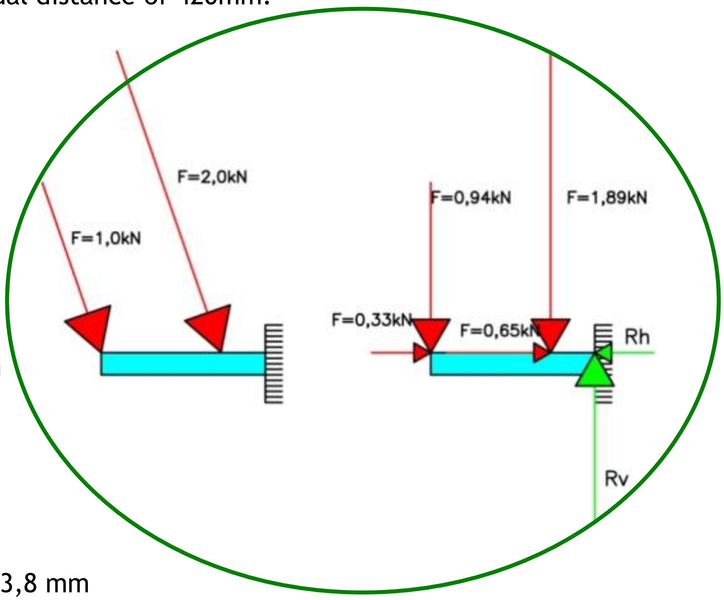
$\tau_{all} = 2,1\ N/mm^2$

$M_{all} = \sigma_{all} * W = 0,76\ kNm$

$V_{all} = \tau_{all} * A / 2 = 3,2\ kN$

The truss will be calculated with the mutual distance of 1,5 meter. The point forces from the roof slats are the reaction forces of the previous calculations and have a mutual distance of 420mm.

The truss supports not only the roof, but also the floor. The beams of the truss are made of the same bamboo culms. The truss will be schematised into a static defined truss. Therefore the forces in the extended beam will be calculated.



Because the cantilever of the beam is part of the beam the support is schematize as a restraint.
For this part we want to know the reaction forces for the following calculations of the truss and the bending and maximum moment in the extension to know if the extension will not bend to much or even break.

$R_h = 0,33 + 0,65 = 0,98\ kN$

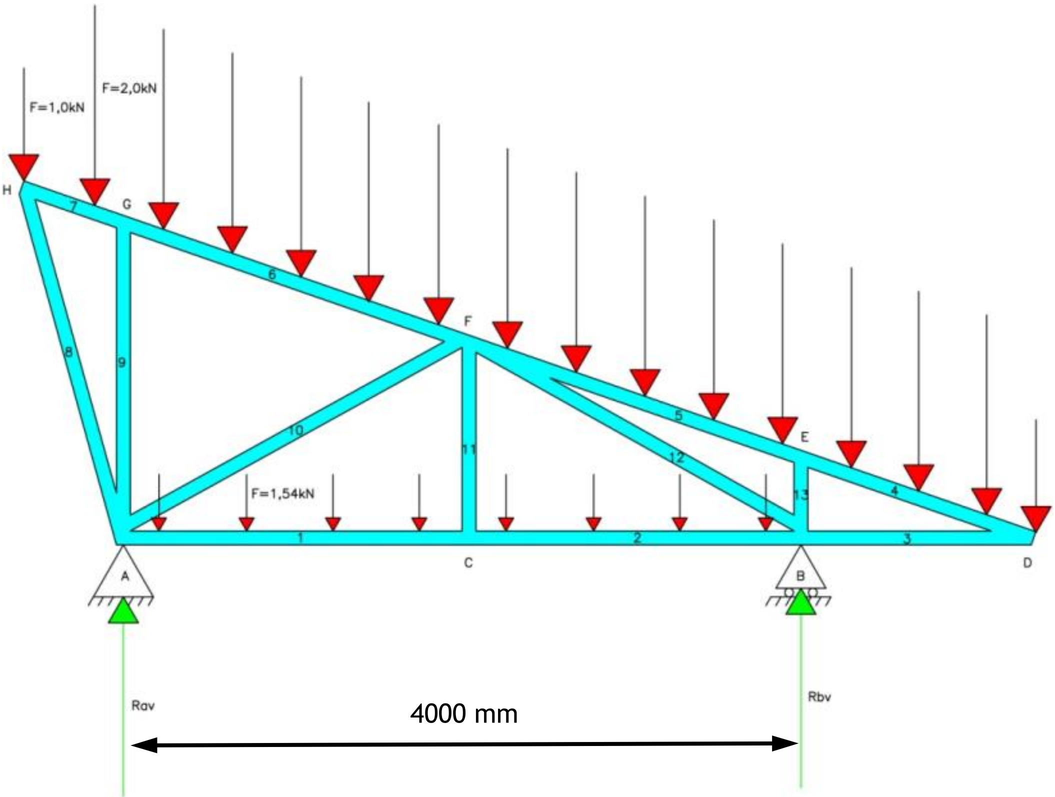
$R_v = 0,94 + 1,89 = 2,83\ kN$

$M = 0,94 * 0,6 + 1,89 * 0,2 = 0,94\ kNm$

$w = 1/3\ FL^3/EI$

$w = 1/3 * ((0,94 * 0,6^3)+(1,89 * 0,2^3))/(11185 * 1,70 * 10^{-6}) = 3,8\ mm$

The moment in this part will become too high so it is recommendable to also support this part of the construction so it will united with the truss.



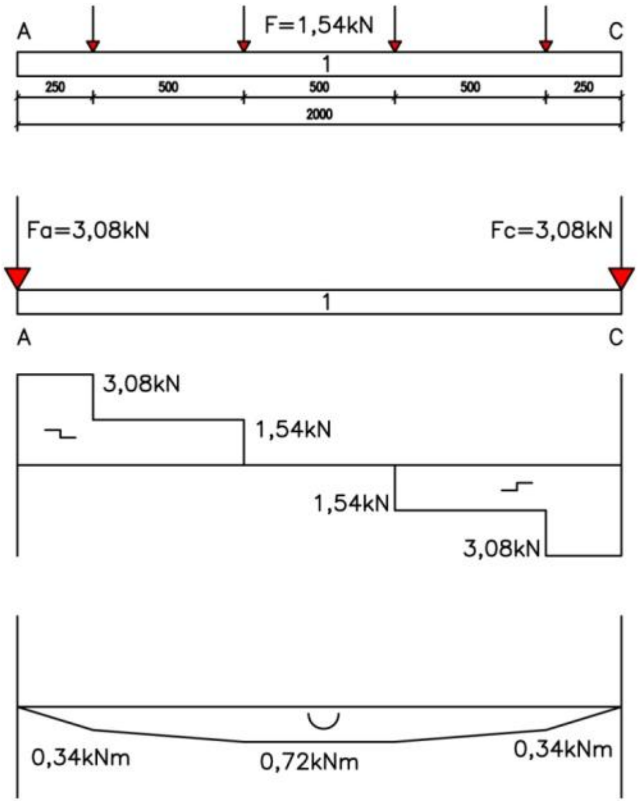
First we are going to define the reaction forces in the supports. The forces caused by the floor are not calculated yet. To make an estimation the weight of the floor is estimated by the weight of a wooden floor = 0,30 kN/m^2 and the variable load as prescribed by Dutch law P_{rep} = 1,75 kN/m^2. The variable load is choosen as if the complete floor can be used, because the house can be extended with an extra floor. (22) The floor is supported by floor beams which rest on the truss lower beam. The floor beams have a mutual distance of 0,5 m. One beam gives the weight of (0,30 + 1,75) * 1,5 * 0,5 = 1,54 kN.

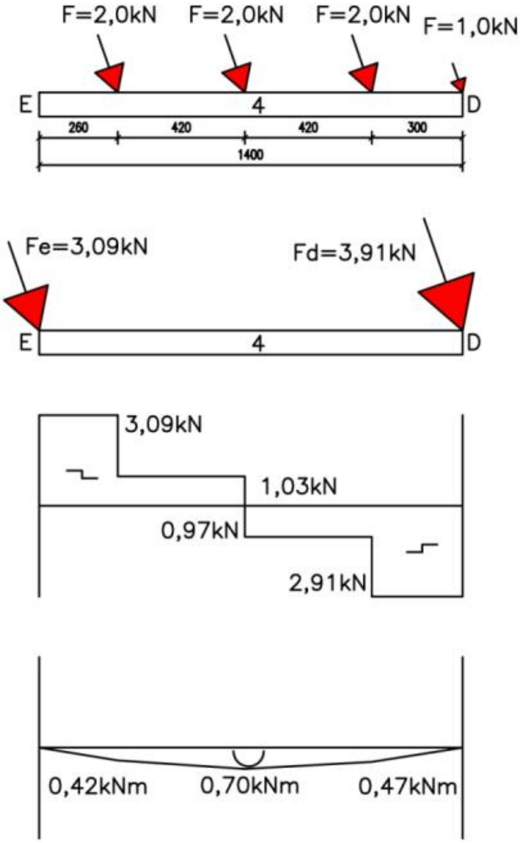
Rah = 0
Rav + Rbv - 15 * 2 – 8 * 1,54 = 0 -> Rav = 42,3 – Rbv
Rbv * 4 + 1 * 0,57 + 2 * 0,16 – 2 * (0,23 + 0,63 + 1,03 + 1,42 + 1,82 + 2,22 + 2,61 + 3,01 + 3,41 + 3,80 + 4,20 + 4,59 + 4,98) - 1 * 5,27 – 1,54 * (0,2 + 0,7 + 1,2 + 1,7 + 2,2 + 2,7 + 3,2 + 3,7)
Rbv = 24,4 kN
Rav = 42,3 – 24,4 = 18 kN

Secondly the forces have to be displaced to the nodes to make hand calculation possible. For every bar the maximum moment and shear forces can be calculated. Bars 8-13 and 3 do not support the roof or floor directly, so only normal force is present in these bars.

Bar 1 and 2:
FA = FC = 1,54 * (250 + 750 + 1250 + 1750)/2000 = 3,1 kN

The forces of the floor also causes a moment in bars one and two. The maximum moment is in the middle of the bar which can be estimated with F*ab/l. The letter “a” is the distance between A and the force. Letter “b” is de distance between C and the force. If we calculate the M in the middle of the beam 1,54 * (0,75*1,25 / 2) = 0,72 kNm
For the estimation of V = F*b/l and F*a/l. When the sear forces for all loads are calculated and add up the maximum shear force is 3,1 kN, located in the nodes. Both, moment and shear force are within the allowable borders of bamboo. As beam 2 has the same forces and size as beam 1 the results are the same.
F_C will be doubled because it gets the same forces from beam 2.
Therefore F_C = 6,2 kN





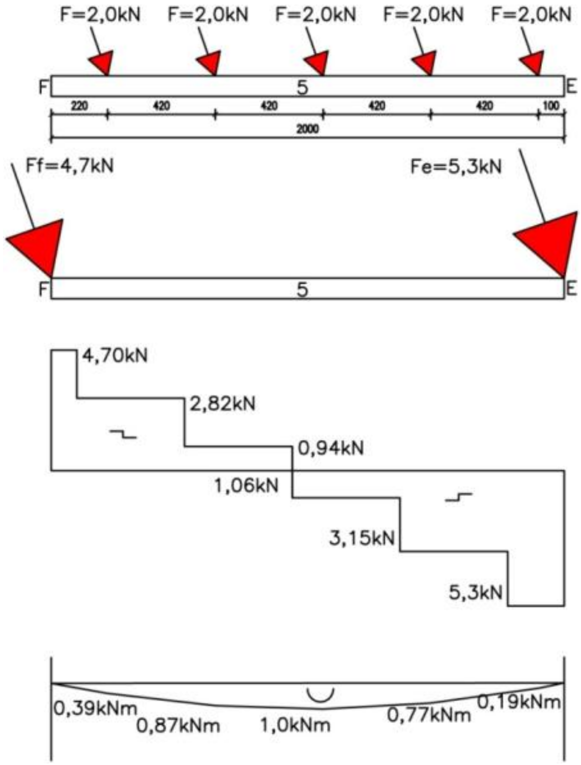
Bar 4:
FE = 2,0 * (0,3 + 0,72 + 1,14)/1,4 = 3,1 kN
FD = 2,0 * (0,26 + 0,68 + 1,10)/1,4 + 1,0 = 3,9 kN

The forces of the roof also cause a moment in bar four. M in the middle of the beam 2 * (0,72*0,68 / 1,4) = 0,7 kNm
When the shear forces for all loads are calculated and add up the maximum shear force is 3,1 kN, located in the nodes. Both, moment and shear force are within the allowable borders of bamboo.

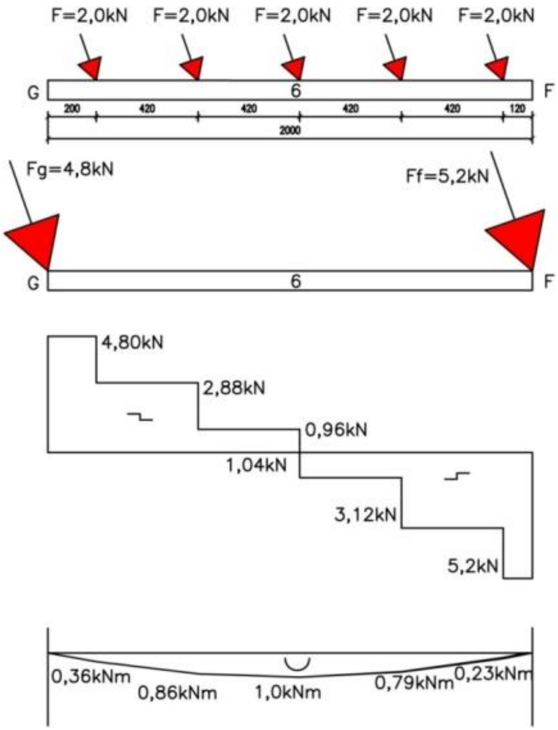
Bar 5:

FE = 2,0 * (0,22 + 0,64 + 1,06 + 1,48 + 1,90)/2 = 5,3 kN
FF = 2,0 * (0,10 + 0,52 + 0,94 + 1,36 + 1,76)/ 2 = 4,7 kN
Part of the forces of beam 4 and 5 come together in node E so therefore the total force in node E is: F_E = 3,09 + 5,30 = 8,39 kN

The forces of the roof cause a moment in bar five. M in the middle of the beam 2 * (1,06*0,94 / 2) = 1,0 kNm
When the shear forces for all loads are calculated and add up the maximum shear force is 5,3 kN, located in node E. Both, moment and shear force are not within the allowable borders of bamboo.



Therefore it is recommendable to double the beams that support the roof construction. Additionally, it is even considerable to leave bar 8 out of the truss.
W = 2 * 38 * 10^{-6} = 76 * 10^{-6} m^3
M_{all} = σ_{all} * W = 1,52 kNm
A = 2 * 3,1 * 10^3 = 6,2 * 10^3 mm^2
V_{all} = τ_{all} * A / 2 = 6,5 kN

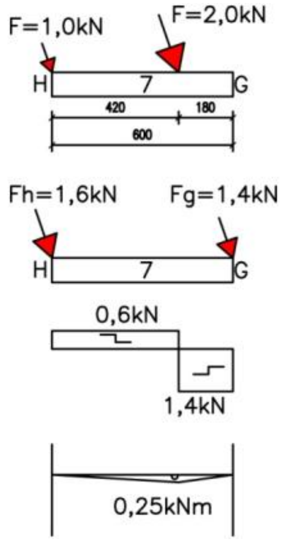


Bar 6:

FF = 2,0 * (0,20 + 0,62 + 1,04 + 1,46 + 1,88)/2 = 5,2 kN
FG = 2,0 * (0,12 + 0,54 + 0,96 + 1,38 + 1,80)/ 2 = 4,8 kN
Part of the forces of beam 5 and 6 come together in node F so therefore the total force in node F is: F_F = 4,70 + 5,20 = 9,9 kN

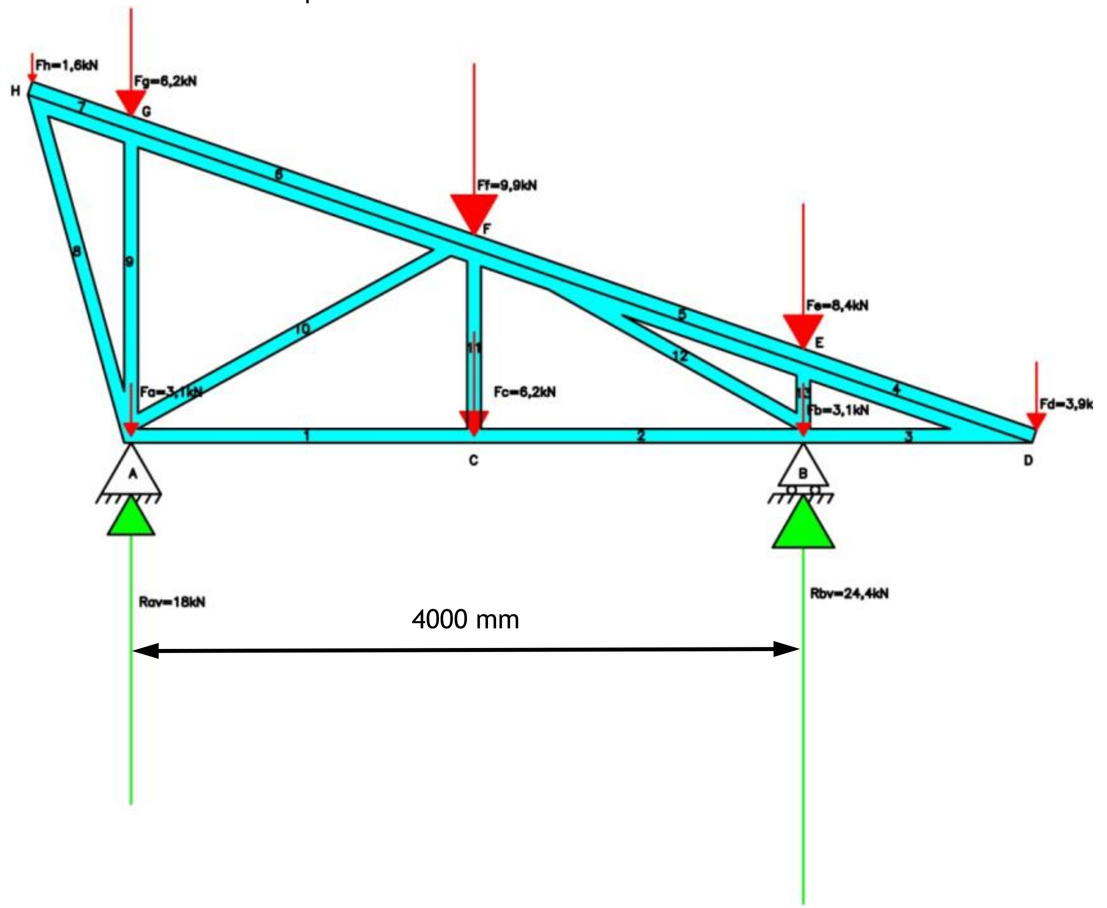
The maximum M = 1,0 kNm and the maximum V = 5,2 kN
Also in this case it is recommendable to double the roof beam.

Bar 7:
FG = 2,0 * 0,42 / 0,6 = 1,4 kN
FH = 2,0 * 0,18 / 0,6 + 1,0 = 1,6 kN
Part of the forces of beam 6 and 7 come together in node G so therefore the total force in node G is: F_G = 4,80 + 1,40 = 6,2 kN



The maximum M = 0,25 kNm and
The maximum V = 1,4 kN with is allowable also with a single beam.

The schematised truss is presented as follows:



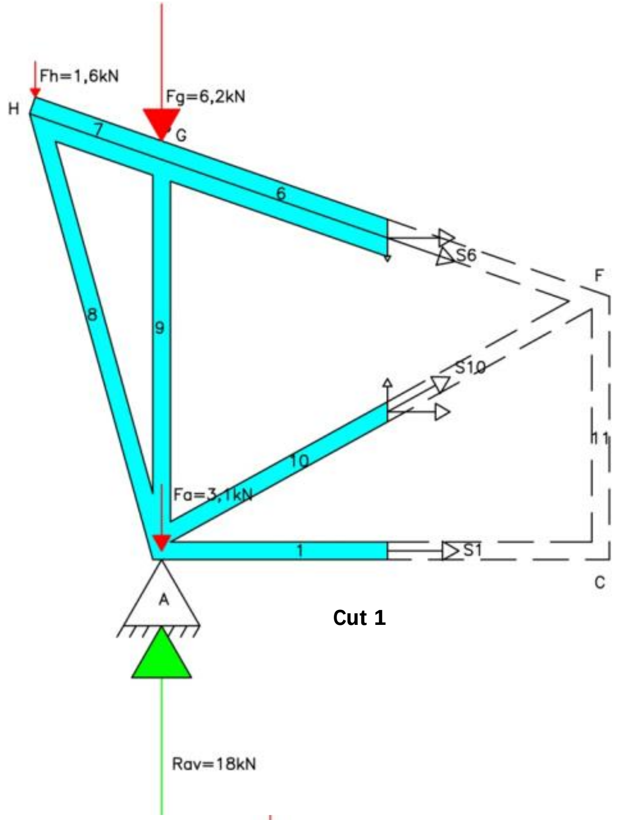
We will make cuts through the truss to calculate the forces in the bamboo bars of the truss.

Cut 1:
Σ Mt.o.v.F = 0
1,2S1 + 2*6,2 + 2,6*1,6 + 2*3,1 – 2*18 = 0
S1 = 11kN (tension)

Σ Mt.o.v.C = 0
1,0*S10 + 1,0 * S6 – 2*6,2 – 2*3,1 – 2,6*1,6 + 2*18 = 0
S10 = -S6 – 13,24

Σ V = 0
18 – 3,1 – 6,2 – 1,6 – 8/25 S6 + 12/25 S10 = 0
7,1 + 12/25 S10 - 8/25 S6 = 0
0,7448 - 4/5S6 = 0
S6 = 0,93 kN (tension)

S10 = -0,93-12,24 = -14,2 kN (pressure)



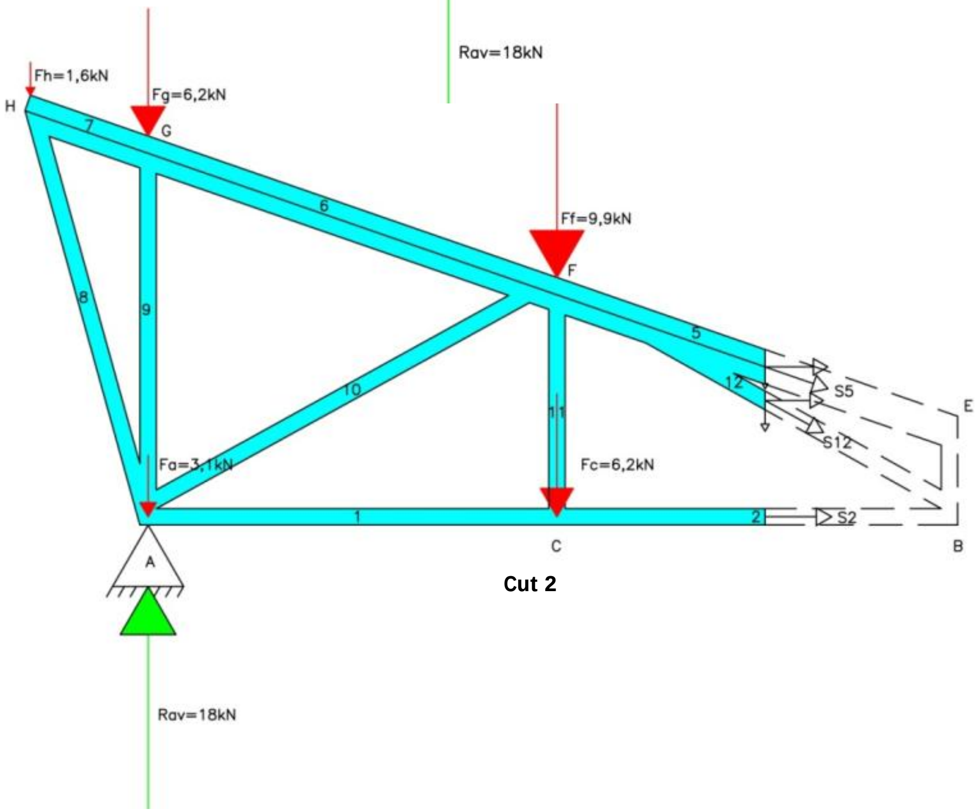
Cut 1

Cut 2:
Σ Mt.o.v.B = 0
0,4S5 - 2*9,9 - 2*6,2 - 4*3,1 – 4*6,2 – 4,6*1,6 + 4*18 = 0
S5 = 11,9kN (tension)

Σ Mt.o.v.E = 0
0,42*S2 + 0,3*S12 + 2*9,9 + 2*6,2 + 4*6,2 + 4*3,1 + 4,6*1,6 - 4*18 = 0
0,42S2 = -0,3S12 – 4,76

Σ V = 0
18 – 3,1 – 6,2 – 1,6 – 9,9 – 6,2 - 8/25*11,9 - 12/25 S12 = 0
S12 = -26,7kN(pressure)

0,42S2 =(-0,3-26,7) – 4,76
S_2 = 7,7kN (tension)



Cut 2

Cut 3:
Σ Mt.o.v.G = 0
0,5S8 + 0,6*1,6 = 0
S8 = -1,92kN (pressure)

Σ Mt.o.v.A = 0
1,7S7 - 0,6*1,6 = 0
S7 = 0,6kN (tension)

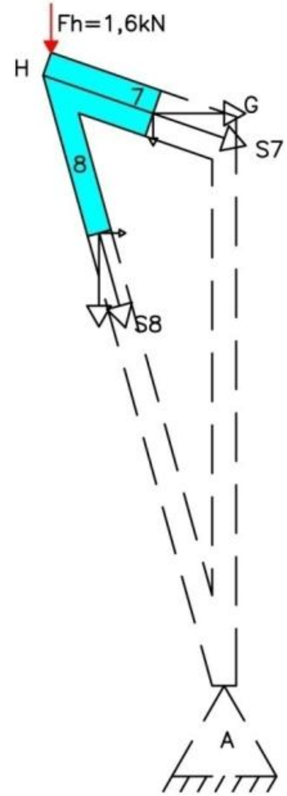
Cut 4:
Σ Mt.o.v.E = 0
0,5S3 + 1,4*3,9 = 0
S3 = -10,9kN (pressure)

Σ Mt.o.v.B = 0
0,4S4 - 1.4*3,9 = 0
S_4 = 13,7kN (tension)

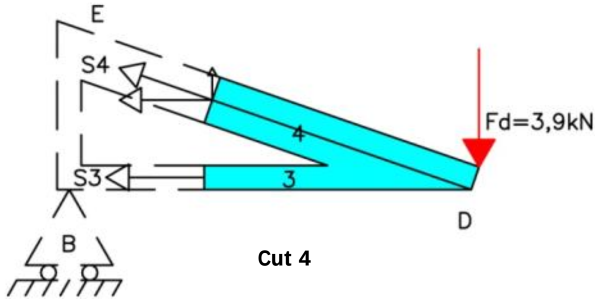
Cut 5:
Σ Mt.o.v.F = 0
2S9 + 2*6,2 = 0
S9 = -6,2kN (pressure)

Cut 6:
Σ Mt.o.v.D = 0
1,4S13 + 1,4*8,4 = 0
S13 = -8,4kN (pressure)

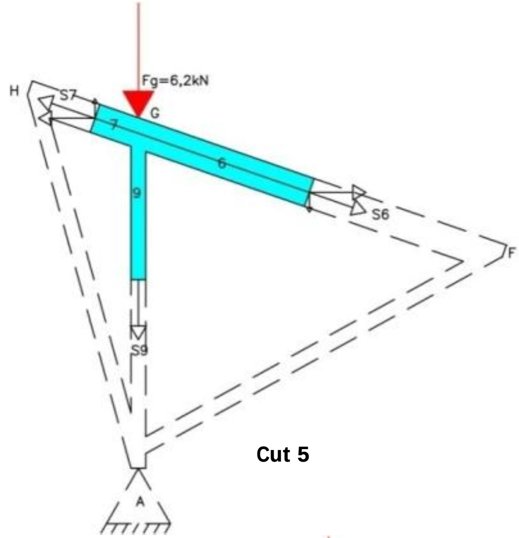
Cut 7:
Σ Mt.o.v.B = 0
2S11 - 2*6,2 = 0
S11 = 6,2kN (tension)



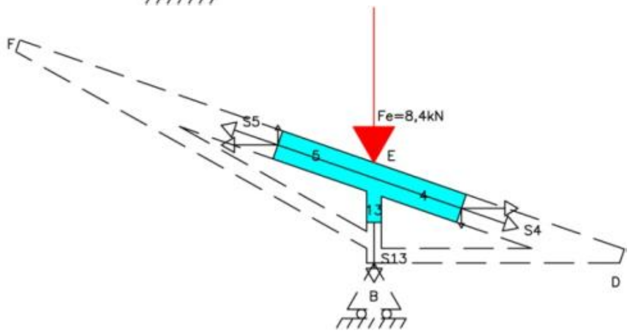
Cut 3



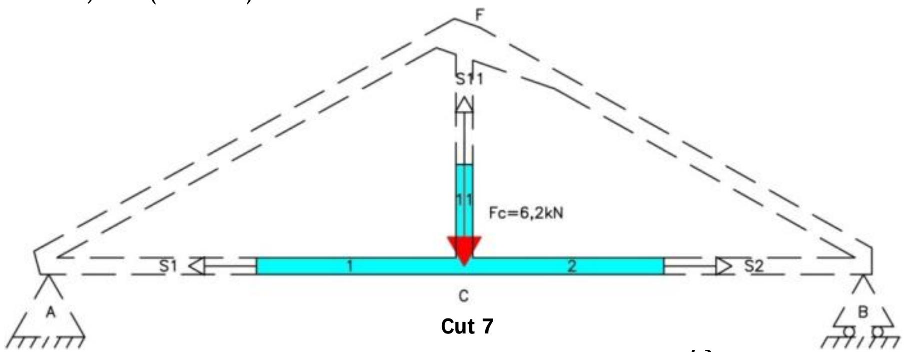
Cut 4



Cut 5

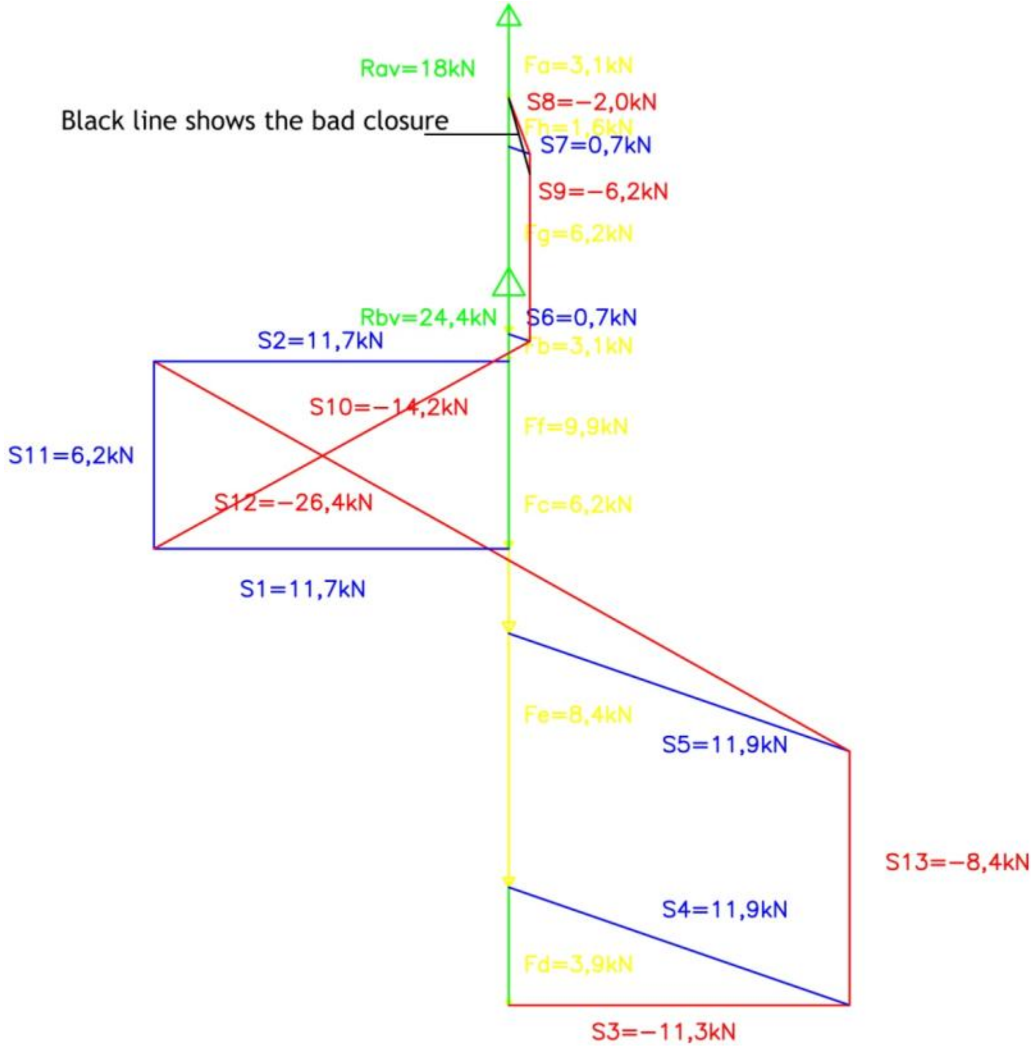


Cut 6

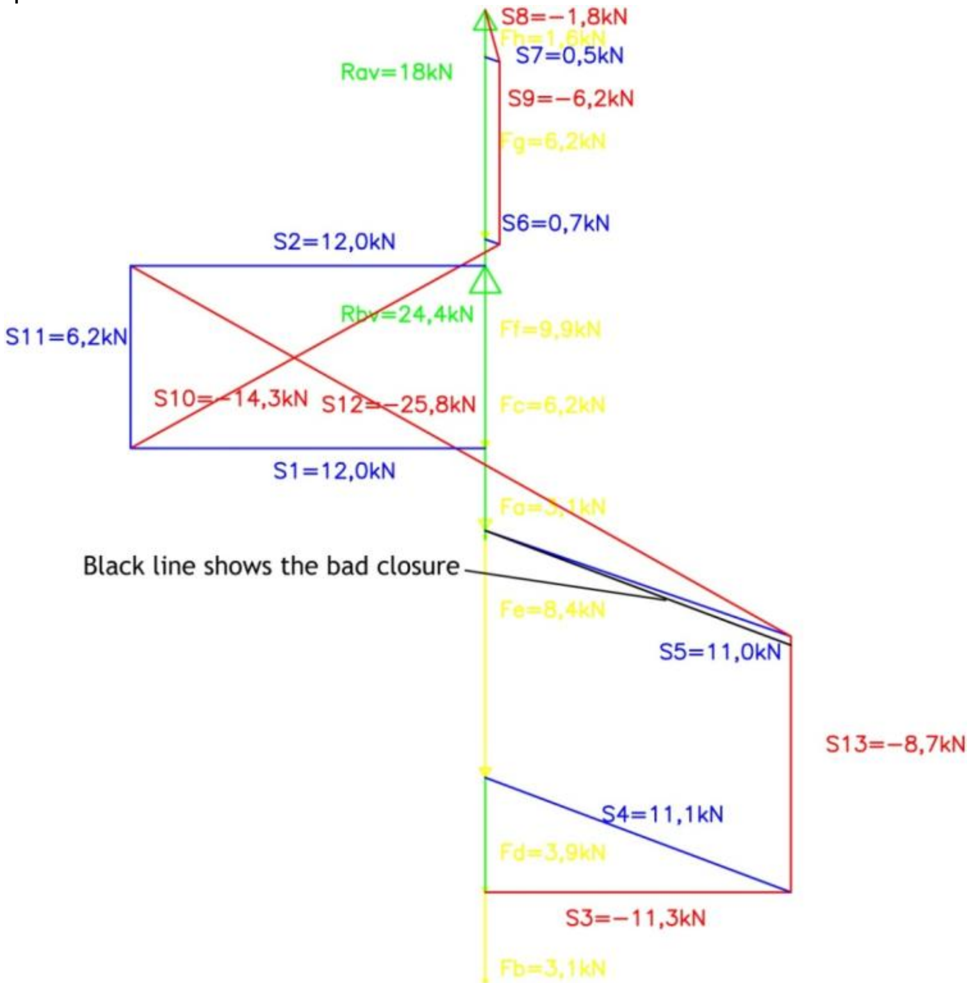


Cut 7

The calculations are controlled by drawing a Cremona diagram first from point D.

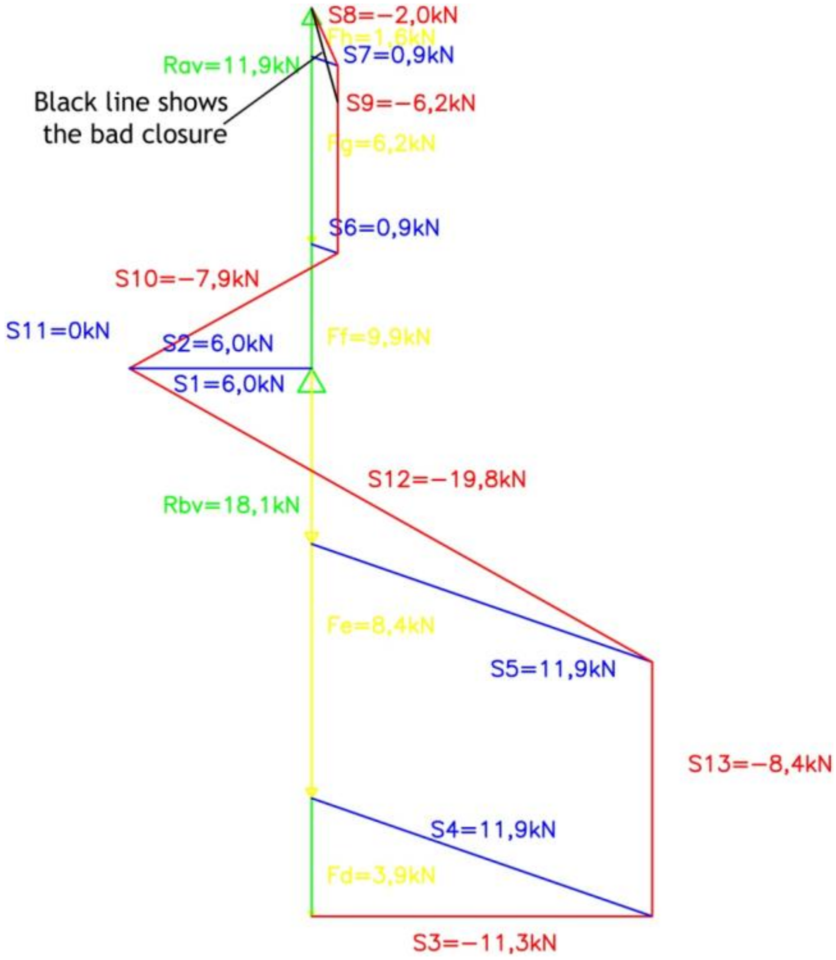


And a second from point H



Both diagrams do not close correctly completely, but the diagrams and the bar forces are quite similar. Finally a Cremona diagram is drawn without the weight of the floor to know the influence of the floor on the truss. Therefore new reaction forces are calculated:

Rah = 0
Rav + Rbv - 15 * 2 = 0 -> Rav = 30 – Rbv
Rbv * 4 + 1 * 0,57 + 2 * 0,16 – 2 * (0,23 + 0,63 + 1,03 + 1,42 + 1,82 + 2,22 + 2,61 + 3,01 + 3,41 + 3,80 + 4,20 + 4,59 + 4,98) - 1 * 5,27
Rbv = 18,1 kN
Rav = 30 – 18,1 = 11,9 kN



Also here the diagram did not close well, probably because of schematisation and rounding off. If we compare the results from the calculation with the first two Cremona diagrams the result is quite similar. Bars 1, 2, 10, 11 and 12 have really different values when the weight of the floor is left out, which is logically, they carry the weight.

	S1	S2	S3	S4	S5	S6	S7	S8	S9	S10	S11	S12	S13
From D	11,7	11,7	-11,3	11,9	11,9	0,7	0,5	-2,0	-5,5	-14,2	6,2	-26,4	-8,4
From H	12,0	12,0	-10,4	11,1	11,0	0,7	0,5	-1,8	-6,2	-14,3	6,2	-25,8	-8,7
- Floor	6,0	6,0	-11,3	11,9	11,9	0,9	0,9	-2,0	-6,2	-7,9	0	-19,8	-8,4
calculation	11,0	7,7	-10,9	13,7	11,9	0,93	0,6	-1,9	-6,2	-14,2	6,2	-26,7	-8,4

The maximum tension allowable in a bamboo bar is
$N_{all\text{-}ten} = \sigma_{all\text{-}ten} * A = 20 * 10^6 * 3,1 * 10^{-3} = 62$ kN
The maximum pressure allowable in a bamboo bar is
$\sigma_{com} = 0,094 * \rho = 0,094 * 700 = 65,8$ N/mm^2 (17)
$\sigma_{all\text{-}com} = (65,8 - 2,33 * 9,87) * 0,5 * 1,5 / 2,25 = 14,3 * 10^6$ N/m^2
$N_{all\text{-}com} = \sigma_{all\text{-}com} * A = 14,3 * 10^6 * 3,1 * 10^{-3} = 44$ kN

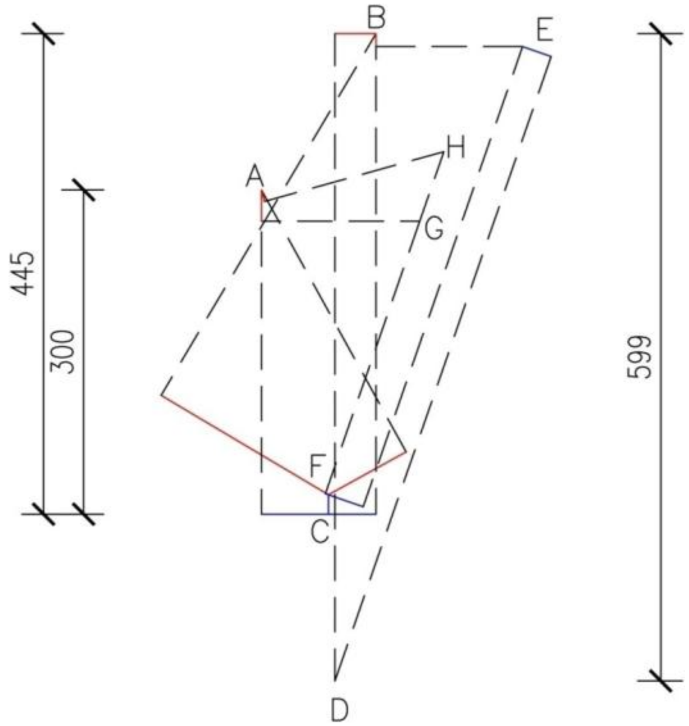
All bars are within the allowable values for pressure and tension.

Besides the forces in the bars also the displacement will be calculated. Length change can be calculated with $\Delta l_i = N_i l_i / E_i A_i$. The calculated N forces will be used to calculate the Δl_i.
$E*A = 11185 * 3,1*10^3 = 34,7 *10^6$ N
Bars 4-7 A is doubled because a double bar is proposed earlier
$E*A = 34,7 *10^6 * 2 = 69,4 *10^6$ N

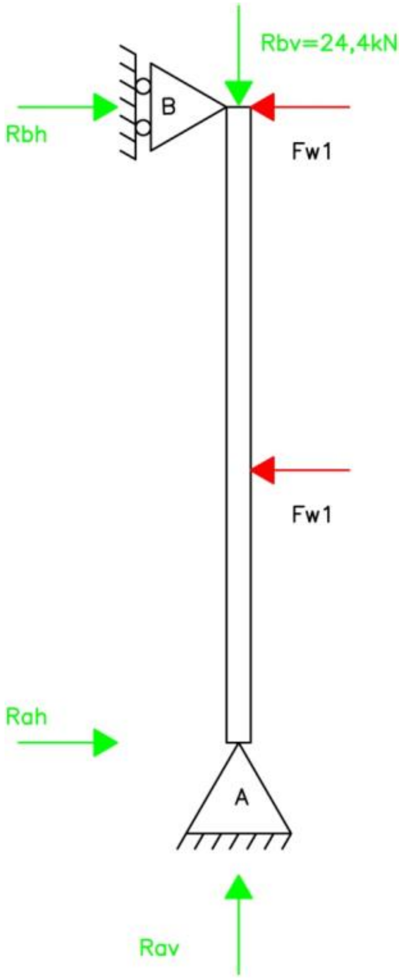
	S1	S2	S3	S4	S5	S6	S7	S8	S9	S10	S11	S12	S13
li	2000	2000	1200	1400	2000	2000	600	2000	1600	2000	1000	1600	500
calculation	11,0	7,7	-10,9	13,7	11,9	0,93	0,6	-1,9	-6,2	-14,2	6,2	-26,7	-8,4
Δli	0,63	0,44	-0,38	0,28	0,34	0,03	0,00	-0,11	-0,29	-0,82	0,18	-1,80	-0,12

With a Williot diagram we can estimate the displacement of the nodes

100 units = 1 mm
$d_{all} = 4000 / 250 = 16$ mm; $d_C = 3$ mm there is no problem
$d_D = 6$ mm $d_{all} = 1200 / 250 = 5$ mm
There is a difference of 1 mm that should be okay for a overhanging roof.



Part 3 Column



For the calculation of the bamboo culms the heaviest loaded culm will be calculated. The bamboo culm has the same qualities as mentioned in the previous calculations

M_{all} = 0,76 kNm; V_{all} = 3,2 kN; d_{all} = h / 300 = 7 mm

Besides the load from the truss also wind load on the side of the culm will be calculated.

First we need to know the wind force that the wall panels will pass on to the culmn. The size of one wall panel is 1,5 * 1,2 = 1,8 m^2

$p_{rep} = C_{dim} * C_{index} * C_{eq} * \Phi_1 * p_w$

C_{dim} = 0,96

C_{index} = wind factor divided in :

C_{pe} = 0,80; C_{pi} = 0,3; C_f = 0,01

$C_{pe;loc}$ and C_t : are in this case not relevant

h < 50 meter and h/b < 5, so C_{eq} = 1,0 and Φ_1 = 1,0

p_w: extreme value of push pressure: 1 kN/m^2

So p_{rep} = 0,96 * 1,11 * 1,0 * 1,0 * 1,0 = 1,07 kN/m^2

F_{w1} = ½ * 1,07 * 1,8 = 0,96 kN

Σ H = 0 -> Rah + Rbh -2Fw1 = 0 -> Rah = 1,9 - Rbh

Σ V = 0 -> Rav – Rbv = 0 -> Rav = 24,4 kN

Σ Mt.o.v.A = 0 -> 2,2*Rbh – 1* Fw1 - 2,2* Fw1 = 0 -> Rbh= 1,4 kN

R_{bh} = 0,5 kN

M_{act} = Fw1 * ab / l = 0,96 * 1 * 1,2 / 2,2 = 0,52 kNm

V_{act} = Fw1 * b / l = 0,96 * 1,2 / 2,2 = 0,52kN

$M_{act} < M_{all}$ and $V_{act} < V_{all}$, so no problems will occur.

The maximum pressure allowable in a bamboo bar is

σ_{com} = 0,094 * ρ = 0,094 * 700 = 65,8 N/mm^2 (17)

$\sigma_{all\text{-}com}$ = (65,8 - 2,33 * 9,87) * 0,5 * 1,5 / 2,25 = 14,3 * 10^6 N/m^2

$N_{all\text{-}com} = \sigma_{all\text{-}com}$ *A = 14,3 * 10^6 * 3,1 * 10^{-3} = 44 kN

Also the pressure from the truss will not give any problem

Buckling

$F_b = \pi^2 EI / l_k^2$; l_k = l = 2200mm

$F_b = \pi^2(11185 * 1,7 * 10^6)/2200^2$ = 39kN

The beam can support the vertical forces without buckling

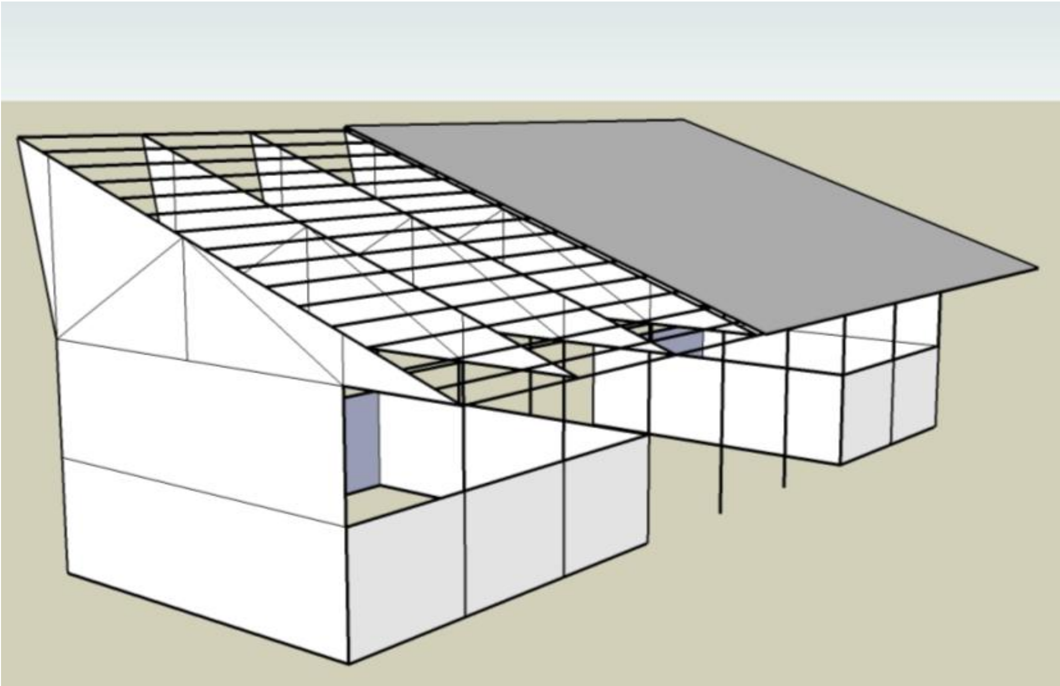
$d_{act} = 1/48 * Fl^3/EI = 1/48 * (0,96 * 2,2^3)/(11185 * 1,7 * 10^{-6})$ = 11 mm

The wind forces will push the columns to much out of place so preferably a double culm is used

$d_{act} = 1/48 * Fl^3/EI = 1/48 * (0,96 * 2,2^3)/(11185 * 2*1,7 * 10^{-6})$ = 6 mm

Which is within the allowable displacement.

Part 4 Node



Until now we assumed the nodes can transfer the forces from one beam to the other. To be sure these forces are transferred well some test are and will be preformed. Therefore we need to know the maximum force transformed trough a node. From the calculation of the truss we see that bar 12 has a 26,7 kN compression, which has to be transferred in node A to the supporting culm, so that will be the maximum node force that has to be dealt with.

Appendix D Result jointing tests

Test report

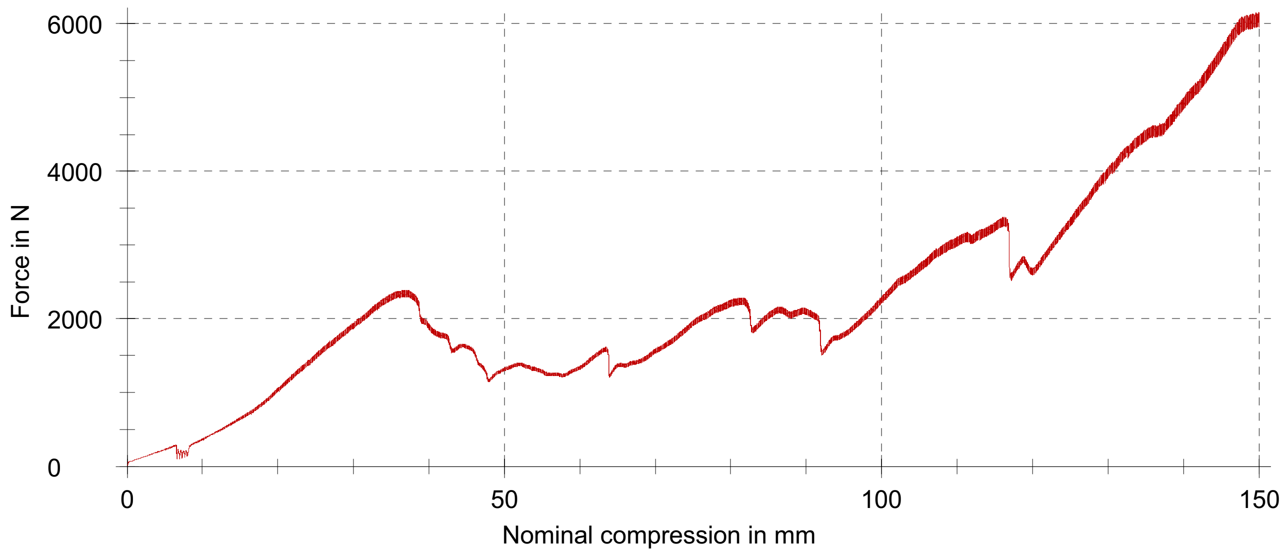
Customer	:		Specimen type	:
Job no.	:		Pre-treatment	:
Test standard	:		Tester	:
Type and designation of	:		Notes...	:
Material	:		Machine data	:
Specimen removal	:			

Pre-load : 5 N
Test speed : 2,5 mm/min

Test results:

Nr	σ_M MPa	ε_M %	d_0 mm	A_0 mm²	Specimen no.
1.1	9,49	600,0	28,75	649,18	1

Series graph:



Statistics:

Series n = 1	σ_M MPa	ε_M %	d_0 mm	A_0 mm²
$\bar{x}$	9,49	600,0	28,75	649,18
s	-	-	-	-
ν	-	-	-	-

Zwick / Roell

26.03.09

Test report

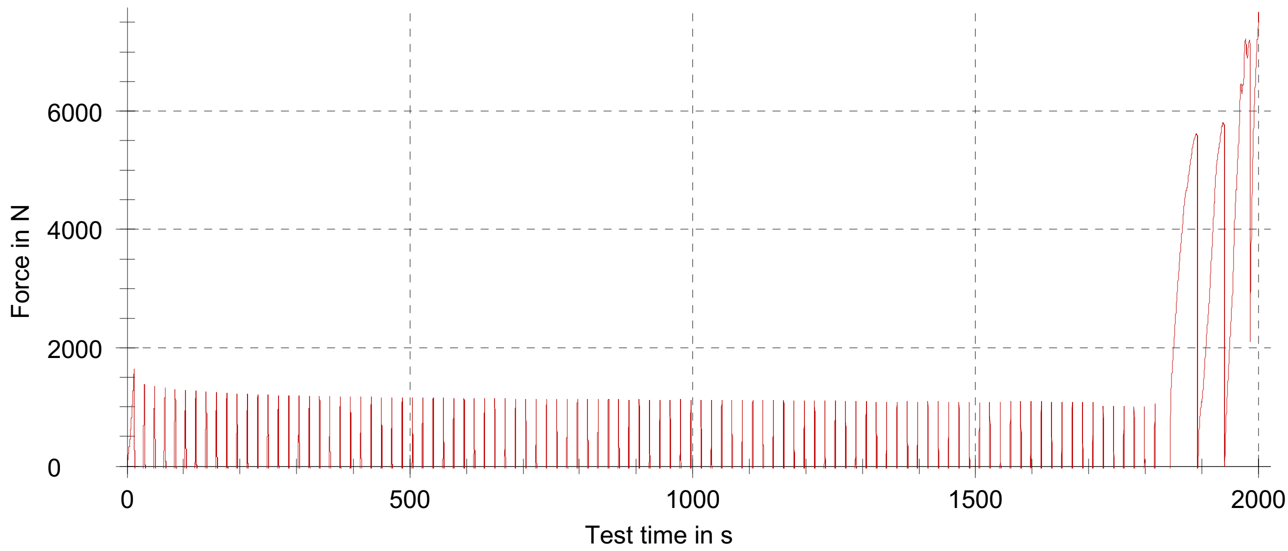
Customer	:	Specimen type	:
Job no.	:	Pre-treatment	:
Test standard	:	Tester	:
Type and designation of	:	Notes...	:
Material	:	Machine data	:
Specimen removal	:		

Pre-load : 5 N
Speed up to the end of test : 50 mm/min

Test results:

Nr	h_0 mm	a_0 mm	b_0 mm
1	464,1	100	100

Series graph:



Statistics:

Series n = 1	h_0 mm	a_0 mm	b_0 mm
$\bar{x}$	464,1	100	100
s	-	-	-
ν	-	-	-

Zwick Roell

Test report

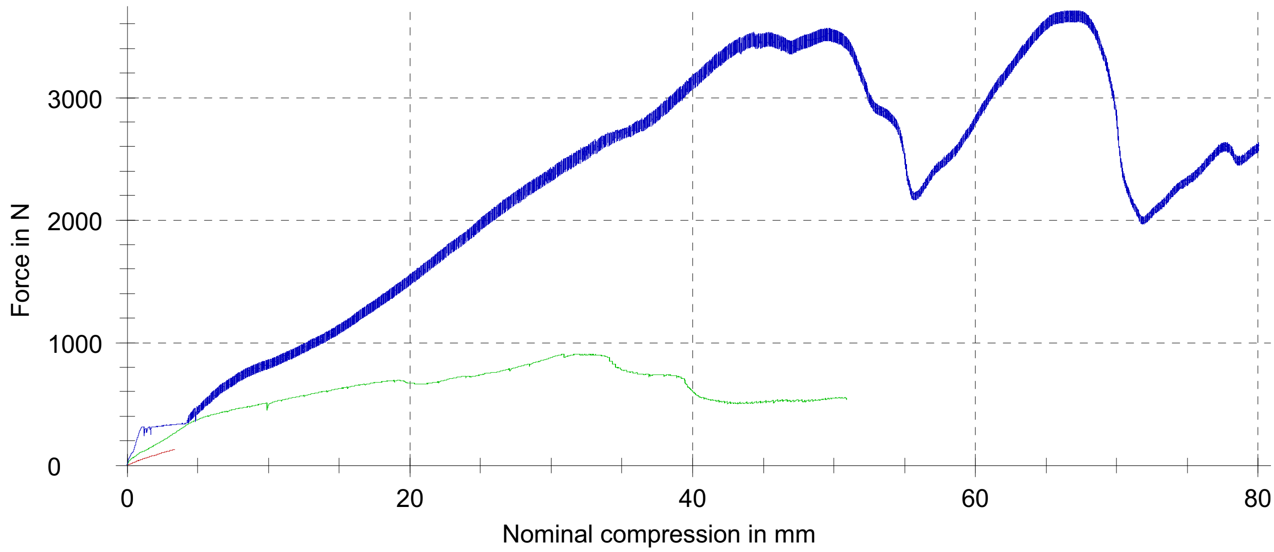
Customer	:		Specimen type	:	
Job no.	:		Pre-treatment	:	
Test standard	:		Tester	:	
Type and designation of	:		Notes...	:	
Material	:		Machine data	:	
Specimen removal	:				

Pre-load : 5 N
Test speed : 1 mm/min

Test results:

Nr	σ_M N	ε_M mm	d_0 mm	A_0 mm²	Specimen no.
1.1	129	3,4	28,75	649,18	1
1.2	906	30,9	28,75	649,18	2
1.3	3710	66,8	28,75	649,18	3

Series graph:



Statistics:

Series n = 3	σ_M N	ε_M mm	d_0 mm	A_0 mm²
$\bar{x}$	1580	33,7	28,75	649,18
s	1880	31,8	0,000	0,00
ν	119,09	94,35	0,00	0,00

Zwick Roell

Test report

Customer	:	Specimen type	:
Job no.	:	Pre-treatment	:
Test standard	:	Tester	:
Type and designation of	:	Notes...	:
Material	:	Machine data	:
Specimen removal	:		

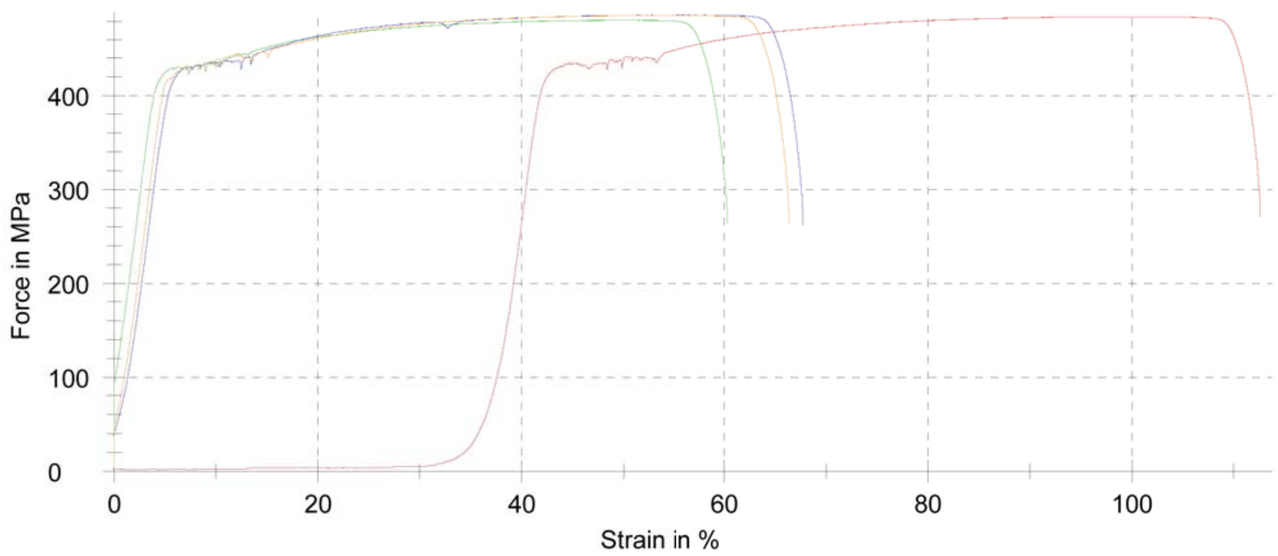
Series n = 4	dL at break %	d_0 mm	S_0 mm²
$\bar{x}$	76.7	3.4	9.08
s	24.1	0.000	0.00
ν	31.43	0.00	0.00

Pre-load	:	10	N
Speed E-Modulus	:	5	mm/min
Test speed	:	5	mm/min

Test results:

Nr	Text	E_{mod} GPa	yield stress (Rp 0.2%) MPa	Tensile strength MPa	dL at break %	S_0 mm²	L_0 mm	L0 ST mm
1.1	test name	1.33	20	485	112.6	9.08	-	20
1.2	test name	3930	100	481	60.3	9.08	-	20
1.3	test name	5.10	400	487	67.7	9.08	-	20
1.4	test name	13.5	70	486	66.4	9.08	-	20

Series graph:



Statistics:

Series n = 4	Specimen no.	E_{mod} GPa	yield stress (Rp 0.2%) MPa	Tensile strength MPa	dL(plast.) at F_{max} mm	dL at F_{max} mm	F_{Break} N
$\bar{x}$	3	987	200	485	8.9	13.0	2410
s	1	1960	200	2.49	1.9	4.6	34.9
ν	51.64	198.66	119.97	0.51	21.44	35.83	1.45