EVALUATION FRAMEWORK FOR SUSTAINABLE, INNOVATIVE, LOW-COST BUILDING PROTOTYPES WITH BAMBOO

WITH CASE STUDIES IN BRAZIL

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ABSTRACT

Bamboo is increasingly applied as a bio-based construction material for it provides distinct answers to the climatological problems the world and the construction industry in particular are facing today; a high carbon sequestration, a low embodied energy, low-cost, earthquake proof and a widespread availability (predominantly in tropical countries) without risk of deforestation. Complementary to the extensive research that has already been done on the engineering aspects of bamboo, this research focusses on the architectural facet by developing a framework to evaluate the quality of a bamboo design. Through literature research, an in-depth analysis of real cases in Brazil and an LCA analysis on two bamboo prototype columns, a **holistic framework** could be developed that goes beyond the methodological and technical features that are drawn up in present building codes or standards.

This dissertation is divided into three parts. The first part consists of **literature research** and aims to provide comprehensive information on bamboo´s application as a construction material. The premise is the iterative approach of the Roman architect Vitruvius to assess architectural design quality by means of three main principles; Firmitas, Utilitas and Venustas - commonly translated as Firmness, Commodity and Delight. Although this research departs from Vitruvius´s perspectives, its original meaning has been adapted to bamboo in particular. Firmitas addresses the **mechanical** and technical specifications of bamboo. Utilitas covers the **performance** of bamboo by means of the three pillars; people, planet and profit, or in other words the ecologic, economic and social aspects of the project. Venustas discusses how **aesthetic quality** of a bamboo design/construction can be attained.

The second part of the research focusses on the **practical application** of bamboo. First, **nine bamboo cases** built by the researcher over the past fifteen years in Brazil are reviewed to uncover their successes and failures with the intent to improve the quality of bamboo constructions in general and fundamentally broaden the acceptance of bamboo as a construction material. Analyzing built bamboo construction is rare in bamboo research and even more after an extended period of time a construction is built, although such research provides indispensable information on the deterioration process. Therefore, also a durability analysis is performed on the community centre 12 years after being built. Multiple factors have an impact on the deterioration of a bamboo construction, e.g. insect attacks, weathering conditions, humidity and ventilation, impossible to replicate in a controlled laboratory setting. As bamboo is a bio-based material, these aspects should be already well-considered from the design process on. Secondly, an **LCA analysis** is performed on two bamboo columns from the cases whereafter these results are compared to conventional construction materials.

The literature research and case studies lead to the third and final part of this dissertation; the development of a holistic **evaluation framework** that allows to assess the quality of a specific bamboo design or construction. The evaluation framework is set up according Vitruvius´s principles as well and pinpoints, by means of a questionnaire with an outcome visualized in colors, the aspects of importance to obtain a qualitative, sustainable, innovative yet low-cost bamboo design. This framework aims to provide the designer/architect a great usability and functionality for only then he/she will be inclined to applicate it. Two versions of the evaluation framework can be found; an extensive Excel worksheet showing all the subdivisions and weight scores for in-depth analysis of a bamboo project and a quick scan that does not visualize the underlying weighing systems but uses these to provide the designer/architect a color scheme indicating the importance of each aspect.

KORTE INHOUD

Tegenwoordig wordt bamboe vaker toegepast als natuurlijk bouwmateriaal, voornamelijk omdat het onmiskenbaar een antwoord biedt op problemen waar de wereld en de bouwsector in specifiek vandaag de dag mee worden geconfronteerd: koolstofvastlegging en -opslag, lage hoeveelheid energie nodig voor de productie ervan, lage kostprijs, aardbevingsbestendig en een wijdverspreide beschikbaarheid (vooral in tropische landen) zonder risico op ontbossing. Aanvullend op het uitgebreide onderzoek dat reeds werd gedaan naar de technische aspecten van bamboe, richt dit onderzoek zich op het architecturale facet door een kader te creëren voor de evaluatie van de kwaliteit van een bamboe ontwerp. Door een literatuuronderzoek, een analyse van de bamboeconstructies gebouwd door de auteur in Brazilië en een vergelijkende levenscyclusanalyse van twee bamboekolommen, kon een **holistisch kader** bekomen worden dat verder gaat dan de technische bouwvoorschriften of richtlijnen.

Het proefschrift werd opgedeeld in drie luiken. Het eerste luik omvat **literatuuronderzoek** om de lezer gedetailleerde informatie te verschaffen over bamboe als bouwmateriaal. Het uitgangspunt is de iteratieve benadering van de romeinse architect Vitruvius om architecturale kwaliteit te beoordelen aan de hand van drie basisprincipes; Firmitas, Utilitas en Venustas, vaak vertaald als stevigheid, gebruiksvriendelijkheid en schoonheid. De oorspronkelijke betekenis van deze drie componenten werd toegespitst op bamboe architectuur. Firmitas heeft betrekking op de **stabiliteit** en behandelt de mechanische en technische specificaties van bamboe in de architectuur. Utilitas behandelt **de prestatie** van bamboe aan de hand van de drie pijlers: people (mensen), planet (planeet) en profit (winst) om een beeld van de ecologische, economische en sociale aspecten van een project te schetsen. Venustas bespreekt hoe de aantrekkelijkheid of de **esthetische kwaliteit** van een bamboe constructie kan gerealiseerd worden..

Het tweede luik onderzoekt de **praktische toepassing** van bamboe. Ten eerste worden **negen bamboe constructies** die de onderzoeker gedurende de afgelopen vijftien jaar in Brazilië heeft gemaakt, geanalyseerd om de successen en mislukkingen ervan bloot te leggen met als einddoel om de kwaliteit van bamboe constructies in het algemeen te verhogen en zodanig de acceptatie van bamboe als bouwmateriaal te vergroten. Analyse van gebouwde bamboeconstructies is zeldzaam in bamboe onderzoek, laat staan na een langere tijdsperiode nadat ze zijn gebouwd, niettegenstaande dat dergelijke analyses waardevolle informatie bevatten over verweringsprocessen. Om die reden werd er een **duurzaamheidsanalyse** verricht op het gemeenschapscentrum 12 jaar nadat deze werd gebouwd. Meerdere factoren hebben een impact op de verwering van een bamboe constructie, zoals insectenplagen, weersinvloeden, ventilatie en luchtvochtigheid, die moeilijk na te bootsen zijn in een gecontroleerde laboratorium omgeving. Aangezien bamboe een natuurlijk materiaal is, moeten deze factoren op voorhand goed in kaart worden gebracht zodat ze al vanaf het ontwerpproces kunnen vermeden worden. Tot slot berekent een **levenscyclus analyse** de milieubelasting van twee verschillende kolomtypes in bamboe waarna deze resultaten worden vergeleken met een gelijkaardig kolomtype in conventionele materialen.

Het literatuur en praktische toegepaste onderzoek leiden gezamenlijk tot het derde luik van het proefschrift; de ontwikkeling van een **holistisch evaluatiekader** dat het mogelijk maakt om de kwaliteit van een specifiek bamboe ontwerp of constructie te evalueren. Dit evaluatie raamwerk is eveneens opgebouwd volgens Vitruvius' basisprincipes en probeert te achterhalen welke aspecten van belang zijn om een kwalitatief, duurzaam, innovatief of kostenefficiënt bamboe ontwerp te bekomen door middel van een vragenlijst met een kleuren score. Het heeft als doel om de architect/ontwerper een grote bruikbaarheid en functionaliteit aan te bieden, want alleen dan zal hij geneigd zijn het evaluatie model toe te passen. Er zijn twee versies van het evaluatiekader te vinden; een uitgebreide Excel werkblad met alle onderverdelingen en gewichtsscores voor een diepgaande analyse van een project, en een quick scan die niet het onderliggende score systeem toont, maar deze wel gebruikt om tot een kleurenschema te komen dat het belang van elk aspect aangeeft.

LIST OF ABBREVIATIONS

ABNT	Brazilian Association of Technical Standards
ACA	Ammoniacal Copper Arsenate
AEDET	Achieving Excellence Design Evaluation Toolkit
Af climate	Tropical Rainforest Climate
AHP	Analytic Hierarcy Process
ASTM	American Society for Testing and Materials
BREEAM	Building Research Establishment Environmental Assessment Method
BQA	Building Quality Assessment
ELCD	European Life Cycle Database
CCA	Copper Chrome Arsenic
CCB	Copper Chrome Boron
CEN	European Committee for Standardization
Cfa climate	Humid subtropical climates
Cfb climate	Temperate oceanic climate
CO_2	Carbon
CWFT	Classification without further testing
DEEP	Design Excellence Evaluation Process
DIN	Dutch Industry Norm
DQI	Design Quality Indicator
DtS	Deemed to Safety
EI	Flexural Rigidity
E-modulus	Elasticity Modulus
EN	European Norm
EF	Evaluation Framework
ICONTEC	L'Instituto Colombiano de Normas Tecnicas y Certificacion
IEA	International Energy Agency
INEN	The Ecuadorian Service for Standardization
IPCC	Intergovernmental Panel on Climate Change
ISO	International Standard Organization
FSP	Fiber Saturation Point
FEM software	Finite Element Method Software
FSC	Forest Stewardship Council
FU	Functional Unit
GABC	Global Alliance for Buildings and Constructions
GHG	GreenHouse Gas
GWP	Global Warming Potential
HVFA	High-Volume Fly Ash Concretes
INBAR	International Network for Bamboo and Rattan

IS	Indian Standard
JG/T	Chinese Technical Building and Construction Standard
LCA	Life Cycle Assesment
LCC	Life Cycle Cost
LCI	Life Cycle Inventory
LEED	Leadership in Energy & Environmental Design
LIFT	Lateral Ignition Flamespread Test
MC	Moisture Content
MCDM	Multi-criteria Decision Model
MMG-method	Milieugerelateerde Materiaalprestatie van Gebouwelementen
MOE	Modulus of Elasticity
MOR	Modulus of Rupture
NaPCP	Sodium PentaChloroPhenate
NBCI	National Building Codes of India
NBR	Norma Brasileira Reglumentadora
NEN-standards	Dutch Standards
NOCMAT	Non-Conventional Materials and Technologies
NPR	Dutch Practice guidelines
NSR	Reglamento Colombiano De Construcción Sismo Resistente
NTC	Norma Técnica Colombiano
PEFC	Programme for the Endorsement of Forest Certification
TCP	Trichlorophenol
TOTEM	Transfer of Technology Models
VITO	Vlaams Instituut voor Technologische Ontwikkeling
WBO	World Bamboo Organization
ZERI	Zeri Emissions Research Institute

CONTENT

INTRODUCTION

CHAPTER 1 Introduction

1.1 **Introduction - orientation of the research**

1.1.1 General information on bamboo in construction

Bamboo as a construction material has been around in regions where it is naturally available as long as human civilization has been sheltering itself. Bamboo can provide in all needs to build a house, from the frame (as bamboo pole or split), the building cover (bamboo mat, split), windows and doors (split), the floor (flattened bamboo), the roof (bamboo shingles) and even the connectors (bamboo pin, rope). Yet, a disadvantage of bamboo is its weaker resistance against insects, fungi and weathering conditions. Additionally, bamboo is prone to split and tends to crush more easily (Widyowijatnoko, 2012). As a result, bamboo has always been perceived inferior to conventional materials such as wood, concrete or bricks and is mainly employed for low-cost housing until the people are economically capable to substitute the bamboo with other more durable materials (Christiaens, 2010). This lack of durability has retained a more widespread application of bamboo in the construction field, despite the fact that bamboo´s characteristics are unprecedented. These advantages are mainly ecological of nature, such as the capacity for carbon capture, oxygen production, renewability, erosion control and low embodied energy, yet bamboo also possesses other advantages of which its low-cost is presumably of the most interest. Especially in tropical countries, bamboo has great potential for poverty reduction and the capacity to nullify social inequality (Da Silva et al, 2017). Besides the issue of durability, another challenge in bamboo construction is the connections. Connecting a bamboo to another material is arduously because of the irregularity of the material with varying dimensions (hollow, round, tapering, protruding rings) and varying properties (Widyowijatnoko, 2012). As the majority of the current knowledge of bamboo construction is based on cultural tradition, one must evaluate these traditional techniques in terms of engineering and architecture in order to develop equivalent methods of design (Sharma et al., 2011). With new technologies of preservation and construction techniques, more durable bamboo constructions can be built. Well-executed examples are imperative in the development process. This research aims at composing an evaluation framework to assess bamboo building designs, but also to contributing to a further technical development by reviewing the impact of different design strategies, which is necessary to guarantee a higher sustainability of bamboo constructions.

1.1.2 Sustainable development and sustainable building

1.1.2.1 Sustainable development

Sustainable development can be defined in many ways. The definition used in the Brundtland report in 1987 popularized the concept as an attempt to bridge the gap between environmental concerns about evident ecological consequences of human activities and socio-political concerns about human development issues (Robinson, 2003). As defined in the Brundtland report '*Sustainable development should meet the needs of the present without compromising the ability of future generation to meet their own needs'*. This definition contains two key concepts namely the concept of needs, in particular the essential needs of the most poverty-stricken and the idea of the limitations by technology and social organizational principles on the ability of the environment to meet present and future needs. Sustainable development focusses on the improvement of the quality of life (well-being) of every person on earth through harmony between society, environment and economy in the long-term (International Institute for sustainable Development, 2010). Figure 1.1. illustrates the Dougnut economics, a visual framework for sustainable development shaped like a doughnut. It combines the concept of planetary boundaries with the complementary concept of social boundaries Kate Raworth explains the doughnut economy is based on the premise that "Humanity's 21st century challenge is to meet the needs of all within the means of the planet. In other words, to ensure that no one falls short on life's essentials (from food and housing to healthcare and political voice), while ensuring that collectively we do not overshoot our pressure on Earth's life-supporting systems, on which we fundamentally depend such as a stable climate, fertile soils and a protective ozone layer. The doughnut model considers an economy prosperous when all twelve social foundations are met without overshooting any of the nine ecological ceilings (K. Raworth, 2013).

Figure 1.1. Dougnut Economics. 2013. Retrieved from https://www.kateraworth.com/doughnut/ on 24/08/2021. Copyright K. Raworth.

In regard to bamboo, its environmental pillar is the most obvious because of its fast growth rate, its afforestation possibilities, the extremely low embodied energy required for the production of bamboo and its high carbon sequestration and carbon storage capacities. Nevertheless, one needs to take into consideration the entire process from the nursery, the harvesting process, the implementation to the end-of-life. If bamboo is fertilized, treated with toxic chemicals, transported over a long distance or addressed in a non-justifiable ecologic manner, it cannot be considered as an ecologically beneficial material just by the mere fact of its natural and renewable origin. Another challenge the bamboo industry needs to take into consideration, is the fact that a higher demand for bamboo, either as engineered products or as raw material, can lead to bamboo forest depletion and even deforestation caused by the extensive harvesting of mature bamboos whilst ravaging new shoots (Manandhar et al., 2019). One of the aims of the research is to examine how the demand for housing and construction material can keep up with the safeguarding of the biosystem formed by bamboo forests, whilst also using as much as this biosystem can handle to ensure a maximum carbon stock in the bamboo stem. Further on the different aims of the thesis will be summarized.

The relevance of the economic pillar consists in the first place of the gross domestic product growth. However, a model based on mere economic growth is no longer viable and the environmental resources should be treated as important economic assets as well (van der Lugt, 2017). Already in the 1970´s, the research ´*The limits to growth*` described the need for an economy in equilibrium with the natural capital. The goals of economic development and environmental conservation are not conflicting and could even reinforce each other (Meadows et al, 2004). Van der Lugt (2017) mentions that worldwide material consumption is predicted to grow at an annual rate of 2.8%. In this context, where a growing demand will put extra strain on the wood sector to ensure production capacity and current attempts to substitute techno-cycle materials, a bio-based economy with alternative preferably fast-growing plants such as bamboo, hemp, flax, miscanthus, fungi,.. has the potential to emerge. In comparison to the other bio-based materials, bamboo has the highest growth potential because of its versality, the fact that the entire plant (leaves, culm, shoots, roots..) can be used as well as the ongoing development of engineered bamboo products such as composites, particle boards, laminated and strand woven panels, endorsed by the fast-growth rate of bamboo, its high annual yield and its natural occurrence in the often indigent regions of the world whereby the cost of bamboo remains relatively low. In this context, the wages for those who plant, harvest and treat bamboo should improve. One of the possibilities to generate a higher income locally is by adding value to the bamboo. This can be done by adding a preservation treatment, processing bamboo poles into other engineered bamboo products or dispensing prefabricated modular bamboo elements (van der Lugt, 2017). Care has to be taken however that these ´new´ construction techniques or materials are not more expensive than existing techniques/materials or that toxic adhesives are not unnecessarily added. In this regard, the architectural design process can help to achieve an economically competitive construction material by using modularity and prefabrication processes in the design. One of the aims of this research is to examine if and how this modularity and prefabrication exactly benefits costs, ecological concerns and human or social issues.

The pillar of social sustainability is multidimensional and includes aspects ranging from social equality, inclusiveness, poverty reduction, education and disaster risk reduction. In general, poverty is caused by a lack of assets which can be either financial savings, physical resources such as land or equipment and education. Due to a shortage of these assets, households are often unable to meet basic needs such as food, housing, water and sanitation. This lack of basic services and infrastructure can cause serious health problems (Henrotay et al., 2006). Bamboo can play a significant role in poverty alleviation because adequate housing offers the potential to evolve in socio-economic growth. Besides, it will reduce the depletion of natural resources thereby diminishing the occurrence of climate-related natural disasters and ecological disruption of the climate. Another social benefit of bamboo is that basic carpentry tools and skills are already sufficient to construct houses and the bamboo construction techniques can be easily taught to people with none or basic masonry skills, including necessitous communities. By developing a bamboo-based construction industry, local and traditional skills can be preserved, new income opportunities can be generated and a stronger social cohesion can be obtained (Manandhar et al, 2019). Therefore, it is important to review how the workers at a bamboo plantation or at the construction site are being treated. Do they work with regulated contracts that ensure an economic viable wage and continued payments when ill or injured? How is the health condition of the workers ensured? Is child labour prohibited? Are unskilled workers being trained or educated to become more skilled?

When working on sustainable development in marginalized communities, the cultural emphasis is a crucial factor in project decisions. As a project in their community largely affects aspects of their lives and traditions an open dialogue, co-designing as well as holistic evaluation of the site of development are necessary. This allows for them to understand each other's thought process and their comprehension of the sustainable projects. By using the method of co-design, the beneficiaries' holistic needs are being considered and decisions and implementations can be made with respect to sociocultural and ecological factors (Grober, 2007; Wikipedia, 2010). One of the goals of this thesis is to show that the integration of shared knowledge, coworking and community building in social design processes is essential to the success there-of.

1.1.2.2 Sustainable building

In architecture, recent movements promote a more sustainable approach towards construction. One that develops smart growth, employs renewable energy, seeks to diminish greenhouse gas (GHG) emissions and builds on architectural tradition and vernacular design. This in contrast to brutalism, modernism and suburban sprawl with long commuting distances and consequently large environmental footprints. According to recent reports by the IPCC (Intergovernmental Panel on Climate Change), IEA (International Energy Agency) and GABC (Global Alliance for Buildings and Constructions), the building construction and operation account for 36% of the global final energy use, 39% of energy related carbon dioxide (CO_2) emissions and 28% of energy-related GHG emissions.

Because the building industry is a major source of energy consumption and gas emissions, it is necessary to go beyond the calculation of the pure emissions of a building or the operational energy consumption and address the full life cycle. A life cycle analysis should be performed including influential impacts such as extraction and processing of the raw materials, manufacturing, distribution, use, recycling and finally disposal (Röck et al, 2020; Woodard & Milner, 2016). Conventional building materials such as concrete and steel that have been widely used during the past century have a high embodied carbon and energy impact as a result of their production process, in contradiction to bio-based materials which have an intrinsically low embodied energy (Woodard & Milner, 2016). Bamboo is increasingly applied as a bio-based construction material for it provides several answers to problems the world and the construction industry are facing today: low carbon pollution (even an uptake), low embodied energy, low-cost, earthquake proof, widespread availability yet without the risk for deforestation. Bamboo is literally produced by solar energy and sequesters (instead of emitting) a high quantity of carbon during its 'production'-phase. In regard to circularity, also the renewability of bamboo plays a significant role. Whereas techno-cycle materials are finite materials, bio-based materials, when managed properly without over-exploitation, can offer a continuous supply of raw material. Finally, bio-based materials also involve a smaller dilemma in the waste phase. Multiple scenarios are possible in the end-of-life phase preferably in a cascading order with as little as possible value loss at each step, going from particle boards, animal fodder, bio-energy to composting (van der Lugt, 2017). The construction techniques used should allow for recycling/reuse, for example by using connections that are dismountable or bio-degradable. In this regard, the jointing of bamboo elements is essential to achieve 'reversibility' of a construction (VUB, 2019). Besides the production process of the applied materials in a construction, also the geographical location plays a role in sustainable building. Vernacular architecture, improved over the years by trial and error, takes into account the local climatic context in the design to reduce the need for active heating and cooling. Since the 1960´s, a growing number of buildings have become typologically identical, irrespective of their geographical location. It is however an illusion that we can build independent of natural conditions because more energy and other resources will need to be added to equilibrate this dysfunction (Krautheim, Pasel, Pfeiffer & Schultz-Granberg, 2014). Instead of mechanically cooling a construction, a building can also be cooled down by natural ventilation. The cooling potential of natural ventilation however greatly depends on the design, the materials and the building techniques used. It is here were bamboo can also have a positive impact. A load-bearing skeleton in bamboo can be designed as such that an optimized height is achieved, e.g. with prefabricated and proportionally sound modules.

1.1.3 Bamboo architecture and design

Several barriers keep bamboo from entering the conventional building industry. Architects as well as the construction industry often remain skeptical about the application of bamboo in construction mainly attributed to the poor image of bamboo and the unfamiliarity of the material by the stakeholders. Nowadays, architects have to cope with their clients or/and users, specialist engineering advisors, governmental bodies and the contractors. Each of these stakeholders can play a decisive role and needs to be willing to participate. Furthermore, architects sometimes have a misrepresentation of what is possible and logic when building with bamboo, sometimes even propagated by popular architectural media that illustrate the most amazing, yet temporary bamboo structures. Qualitative design seeks to blend the technical aspects with the aesthetic while making the technical look apparent (Ashby & Johnson, 2002). Design quality can only be achieved when the three quality fields of functionality, built quality and impact (a refinement of 'commodity, firmness and delight') all work together as overlapping areas of concern (Volker et al, 2008). It is for this reason that a section on aesthetics is unmissable. The question hereby rises what is considered as aesthetically pleasing and how can this be attained in a design process. Design is not a linear running but an iterative process and cannot be standardized easily. Yet, can there be drafted certain rules of thumb to follow? Can proportional design principles be reinvigorated in the current design process?

De Botton (2008) proposes several keystones that are interlinked with ethics and philosophy. A set of general guidelines can help architects in the design process. Also, the proportional systems are historically explained to give a wider context of their significance and relevance to bamboo design.

1.1.4 Background on the case studies in Brazil

The author has been living for 6,5 years in the Southeast of Brazil in the context of bamboo related projects and the PhD research. Initially, a community development project Bamboostic was set out in Camburi from the period 2004 to 2006 in collaboration with KU Leuven (Human Settlements) and the PUC Rio (Department of Engineering). Multiple bamboo constructions were built at that time with the community center with its 172m² as the largest and most impactful project. The main goal of Bamboostic was to provide tech-transfer from the university to the local community. To obtain an equilibrium between the three dimensions of sustainability (environmental, economic and social), it is imperative for an architect to understand in-depth the living conditions of the people for whom (s)he is designing. A participatory approach was therefore seen as crucial. This participatory approach implies that the decisions on the function, usage, location and other aspects that are not structural are made together with the community. Empathic design emphasizes the importance of an emotional connection between the designer and the inhabitants to understand better the social and cultural aspects. It is assumed that when people are engaged from the very beginning, they feel responsible for the project (i.e. ownership) and better commit to the success of the project, which typically leads to more sustainable outcomes in all dimensions of sustainability. This strategy proved to be essential for the adoption of the building as well as the bamboo construction techniques (Sandman et al., 2018). From 2015 to 2020, the author returned to Brazil to conduct his PhD research while continuing to experiment with bamboo in construction and support/execute new Bamboostic projects. In addition a technical quality analysis was performed on the community center which provided valuable insights on the aspects of durability of a bamboo construction. These findings are presented in this PhD research, alongside a theoretical overview of the aspects considered.

1.2 **Justification and positioning of the research**

1.2.1 Justification

Despite the fact that extensive research has already been conducted on bamboo, the majority of the research focusses on the engineering aspects. Research on the architectural aspects of bamboo in construction has only been done to a limited extent. Discussing the designed and constructed cases and the problems that occurred during construction and during the use phase can be a useful diagnostic tool for designers and architects to improve their designs. In the cases of the author, special attention has been given to design and construct newly developed joints and column designs which can be inspiring for others. Especially because there are more factors at play in a real-life construction than a laboratory testing set up can simulate. Design-based errors that lead to rapid degradation are seldom uncovered. As bamboo is an emerging construction material, exemplary buildings can play an important role to encourage a more widespread use of the material. In the transition theory as envisioned by Rotmans and Loorback (2009) demonstrated in

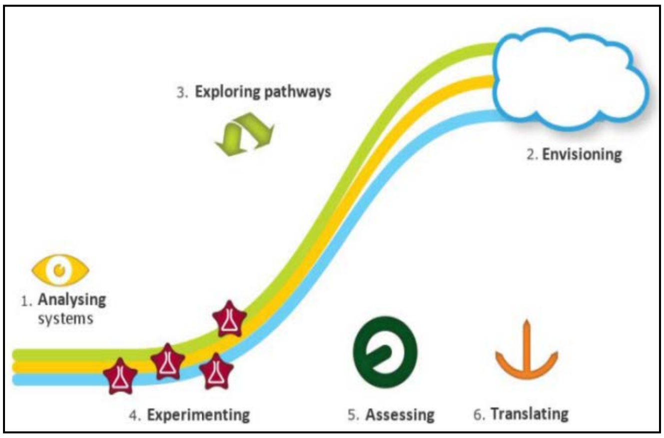

Figure 1.2. Transition to sustainable development. Retrieved from Transition in research. Research in transition. When technology meets sustainability (p. 20). by F. Nevens. Mol. VITO nv. Copyright 2012. VITO nv.

Figure 1.2, it is proven that new ideas follow a certain sequence of actions before they can lead to actual change or societal transition. In this sequence, experimenting is a first essential step followed by assessment. The latter is a key element before a so-called 'take-off' of new ideas and techniques can occur. When exploring new pathways, such as is the case in modern bamboo architecture, experimenting in the construction phase and afterwards assessing weaknesses and successes is essential to enable an upscale in the use of bamboo. Besides the challenges bamboo possesses in jointing techniques and conducive deterioration, integrative and well-executed bamboo designs based on sustainable building (economic, environmental and social) are imperative for there can be no widespread acceptation without changing the current perception-paradigm. An understanding of the material is crucial for bamboo architecture to become relevant and justifiable. In the first through a good comprehension of the material properties, secondly by deciding what type of bamboo and diameter are used best for the intended structural system and finally by deciding and designing the jointing method.

1.2.2 Positioning of the research in relation to other studies on bamboo

Universities have contributed significantly with research on bamboo in the past decades. One of the first universities to research bamboo was the PUC-Rio in the 1970´s at the department of Engineering Sciences under the supervision of Prof. Ghavami. In the Netherlands, interesting contributions on the topic were done by Prof. Janssen at TU Delft and around the same time, Prof. Liese at the University of Hamburg provided groundbreaking insights in the treatment of bamboo. China has produced, through INBAR and several universities, the largest amount of technical reports on all aspects of bamboo; from harvesting to treatment, construction, different usages and many more. In 2003, Prof. Hidalgo-Lopez at the Universidad Nacional of Colombia, contributed greatly with his publication "*The Gift of the Gods*", presenting an overview of his study on bamboo as a plant and as a construction material, widening the general public interest on bamboo. Currently, universities worldwide contribute with new research on bamboo, although it has to be noted that most of this research focusses on the engineering part of bamboo. In this context, worth mentioning is the research by Prof. Harries at the Pittsburg University on codes and norms and the characterization of bamboo materials, the LCA-studies on bamboo performed by Dr. van der Lugt at TU Delft, the research on bamboo structures and earthquake resistance by Prof. Truijlo at the University of Coventry, the research on taxonometry by Prof. Londõno at the National University of Colombia and finally the research on low-cost bamboo housing and earthquake resistance by Prof. Moran at the Catholic University of Guayaquil. Interesting studies with an architectural focal point is the PhD research on jointing techniques by Prof. Widyowijatnoko at the RWTH Aachen University, the research on prefabrication and modularization of bamboo elements by Prof. Achila at the University of the West of England and the future cities laboratory at ETH Zurich (Prof. Hebel). Many of these academics divulgate their research at conferences organized by the following interlinked institutions; INBAR (Beijing), WBO (World Bamboo Organization) and NOCMAT (Non-Conventional Materials and Technologies).

This research aims to contribute to the existing knowledge on bamboo construction by:

- providing a comprehensive overview of bamboo practicalities in construction, based on
    - Providing an overview of the mechanical and physical properties, treatment methods, sustainability and design elements,
    - A critical analysis of case studies performed by the author,
    - A durability analysis of the community center fourteen years after construction,
- introducing a classification for structural systems in bamboo architecture,
- contributing to the development of new jointing techniques based on:
    - Describing and discussing the jointing methods employed in the case studies,
    - Providing necessary criteria to support the development of new joints,

- assessing the life cycle environmental impact of two easy to employ bamboo column prototypes and comparing these with the impact of conventional materials,
- producing an evaluation framework that can be used by designers and architects to evaluate their bamboo design and to create an integrated design approach, and avoid design mistakes.
- assessing one of the cases built by the author in Brazil with the framework developed to illustrate its use and improve the framework.

1.3 **Outline of the research**

1.3.1 Aims / hypothesis

This research departs from the hypothesis that bamboo has a significant potential as a sustainable bio-based construction material, even more so when implemented in an innovative way, at low-cost and on the condition that one understands the material well in terms of its performance and structural characteristics because these determine how this material should be employed. The performance in this research alludes to the environmental, economic and social pillars in order to achieve a sustainable development. The author aims at filling the current knowledge gap by firstly presenting a theoretical outline of how bamboo in its raw form should be applied as a constructive element and secondly by discussing and evaluating, based on the relevant aspects retrieved from the literature, the constructions built by the author. Thirdly, an environmental impact assessment of two different bamboo columns is made to analyze the performance implications of a prototype bamboo column. Finally, addressing design evaluation as a critical yet under-researched domain, this study analyzes the design evaluation structure and its variables and criteria that guide its outcomes. The relevant findings are translated into an evaluation framework to accompany architects and designers to evaluate their designs and use bamboo in a correct, low-cost, innovative and sustainable way.

1.3.2 Structure

This dissertation is divided into three main parts. The **first part** is based on a literature study and is divided into four chapters and aims to extract the components that can serve as criteria for the evaluation framework and aspires to provide the reader with a holistic overview on bamboo in architecture. In chapter two, the **state of the art** on modern bamboo architecture is presented. The subsequent chapters discuss the theoretical aspects of bamboo according three components already applied since classical architecture; Utilitas, Firmitas and Venustas or Commodity, Firmness and Delight. Vitruvius established one of the first defined frameworks for criteria used to assess architectural design quality and is up till today an essential base in architectural theory. The first component ´**firmitas**` (chapter 3) focusses on the physical and mechanical properties of bamboo complemented with a synopsis of current standards and building codes. It moreover establishes a structural system classification and contributes with newly developed joints by the author to the existing jointing methods. Finally, this chapter addresses possible bending methods and bamboo´s fire resistance. The second component ´**utilitas**` in chapter 4 deviates slightly from the pure utility aspect that normally discusses the entire building envelope and in this case merely focusses on the performance of bamboo. The sustainability aspect of bamboo in its raw form is assessed by means of the environmental, economic and social pillars. Both the benefits as well as the challenges/points of attention are outlined. The final component ´**venustas**` is discussed in chapter 5. First, indications are given to obtain aesthetic quality and finally one of the case studies (the art gallery) is analyzed based upon these indications that interrelate to aesthetic qualities (with an emphasis on proportionality).

The **second part** of the research focuses on the description of the learnings of the practical expertise with bamboo as well as the assessment of the environmental impact. Chapter 6 discusses ten **case studies** designed and built by the author. These experiments, all executed between 2004 and 2019 in Brazil, are predominantly a combination of structural bamboo frames with rammed earthen walls.

Multiple of these were built as part of the community development project Bamboostic, in collaboration with the Human Settlements Program of KU Leuven and the Engineering Department of the PUC-Rio de Janeiro. Although a **life cycle assessment** is actually part of the environmental performance discussed in chapter 4, it is addressed separately in chapter 7 to allow for a more elaborate analysis. The environmental impact of two exemplary constructive columns as employed in the case studies is assessed. The assessment includes a detailed assessment of the two types of columns and a comparative assessment of both and with conventional construction materials (i.e. steel, concrete and wood). Van der Lugt has already done extensive research on the LCA of bamboo materials. Yet, this analysis aims to contribute to the preceding research by analyzing applicable bamboo column prototypes whereas van der Lugt performed the analysis on the raw and engineered bamboo material itself.

The **third part** of the research summarizes the findings of the previous sections and answers to the general research questions. Chapter 8 establishes an integrative **evaluation framework (EF)** for designers to evaluate or compose a bamboo design with emphasis on sustainability, innovation and cost reduction through prefabrication, efficient jointing and modularization. This evaluation framework is then applied on one of the case studies in order to establish whether additional adaptations to the framework are required and what these should consist of. Chapter 9 presents the **conclusions**, general contributions of the research followed by recommendations for future research. Figure 1.3 provides an overview of the structure of the manuscript.

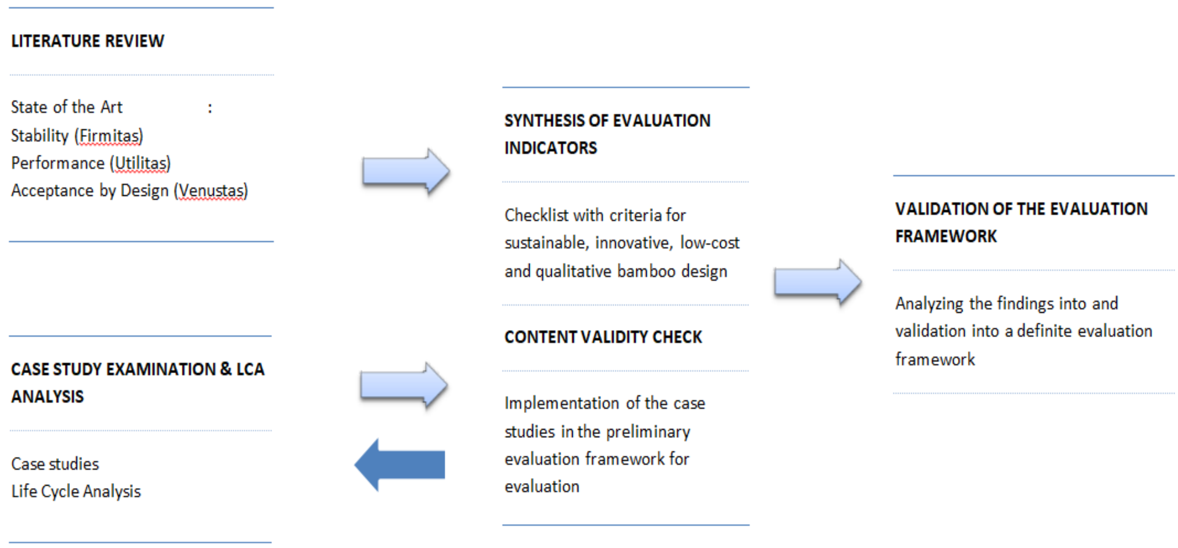

Figure 1.3. Scheme of the manuscript structure.

1.3.3 Limitations

It is not the intent of this research to discuss every possible bamboo application or to address a complete building envelope. This research remains restricted to structural load-bearing skeletons constructed with raw bamboo stems with an emphasis on sustainability, innovation and low-cost by means of prefabrication and modularity. Although in the future, the bamboo industry may shift its emphasis towards engineered bamboo products since the Chinese mimic engineered wood-based products in bamboo (van der Lugt, 2017) and companies such as Moso in the Netherlands distribute such engineered bamboo products to the European market, the author has decided not to discuss engineered bamboo products as a consequence of its personal architectural and constructive background in the load-bearing application of the hollow bamboo stem.

The author does not analyze bamboo structures designed or built by other architects, although a study hereon might reveal valuable insights. This research is limited to the discussion of cases that were executed by the author in Brazil between the periods of 2004 to 2019. Only a short overview is presented of the work of relevant bamboo architects and the techniques they generally apply. In this regard, the presumable subjectivity of the applied cases has to be noted as they were performed by the author himself and because the design approach follows the demands of actual clients or those of the community of Camburi. No laboratory tests were performed, either because the construction no longer exists or the extraction of the bamboo poles for testing could cause a detrimental effect to the construction. Therefore, the discussion of the case studies remains restricted to observation. In addition, a durability analysis was conducted on the community center a decade after being completed in 2006. Although it is difficult to draw general and objective conclusions, the mere observation regarding the design and construction process can proof to offer valuable key-indicators complementary to the preceding literature. Moreover, the findings from these case studies are cross-examined with the relevant literature found on these topics in order to enable extrapolations regarding the evaluation framework.

1.4 **Research questions and methodology**

1.4.1 Research questions

The research hypothesis as discussed in 1.1.7. is translated into five main research questions divided in various sub-questions.

A) Which structural criteria should be met in order to attain a qualitative and durable bamboo building?

- How can the stability of a bamboo construction be ensured?
- Which key factors have an impact on the durability of a bamboo structure? How can the service life be enhanced?
- What kind of structural systems can be distinguished in bamboo construction and what is the consequence in terms of durability and sustainability?
- How can joints/connections be designed to ensure fast construction at a low cost and low environmental impact?

B) Which key factors have an impact on the performance of bamboo as a construction material and need to be fulfilled in order to obtain a sustainable bamboo structure.

- Which factors play a role when it comes to environmental, economic and social performance of bamboo?
- How to build bamboo structures with an efficient resource (and energy) use?
- How can bamboo structures be designed to enable adaptability and circularity?

C) How can designers/architects achieve aesthetical, durable yet innovative bamboo architecture?

- Which factors determine the aesthetical quality of a bamboo design?
- To what extent can proportionality and prefabrication be valuable strategies in terms of durability and cost-reduction?

D) Which learnings can be drawn from the cases?

- Which successes or mistakes were noted that (dis)accord with literature?
- Which aspects proved to be beneficial to the sustainability, innovativeness and the cost?
- Which points of attention need to be included in the evaluation framework?

E) What conclusions can be drawn from the Life Cycle Analysis?

- What are the main drivers in the life cycle environmental impact of a bamboo column (two types) and hence what are the points of attention to limit the environmental impact of bamboo columns?
- How does the environmental impact of a bamboo column perform compared to conventional materials?

F) How can the evaluation framework contribute to more qualitative bamboo architecture?

- Which evaluation indicators can be defined to determine a holistic framework?
- How can these criteria be translated into a framework that enables the evaluation of bamboo designs?

1.4.2 Research methodology

To answer the research questions, a combination of methods has been used. First of all, a literature research was conducted. Published research on bamboo was searched for and synthesized. The literature review was limited to peer-reviewed papers published in English or Dutch with some exceptional ones in Spanish/Portuguese. Information from the institutions and the professors mentioned in section 1.2.2. was gathered and studied. References in these publications often led to other valuable information.

Nine bamboo constructions, designed and built by the author in Brazil, were assessed to complement the key indicators for the evaluation framework extracted from the literature study. The case study approach allows in-depth, multi-faceted explorations of complex issues in their real-life settings. The reporting aspect of a case study is presumably the most useful from the user´s perspective as it serves as a contact point between the user and the researcher. In this section the researcher preferably refrains himself from technical jargon and resort to clear explanations to help the user understand the implications of the findings (Tellis, 1997). The issue of generalization of case study research is a returning critic and Stake (1995) emphasizes that beside analytic and statistical generalization, a more intuitive, empirically-grounded generalization approach is required for case studies which he termed as a naturalistic generalization.

For the calculation of the environmental impact, the LCA software SimaPro v.9.1.0.8 is used and for the inventory data, the generic database Ecoinvent v.3.0 (compiled in October 2016) is applied, alongside with the ELCD library (European Life Cycle Database v.3.2, November 2016.). Although the MMG-method was used to calculate the environmental impact of the bamboo columns, special attention is given to the effect on climate change (in line with the IPCC 2013 GWP 100a method) because this is one of the most problematic environmental issues the world is facing to date, requiring urgent action.

The findings of the research and case studies determined the criteria for the evaluation framework. A comprehensive scheme was kept intentionally as compact as possible for it to be a workable and interactive user friendly framework. The framework was applied to one of the case studies in order to establish whether any adaptations or improvements could be made.

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PART I:

LITERATURE STUDY

CHAPTER 2 State of the art on the use on bamboo architecture

2.1 Introduction to the literature study

Part I of this dissertation consists of a literature study in order to gain insight in bamboo as a sustainable construction material. The first chapter presents an overview of contemporary bamboo constructions based on architectural publications, reviews and books. As the structural system and jointing method of bamboo are the most significant aspects in determining the building´s appearance and overall construction techniques, the construction methods other contemporary bamboo architects apply is discussed. The aim of this chapter is not to give an exhaustive overview of each construction method nor of every architect or engineer working with bamboo. Only the most influential bamboo architects and projects are mentioned.

After discussing the state of the art on bamboo architecture, more background information on bamboo is given based on three components: stability, performance and appearance in order to understand their impact on sustainable, low-cost and innovative bamboo construction forming the critera for the evaluation framework, the subject of this dissertation. These three subdivisions derive from Vitruvius whom determined this ´triad` of characteristics for architecture in his ten books on architecture: Utilitas, Firmitas and Venustas (Vitruvius, 1999). It is generally assumed that these three elements provide a holistic overview of architecture whereas Firmitas discusses the structural stability of a construction, Utilitas covers building performance and appropriate spatial accommodation and Vitruvius elaborates in Venustas how a timeless and attractive building appearance can be obtained based on universal laws of proportion and symmetry. However, it has to be noted that the original subcategories as described by Vitruvius (1999) are interpreted slightly differently.

The first component **Stability** is the most straightforward of the three terms. Every building is supposed to be firm and stable. A construction has to withstand its own weight, the loads of use and forces from wind, water, snow, earthquakes, etc. Chapter 3 discusses the mechanical properties of bamboo and outlines different structural systems and jointing possibilities in bamboo. Moreover, the codes and norms on bamboo are compared to each other and the fire resistance and bending of bamboo is discussed.

The second component **Performance** deviates slightly from the original Utilitas. In Vitruvius texts Utility is about the function of a building as well as its role as a protective shelter. The function of a building influences the different spaces as well as their dimension and form. The protective form of a building is most evident in its building envelope, the separator between the inside and outside environment including resistance to air, water, heat, light and noise. It included architectural aspects such as light, orientation, ventilation, protection, etc.. As not an entire building, but merely the structural frame is the scope of this research, Utilitas will not be discussed in the true Vitruvian sense. In this research, Chapter 4, Utilitas is regarded upon as the performance on structural level. What are the environmental, social and economic consequences when applying bamboo in a construction? What is the impact of the use of bamboo on the building envelope?

The third component **Aesthetic Quality** is probably the most subjective. What is considered to be beautiful is a relative aspect which varies in different societies and eras. Whereas Vitruvius describes in Venustas clear criteria for beauty as assumed in the Greek and Roman architecture, contemporary architecture possesses few or nearly no rules for beauty for the architect should be free. Although attempts were made to create objective beauty such as the Modulor by Le Corbusier, these guidelines were not as accepted as the rules in classic times.

2.2 **State of the art on bamboo architecture**

2.2.1 Introduction

Bamboo as a construction material has many applications ranging from scaffolding, bridges, fencing to housing. Besides these applications of bamboo in its raw form, bamboo can also be processed into strips, laminated or strand-woven products for applications in walls, flooring or composites and its fibers can also be applied to reinforce concrete (Heinsdorff, 2011; Minke, 2012). As this research focusses on the use of raw bamboo stems in structural applications for sustainable and low-cost housing, other potential bamboo applications will not be further discussed. The majority of bamboo construction knowledge relies on cultural tradition. It has been used in vernacular architecture for many centuries (or even millennia) predominantly in South Asia, East Asia and the South Pacific and to a smaller extent in Central & South America and Africa. The utilization of bamboo in construction is directly linked to its availability in these tropical and subtropical climatic regions (Ghavami, 2009). All parts of a house, from structural columns to walls, floors, doors, windows and even roofs can be provided in bamboo. Although different types of such vernacular bamboo constructions can be found around the world, it can be noted that for the structural frame the bamboo poles are connected by lashings or pins and woven bamboo strips are used to compose the walls and floors. Despite this long tradition of using bamboo in construction, bamboo is considered an inferior construction material, probably due to the low-cost, abundant availability and predominantly artisanal applications often of poor quality (van der Lugt, 2017). Bamboo gained a renewed interest as a building material during the global shortage of housing materials, especially the timber industry, in the 1980´s. In the beginning this renewed interest was mainly focused on finding a cheaper substitute for timber to construct cheaper houses in developing countries (Manandhar et al., 2019). To develop bamboo as a sustainable construction material, in both engineering and cultural terms, one must evaluate these vernacular building techniques and develop an equivalent design method that improves the performance (Sharma, 2010). Although bamboo is officially a grass, the chemical composition of bamboo is almost equal to wood both existing of water, hemicellulose, cellulose and lignin. Because bamboo exhibits such similar properties to timber and the fact that forests worldwide are under pressure for their timber, bamboo has become of increasing interest to the timber industry. Even though bamboo will certainly not replace wood, it can offer a sustainable alternative (Heinsdorff, 2011). There exist approximately 1.200 bamboo species worldwide, of which 750 in Asia and 430 in the U.S. In the U.S., the greatest diversity is found in Brazil where there are twice as many bamboo species as in Venezuela and Colombia together (Hidalgo-López, 2003; Bystriakova, Kapos & Lysenko, 2004). There are vast differences between the various genera of bamboo and only six species are generally considered suitable for construction: Bambusa, Chusquea, Dendrocalamus, Gigantochloa, Guadua and Phyllostachys (Minke, 2012).

Because of the efforts and contribution of several architects in the past two decades bamboo has also successfully been used outside vernacular architecture. They showcased the possibilities of the material to a wider public at exhibitions, restaurants and hotels. Additionally, these projects have been mediatized worldwide. As such, bamboo has gained popularity, even in Europe and Northern America where bamboo types used for construction do not natively grow. Although current experiments of growing bamboo outside of its traditional distribution could enhance this. When looking at this contemporary bamboo architecture and the methods of jointing used, two main streams can be differentiated. One that applies bamboo in a more traditional way and where jointing is done by rope lashings, although often executed with more challenging and organic designs than traditionally was done. Another stream applies a more modern approach, where bamboo is used less organically and connections are made with steel and/or concrete. It can be arguably said that bamboo architects in Asia tend to apply more lashed joint techniques while European and (North- and South-) American architects resort to steel and concrete connections. Although this is of course not applicable to every single architect working with bamboo, it is a tendency that can be noticed, probably due to the long artisanal traditions with bamboo and lashing in Asia. In this context, Ghavami points out the following; *´At present time, even the most modern construction where bamboo is used, relies on a craft approach, with the know-how of construction techniques restricted to a small group of researchers, engineers and architects. To enable wider application standardization and a definition of a correct construction practice is required`* (Ghavami, 2009, p.3). The greatest danger for the reputation and a more widespread application of bamboo exists nowadays in the fact that many architects and/or designers insufficiently fathom the material and start using it without proper background information or building experience. In the media many contemporary and even temporary designs appear with bamboo that looks spectacular at first sight, but raises questions with the author whether these can withstand time as bamboo culms are fully exposed to sun radiation and precipitation or even green bamboo is applied.

2.2.2 Overview of contemporary bamboo architects

Linda Garland, Bali-based, was one of the pioneers of modern bamboo architecture. As a creative designer, Linda integrated giant bamboo into many of her interior designs. She designed sofas, beds, chairs, jewelry,.. Many of her clients were very high profile, such as David Bowie, Richard Branson and others, thereby spurring the interest in bamboo by a wider public. In 1993, she founded the Environmental Bamboo Foundation, a non-profit organization that has been instrumental in the development of the modern use of bamboo (environmental bamboo foundation, 2021).

Simón Vélez is a Colombian architect whom started building with bamboo about 30 years ago and created instead of lashings, a joinery system by filling the connections with mortar using bamboo as a permanent structural element. As Vélez explains in an interview: *´I discovered that injecting liquid cement at the points where I wanted to make joints and then inserting steel plates and screws, I could make efficient connection points. From that moment on, bamboo became for me a real "vegetable steel". I had discovered a tensile bond strength for bamboo that no one before had achieved`* (Fairs, 2014). Vélez designed and built over 300 bamboo constructions (Simonvelez.net, n.d.), but became internationally known designing and building the bamboo pavilion at the Expo 2000 in Hannover (Germany) commissioned by the ZERI Foundation. Vélez designed a circular bamboo structure (40m diameter) with a seven-meter peripheral overhang for the bamboo to be protected and no window panels would be needed as seen in Figure 2.1. The two-story building with a total of 2.150m² was structurally entirely made with Guadua bamboo. Additionally, cement and copper for lifting the bamboo from the floor and terracotta tiles for the roof were used. Minke articulates that it was the first time for a bamboo structure to receive a building permit in Germany as there did not exist any regulations or a building code for bamboo in Germany in 2000. The Zeri Foundation and Vélez were obliged to build a one-to-one scale model in Manizales, Colombia. Lindemann and Steffens, two German engineers, came to Manizales to test the construction. They attached loads (sand and water) to the building while measuring the resistance to the applied forces. Afterwards, the building permit was granted yet with perquisite that the pavilion in Germany was built by the same team as in Colombia. With 6.4 million visitors, the bamboo pavilion was the most popular construction of that World Expo (Minke, 2012; Lindeman & Steffen, 2000).

Other famous projects by Vélez are the temporary bamboo church in Pereira Risaralda, Colombia built in 2002 (Figure 2.2) the Nomadic Museum in Mexico City, Mexico built in 2008 (Figure 2.3) and the Indian Pavilion at the Expo 2010 in Shanghai China, in collaboration with Sanjay Prakash (Figure 2.4) (Simonvelez.net, n.d.). The latter is the world´s largest bamboo dome. The dome is 35m in diameter and 17m high. The structure consists of 36 arches, each formed with a triangular section of six bamboo canes. The dome supports a micro-concrete shell and is covered with earth and live plants forming an ornamental design with integrated copper plates, inspired by the ´tree of life` (Minke, 2012).

Figure 2.1. Bamboo pavilion at Expo 2010 Hannover. Retrieved from Building with bamboo (p.133) by Gernot Minke. 2012. Basel, Birkhäuser. Copyright Birkhäuser.

Figure 2.2. Bamboo church in Pereira, Colombia. Retrieved from Building with bamboo (p.119). by Gernot Minke. 2012. Bäsel. Birkhäuser. Copyright Birkhäuser.

Figure 2.3. Nomadic Museum in Mexico City. Retrieved from Building with Bamboo (p.121) by Gernot Minke, 2012. Basel, Birkhäuser. Copyright Birkhäuser.

Figure 2.4. Indian Pavilion at Expo 2010 Shanghai China. Retrieved from Building with Bamboo (p.133) by Gernot Minke. 2012. Bäsel. Copyright Birkhäuser.

Originally, a master carpenter in Germany, **Jörg Stamm** became an apprentice of Simón Vélez in Colombia, where he resided after joining the Peace Corps in Ecuador. He is credited for building the longest bamboo bridges in the world (Conbam.info, 2005). Jörg Stamm completed a footbridge in 2005 in Santa Fé de Antioquia, Colombia with a 30m span and 3m free width. Figure 2.5 shows this bridge built with 600 canes of Guadua. The arched elements are formed by five bamboo canes held together in a permanent curve with timber nails for which bamboo with a natural curvature was selected. The bridge floor is in concrete and the roof in terracotta tiles. Jörg Stamm built another bridge in 2008 similar to the one in Santa Fé with this difference that the bridge in Cúcuta, Colombia, is foreseen with a membrane roof instead of a terracotta-tiled roof which is much heavier. Jörg Stamm also designed a 22m long access bridge for the Green School (Minke, 2012).

The Green School is an eco-friendly school set up by the Canadian jewelry designer **John Hardy** and his wife Cynthia in Bali, Indonesia (Greenschool.org, 2019). The school was completed in 2008 and encloses multiple bamboo buildings spread over the site (Figure 2.6 andFigure 2.7). The school consists of several classrooms, a gymnasium, a kitchen, a kindergarten and an administrative center. The heart of the school is a three story building in bamboo. The roof is shaped in the form of three nautili spiraling into one another and the structure is designed as such that no walls are needed allowing for cross-ventilation. Dendrocalamus Asper (diameter <20cm) and Phyllostachys Aurea (diameter 2cm) are used. The connections are made with lashings and bamboo pins (Greenschool.org, 2019; Minke, 2012). In 2010, his daughter **Elora Hardy** entered the bamboo business and started her proper design office called Ibuku (Ibuku.com, 2019). Ibuku has designed multiple bamboo guesthouses on and close to the green school site that can either be rented by tourists or are privately owned such as the Sharma Spring residence in Figure 2.8. For the execution of their projects, Ibuku works closely with the construction firm PT Bambú. The houses designed by Ibuku are constructional very challenging and one of a kind. As Elora Hardy states on her website; *´With our organic designs, we defy conventional bamboo building´* (Ibuku, 2019). In their projects, every detail is designed and locally made in bamboo, from the structure to the flooring and even the furniture (Ibuku.com, 2019). In an interview, she expresses the fact that their buildings are as expensive as a conventional high-end villa as the lower cost of the bamboo is overhauled by design and craftsmanship hours (Mertens, 2019).

Figure 2.5. Bamboo bridge Santa Fé, Colombia. Retrieved from Building with Bamboo (p.151) by Gernot Minke, 2012. Basel, Birkhäuser. Copyright Birkhäuser.

Figure 2.6. The Green School, Bali. Retrieved from Ibuku website. 2019. ibuku.com/heart-of-school. Copyright Ibuku.

Figure 2.7. The Green School, Bali. Retrieved from the Ibuku website. 2019. ibuku.com/heart-of-school. Copyright Ibuku.

Figure 2.8. Sharma Spring Residence, Bali. Retrieved from the Ibuku website. 2019. ibuku.com/sharma-springs-residence. Copyright Ibuku

Anna Heringer is a German architect and honorary professor of the UNESCO Chair of Earthen Architecture, Building Cultures and Sustainable Development. She does not only focus on bamboo but also other bio-based materials such as rammed earth and mud. Heringer resided a year in Bangladesh hence her strong link to this country. Since 1997, she is also actively involved in development cooperation in Bangladesh. For the METI School in Rudrapur, Bangladesh, she won the Aga Khan Award for Architecture in 2007. She argues that "*sustainability is a synonym for beauty*" (Anna-heringer.com, 2019). Heringer combines local materials such as bamboo and cob-style earth with modern building components (Figure 2.9). The building itself consists of two orthogonal, two-story sections connected by an open staircase. The upper floor is made of a bamboo structure that rests on a massive loam base. It is constructed entirely by hand by local people, without the need for machinery or dependency on outside market. The joints are made with rope lashings. In this community-built structure, she proves that 'progress' can be ecologically sensitive and support local craftsmanship at the same time. (Anna-heringer.com, 2019; Minke, 2012).

In 2016, on the account of an international bamboo architecture biennale in the village of Baoxi (China), twelve architects including Kengo Kuma, Anna Heringer, Simon Vélez and Vo Trong Nghia were invited to demonstrate the possibilities of bamboo in various constructions (Kwok, 2017_a). Unlike most biennales, each pavilion and structure hosted and served a specific purpose such as the ceramics museum designed by Kengo Kuma or the youth hostel designed by Anna Heringer. There was also a bamboo bridge, art & design hotel, restaurant and a ceramics atelier (Kwok, 2017_a). The youth hostel by Heringer (Figure 2.10) was influenced by the rich tradition and heritage of the Baoxi and hosted a guesthouse, a female and a male hostel. The form and weaving technique of traditional baskets was translated to the structures, again with the aid of lashing techniques. A rammed earth core inside a woven skin provided sleeping units designed like Chinese lamps (Kwok, 2017_b).

Figure 2.9. METI school in Rudrapur, Bangladesh. Retrieved from Anna Heringer´s website. 2019. http://www.anna-heringer.com. Copyright Julien Lanoo.

Figure 2.10. Bamboo hostel in Baoxi, China. Retrieved from Anna Heringer´s website. 2019. http://www.anna-heringer.com/index.php?id=68. Copyright Julien Lanoo.

Another pioneer is the Vietnamese architect **Vo Trong Nghia**. Since establishing his firm in 2006, the Vietnamese architect has completed many bamboo projects, including restaurants, bars, hotels and Vietnam´s national pavilion at the 2015 Milan Expo (Votrongnhia.com, 2019). He elaborates his designs on the technique of bundling multiple small diameter bamboos together by rope lashing. The wind and water café, built in 2006, is one of Vo Trong´s earliest experiments to use bamboo with a contemporary architectural expression (Figure 2.11). The roof, made by a combination of bamboo and steel tensile members, provides an open space reaching a width of 12-meters. The V-shape was generated to maximize the wind flow entering the building (vtnarchitects.net, 2020). Another well-known project by Vo Trong Nghia is the Naman Retreat Resort near Danang, which contains a hotel, 80 bungalows, a conference hall, a beach bar and a restaurant. As this resort aims to achieve an atmosphere suited for relaxation, Vo Trong Nghia used bio-based materials such as greenery, stone and bamboo. The beach bar, reception and the conference hall are made of bamboo. The beach bar has a pitched roof created by eight bamboo frames. Each frame consists of bended and straight bamboos connected by bamboo nails and rope lashings (vtnarchitects.net, 2020). The bamboo poles for this beach bar were all naturally treated in situ, a process consisting of bending by fire, soaking in water and mud in order to diminish the sugar content in the stem to avoid insect attacks. A procedure that needs four months to obtain bamboo of a better quality. The frames were prefabricated on the ground, a construction method that according to Vo Trong Nghia proved to be very efficient and facilitated the quality control during the construction (Archdaily.com, 2015). The conference hall in Figure 2.12 consists of two parallel spaces; a closed hall with a span of 13,5m and an open corridor with a span of 4m. The roof height is 9,5m. Multiple small diameter bamboos are tied together with rope lashings to form the structural frame (vtnarchitects.net, 2020). Several times Vo Trong Nghia applied other jointing techniques such as for example in the Diamond Community Hall was a weaving technique was applied, yet he prefers to apply the bundling technique of multiple small diameter bamboos with rope lashings.

Figure 2.11. Wind and water café. Retrieved from VTN Architects website. 2019. Copyright Hiroyuki Oki. http://votrongnghia.com/projects/wnw-cafe.

Figure 2.12. Conference hall in Naman Retreat Resort. Retrieved from VTN Architects website. 2019. Copyright Hiroyuki Oki. http://votrongnghia.com/projects/naman.

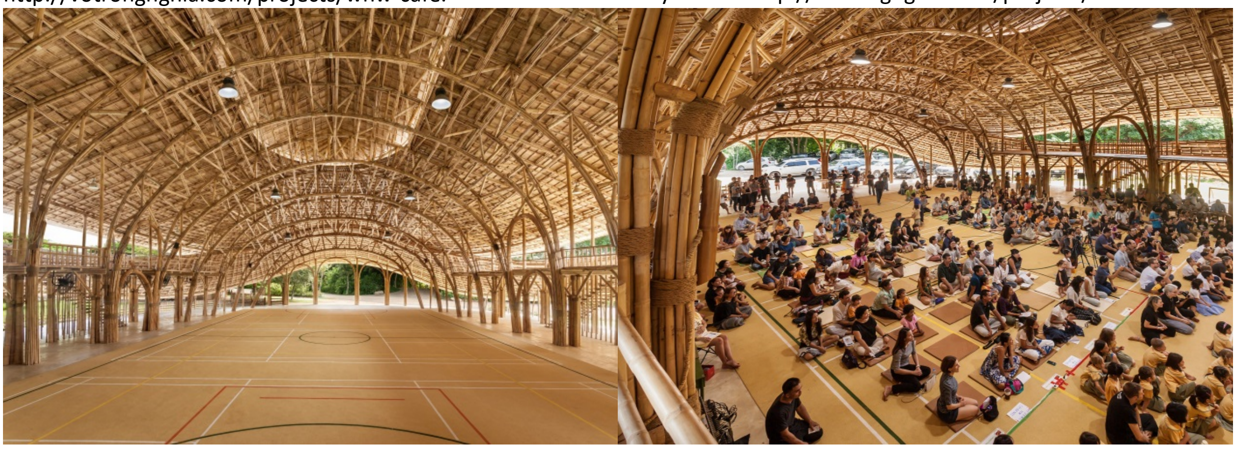

Figure 2.13. Sports hall Panyaden Int. School, Thailand. Retrieved from Chiangmai Life Construction website. 2019. https://www.bamboo-earth-architecture-construction.com/portfolio. Copyright CLC.

Chiangmai Life Construction is an architectural firm from Northern Thailand that won several (inter)national awards as recognition for its flowing designs (bamboo-earth-construction.com, 2019). Their designs remind the way Ibuku applies bamboo, however in their more recent designs they also bundle smaller bamboos to achieve bending equal to Vo Trong Nghia´s techniques. Figure 2.13 illustrates a well-known project, a 782m² bamboo sports hall for the Panyaden International School. The innovative structural design is based on prefabricated bamboo trusses with a span of 17 meters without steel or other reinforcements. These trusses were prebuilt on site and lifted into position with the help of a crane (bamboo-earth-construction.com, 2019).

Markus Heinsdorff is a German installation artist active in the areas of design, architecture and photography and prefers to work with materials available in the surrounding of the installation site (Heinsdorff.de, 2017). He spends a great time studying the design and technical possibilities of bamboo in Asia resulting amongst others in a series of pavilions for Germany during the EXPO 2010 in Shanghai, China (Heinsdorff, 2011). His use of bamboo does not remind of traditional construction methods used in Asia but occurs in a modern context with steel, concrete and translucent membranes such as ETFE and polycarbonate. For the German-Chinese house (Figure 2.14) Heinsdorff designed and built a two-story bamboo membrane structure of 330m². He developed new forms of connecting bamboo culms together and to connect to the membrane film for the façade and roof. The bamboo culms were prefabricated in a warehouse and tested by the University in Darmstadt. Steel connectors are inserted into the open hollow cavities on the outside edges of the bamboo and filled with a low water/binder innovative concrete mix formula (Figure 2.15). His objective to use steel connectors was to significantly increase the load-bearing properties for tensile and compressive forces on the nodal points (Heinsdorff, 2011). This high-tech manner of connecting bamboo culms facilitates the prefabrication process and later (re)assembly, yet increases the building cost.

Figure 2.14. The German-Chinese house at the Expo 2010 in Shanghai. Retrieved from Heinsdorff´s website. 2017. https://heinsdorff.de/en/work/installations/expo-shanghai. Copyright Markus Heinsdorff.

Figure 2.15. Detail of German-Chinese house. Retrieved from https://heinsdorff.de/en/work/installations/expo-shanghai. 2017. Copyright Markus Heinsdorff.

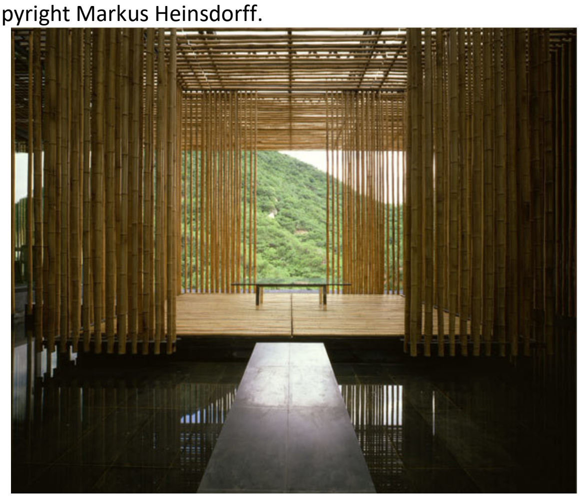

Figure 2.16. Great Wall Bamboo House, China. Retrieved from Kuma´s website. 2019. https://kkaa.co.jp/works architecture/great-bamboo-wall. Copyright S. Asakawa.

Although **Kengo Kuma** has used bamboo in several of his projects and exhibitions, he never utilizes bamboo in a structural manner. For the Great Wall House built in China in 2002 (Figure 2.16), bamboo served as a filter between the spaces instead of walls or doors. Kuma enjoyed the contrast between bamboo and the solid stone of the Chinese wall itself. He views bamboo as a symbol of cultural interchange between Japan and China as it was China was who brought bamboo to Japan (Kkaa.co.jp, 2019; World-architects.com, 2002). Another example of a bamboo project by Kengo Kuma is a bamboo ring at the London Design Festival in 2019. The structure is a two-meter-diameter ring made by combining strips of the bamboo Phyllostachys Edulis with a layer of carbon fiber (Frearson, 2019).

2.3 Use of bamboo as constructive element in the Atlantic Rainforest of Brazil

Bystriakova, Kapos & Lysenko (2004) studied the distribution and biodiversity of bamboo. For Brazil, São Paulo state is indicated as the area with the largest number of potentially co-occurring woody bamboo species. At generic level, the Brazilian state Minas Gervais appears to have the highest concentration of woody bamboo diversity (nine co-occurring genera) while others previously had reported a higher generic diversity of all bamboo species (woody and herbaceous) in the coastal state of Espírito Santo (Bystriakova et al, 2004). These data confirm the importance of the Atlantic Rainforest of Brazil for the bamboo diversity in South America as the Atlantic rainforest extends from São Paulo state to the state of Espirito Santo above Rio de Janeiro and Minas Gerais.

South America doesn´t have a deep-rooted tradition in the use of bamboo for construction as Asia or the South Pacific has, with exception of the region of southern Colombia and northern Ecuador were the availability of Guadua is widespread and inherently its application for housing (Manandhar et al, 2019). The baharaque technique used in these regions consist of a composite structure of load bearing pillars in Guadua with single or double horizontal lines of reeds and walls covered with a compound mixture of earth, straw and rubble (Tuccillo, 2010). The FAO studied the exploitation of bamboo in Latin America and concluded that cultivation remains limited to local use of species. Only in Colombia, Ecuador and Brazil bamboo plays a more significant role in the local economy. In the northeastern region of Brazil the largest private area of planted bamboo can be found with 30.000ha of Bambusa Vulgaris providing raw material for a paper mill. Interest in bamboo, particularly in its industrial utilization, is growing rapidly (Lobovikov et al, 2007; Manandhar et al, 2019).

The reason for this lack of bamboo tradition in South America, and more specifically in Brazil, can presumably be diverted from history. The Indians traditionally applied bamboo and wood in their architecture. However within the first century after being colonized, 90% of the indigenous people died because of warfare and diseases brought by the colonists. In the following centuries, thousands more died enslaved in rubber and sugar cane plantations. There are about 305 remaining tribes living in Brazil today, totaling about 900.000 people, which are a small representation of what it once was (survivalinternational.org/tribes, 2019).

The Portuguese colonizers, when building their proper settlements, used the Portuguese style of building of typical white washed walls combined with woodwork for the structure, roof, windows and doorframes. As bamboo suitable for construction did not exist in Europe at that time, the Portuguese had no experience with the material and never considered its application (Tuccillo, 2010). Moreover, it was perceived as a material from the local inhabitants, ´the poor`. This perception of bamboo is still widespread. In most cultures that use bamboo, from China to India, it was the poorest people who used bamboo as building material for their homes because it is the cheapest construction method (Mertens, 2019).

When the Indigenous population did no longer suffice for all the work that needed to be done on the plantations, the Portuguese started to import slaves from Africa, whom brought also their proper building traditions along with them. This vernacular construction technique called "pau-à-pique" or "wattle and daub" exists of vertically put stakes, or wattles, woven with horizontal intertwining twigs or branches and afterwards daubed with clay or mud. Wattle and daub is one of the oldest known building techniques for making a weatherproof structure (Britannica.com, 2018). Wattle and daub is similar to the bahareque technique from Colombia and Ecuador, despite the fact that the bahareque technique utilizes bamboo instead of twigs or other branches. When poorly executed and left unfinished without any plastering, the wall can deteriorate in a short period because the clay dries and cracks. These cracks become a target of insects and rodents that hide themselves in these vents of the walls. The untreated wood put directly into the earthen ground is subject to deterioration. More advanced techniques provide a stone or cement foundation that rises at least 30cm above the ground to avoid moisture upward. When properly built, wattle and daub walls ensure that temperatures are kept at a constant level inside the room. Heat or cold are hold/released in accordance to the outside temperature and the porosity of the walls allows a free flow of air ensuring continuous ventilation (De Araujo et al, 2016). Although some "pau-à-pique" houses such as in Figure 2.17 can still be discerned in Camburi (location of most of the case studies in this dissertation), most of these houses have been replaced by mostly unfinished and more expensive brick and concrete houses, resulting in the fact that knowledge and tradition of building wattle and daub houses is slowly getting lost.

Figure 2.17. Wattle and daub house in Camburi, Brazil. 2006.

There are currently few architects actively working with bamboo in the region of the Atlantic Rainforest of Brazil. **Celine Llerana** from Ebiobambu has many years of experience. She started in 2002 and is active in bio architecture and bamboo technologies. Besides workshops on building with bamboo organized on her property in Visconde de Mauá, she also does private commissions (Ebiobambu.com.br, 2019). In her works, she applies the techniques of Simon Velez. Celina´s former partner **Roberto Zunn**, who is a bamboo builder and not an architect, continued working with bamboo on his own. One of his accomplishments in the region are a restaurant and yoga area for the Bananal Ecolodge in Ubatumirm (www.bananabamboo.com.br, 2019). Former students of professor Ghavami at the PUC-University, **Mario Seixas and João Bino** started in 2004 Bambutech which is specialized in bamboo structures for events. As their focus is on temporary constructions, they use rope-lashing techniques for their connections (Bambutech.com.br, 2018). **Danilo Candia,** whom started by suppling bamboo shoots started Bambu Carbono Zero active in bamboo building. Currently he has a showroom in São Paulo and a work atelier in Cunha and mainly does bamboo finishing, doors/shutters, garden fences and bamboo structures commissioned by architects. For the structural bamboo frames, he applies Markus Heinsdorff´s type of connection techniques with steel and concrete (Bambucarbonozero.com.br, 2019). Although not actively working on bamboo, yet still worth mentioning is **Johan Van Lengen**, a Dutch architect living in Rio de Janeiro whom started in 1987 the TIBA Institute for bio-architecture. His book ´The barefoot architect` is a well-known work on bio-architecture and contains information on various low-scale bamboo construction techniques (Van Lengen, 2002; Tibarose.com, 2019).

Furthermore, there are various Brazilian architects who have used bamboo in some of their projects without limiting themselves just to bamboo as they work with a wide range of materials. An example hereof is **Leiko Motomura** from Amima Arquitetura who has designed the Max Feffer Institute in Pardinho, São Paulo and a summer classroom for the Anama Key institute, both with a bamboo roof structure. For the connections in the Max Feffer Institute Simon Velez´s techniques were used. A steel rebar was inserted in two connecting bamboos fixated with concrete. More interesting however, is the bamboo space frame with steel plates used for the Anama Key Institute in Figure 2.18 (Amima-arquitetura.com.br, 2019). An advantage in the utilization of a bamboo in a space frame is that it enables prefabrication on the floor, replacement of bamboo when needed and is adjustable to different building sizes and shapes. Nonetheless, space frames with bamboo are hardly used by designers. Other known Brazilian architects that applied bamboo in their designs are Marcio Kogan and Vilela Florez, although merely as a finishing material (doors, shutters, interior divisions, etc.). In North Brazil, ´casa bambu` designed by **Vilela Florez** (Figure 2.19) is provided with a structural masonry exists of vertical concrete ribs where short bamboo sticks arranged in a fishbone pattern are placed in between for aesthetical reasons (Vilelaflorez.com, 2017). **Marcio Kogan** of Studio MK27 used in his design for a vacation house in Ilha Bela bamboo shutters to close off the spaces. The execution of this project was done by Bambu Carbono Zero (http://studiomk27.com.br, 2019).

Figure 2.18. Anama Key Institute in Cotia (SP), Brazil. Retrieved from Amima Architecture´s website. 2019. http://amimaarquitetura.com.br/projetos/institucional/amana-key-saladeauladeverao. Amima Architects.

Figure 2.19. Bamboo house in Pipa (RN), Brazil. Retrieved from Villela Florez´s website. 2017. www.vilelaflorez.com. Copyright Guillermo Florez and Maira Acayaba.

2.4 Conclusion

Thanks to its mechanical properties (lightweight, highly elastic and ductile), low environmental impact, low-cost and abundant availability, architects have in the past decades rediscovered bamboo for construction purposes, ranging from private residences, airy pavilions to bamboo bridges. The examples discussed in this chapter are an illustration of this renewed interest. It can be noticed that most of these examples are built in the tropical region where bamboo naturally occurs. The bamboo constructions built by John and Elora Hardy, Chiangmai Life Construction, Vo Trong Nghia, Anna Heringer, Markus Heinsdorff and Kengo Kuma are all situated in Southeast Asia. Simón Vélez and Jörg Stamm are predominantly active in Colombia, South America. Only few architects built with bamboo in Europe, Australia or Africa. It is unclear if this is due to the fact that there exists little tradition in building with bamboo in those continents or wether other factors play a role as well. It is clear however that bamboo often has a negative connotation as a rustic, tropical, handicrafted poor man´s material (van der Lugt, 2017). To overcome this connotation, good examples of bamboo buildings from various architects help to inspire in creating new bamboo architecture. Qualities in these examples that help overcome this negative connotation are the manner in which they are constructed in a aesthetically contemporary architectural manner, in a cost-efficient way (largely depending on working hours – speed of construction is essential).

It can be furthermore noticed that each architect applies bamboo in his/her way and that a wide range of bamboo structures, joints and designs are possible. The jointing techniques are in most cases done artisanal and require specialized craftsmanship. This fact makes bamboo construction difficult to replicate and economically uncompetitive in comparison to other types of building materials. Constructing with bamboo should be simplified and standardized as is the case for wood before its application can become more widespread.

The pictures of the bamboo projects discussed in this chapter are often taken shortly after or even during construction. However, valuable lessons could be learned from how bamboo constructions have withstood time and weather conditions. For example, the thatch roof of the green school has been replaced by shingles, but no information can be found about the exact reason why. How would the bamboos in the Meti school by A. Heringer in Bangladesh look today or those of the bamboo house by V. Florez in Brazil? It is in this regard that the author has performed a durability analysis on one of his own projects, the community center in Camburi. More information on how bamboo constructions withstand or deteriorate over time should be shared in the bamboo community. Unfortunately many of the constructions that were built as temporary constructions no longer exist such as the Zeri Pavillion by Simón Vélez, the bamboo pavilions by Markus Heinsdorff or the Baoxi Hostel by Anna Heringer.

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CHAPTER 3 Component 1: Stability (Firmitas)

3.1 Types of bamboo

Bamboo is a giant grass and belongs to the grass species Poaceae or formerly known as Gramineae and sub-family Bambusoideae (Hidalgo-Lopez, 2003) and it grows on all continents, except Europe, from 51° north and 47° south. This bamboo ´belt` is situated in tropical, subtropical and more temperate climates. There even grow particular bamboo species up to 4.000 meters above sea level. However, the majority is found in warm zones with air humidity levels above 80% and in clayey/humid soils (often near water) (Minke, 2012). Bamboo can be divided into two groups: herbaceous and woody bamboo. The first tends to have a small diameter and resembles grasses, while the latter are large diameter ones that can be used for construction, which will be the focus of this dissertation (Kaminski et al., 2016).

The rhizome system is very important to bamboo as it provides the foundation. Woody bamboo has two main types of rhizome formation or root systems being ‘clump forming rhizomes’ and ´running rhizomes` as can be seen in Figure 3.1. In taxonometric terms these systems are called pachymorph and leptomorph. Although bamboo clumpers usually have a sympodial kind of branching pattern, running bamboos are considered to be monopodial (Kigomo, 2007). Sympodial branching (clump forming bamboo) implies that each branch or axis becomes dominant; each rhizome grows upwards and turns into a culm. This way the bamboo bush grows in a confined (circular) area, varying from one to several meters in diameter depending on the species. These bamboo types rarely become invasive because there is a certain maximum diameter in which it will keep growing. This type is native from tropical climates. Monopodial (running) rhizomes on the other hand have a subterranean stem or axis that is dominant and from which secondary stems are developed, either as a lateral extension of the root or turning upward forming a culm. This system can extend up to hundreds of meters in shallow depth of soil, somewhat comparable to a parallel circuit in electricity. The axis can keep moving further whilst the new shoots desprout from this underground root at a certain distance from each other, without forming a closed bush. These are temperate climate species, distributed mostly in Japan, China and Korea (Widyowijatnoko, 2012). There also exists a mix of both systems called amphipodial (Kigomo, 2007; Janssen, 2000).

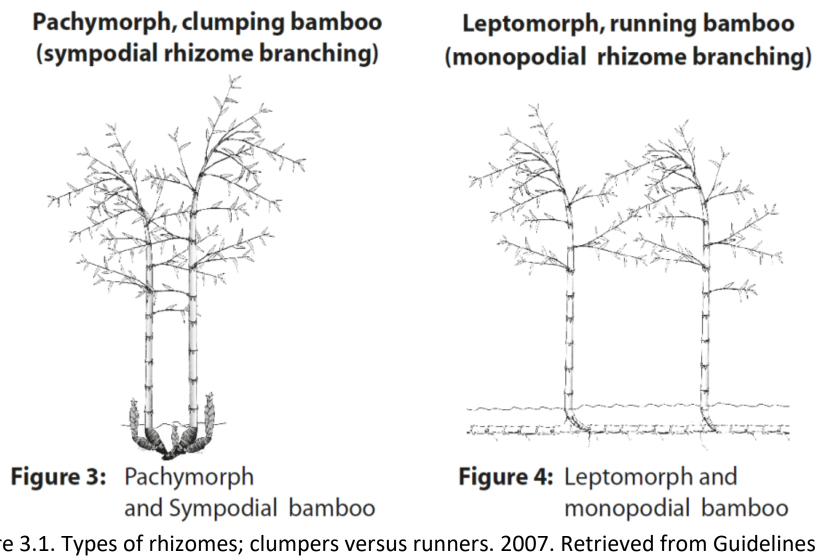


Figure 3.1. Types of rhizomes; clumpers versus runners. 2007. Retrieved from Guidelines from growing bamboo (p. 7) by B.N. Kigomo. Copyright KEFRI.

Most bamboo stems are hollow and divided into multiple partitions by horizontal diaphragms. On the outside, these partitions are denoted by a ring around the culm and together with the diaphragm they form a node. Branches grow from these nodes. The hollow part between two nodes is called an internode. The three most common types of bamboo used for construction are Phyllostachys Pubescens (Moso), Dendrocalamus Giganteus/Asper and Guadua Angustifolia Kunth. Although also others species are being used as well, certainly in Asian countries, these three species are most prominent. Whilst many known architecture examples in bamboo are built with Guadua, it is possibly surpassed in volume and economic relevance by Phyllostachys (Moso). Dendrocalamus is used less, yet depending on the region more intensively applied in local architecture (Widyowijatnoko, 2012).

Phyllostachys Pubescens, Phyllostachys Aurea and other subspecies originate from China and have leptomorph rhizomes. It prefers more moderate temperatures such as for example the mountainous interior of Brazil (region São Paulo) where there are several cultivated plantations. Because this species is a 'runner' type, great care needs to be taken when proposed in a closed bio system (Kigomo, 2007). It can invade local eco-systems and become detrimental to biodiversity. Precautions could exist of root barriers (at least 70cm deep), water-surfaces at boundaries or other proven manual, physical and chemical options (Pagad, 2016).

Dendrocalamus Giganteus is originally from India, Burma, Sri Lanka and Thailand (Minke, 2012). Although the Atlantic rainforest in Brazil possesses one of the largest diversity of indigenous bamboo genera and species measured (22 genera and 62 species), Dendrocalamus is not a native plant to South America (Londoño et al., 2002). Nevertheless, this species is abundantly present and thrives well in this particular climate type. Dendrocalamus is a pachymorph (clumping) type of bamboo with short-necked rhizomes and appears in tight or densely tufted clumps (Kigomo, 2007; Londoño et al., 2002). Loamy or sandy-loamy soils are preferred, but as bamboo in general does not stand water logging very well, sloping land of about 5% is ideal (Brias et al., 2009). Hill tops and valley bottoms provide less ideal conditions. Preferentially the soil-pH should be neutral or slightly acidic, with a groundwater-level not below one meter (Banik, 2001). Spacing should be at least 10x10m (100 clumps/ha) and preferably even wider. Clumping bamboo such as Dendrocalamus tends to be become congested when not properly managed, which is detrimental to both the quality and quantity. As new culms of a clumping bamboo bush sprout on the outer of the bush, the older ones ready for harvesting are located in the inner circle. Therefore, it is recommended to cut a part of the younger culms in a horseshoe figure in order to access the older stems (Kigomo, 2007; Brias et al, 2009). Because the age of a bamboo shoot is hard to determine, new shoots are often marked when emerging to determine their exact age. INBAR divulgates its system of TOTEMS that provides directions for an optimal planting methodology. Additional information on treatment, propagation and hands-on guidelines can be found on the INBAR website (Inbar.int, 2020).

Guadua Angustifolia is a bamboo species endemic to South America (Minke, 2012). The rhizomes of Guadua angustifolia are pachymorph (clumping) with a sympodial branching pattern. Unlike Dendrocalamus whose roots are sympodial-tufted, Guadua has sympodial-scattered rhizomes and is also called an open clumper. Whereas Dendrocalamus has a rhizome system that cannot extend for a long distance because on its stem base new auxiliary buds develop into new shoots, Guadua has longer petioles forming false rhizomes. These can easily extent to 50 to 100cm distance. Hence, Guadua has monopodial growth habits while being a clumper and invasiveness can become an issue here as well. Guadua grows best in humid tropical climates with preferably a loamy rich soil. In its native habitat, it is found from sea level to elevations up to 2.000m, mainly along creeks, in meadows or on inclinations. Guadua can tolerate well waterlogging (guaduabamboo.com, 2019; Londoño et al, 2002).

3.2 **Mechanical properties**

Bamboo is significantly different than wood whereas the first is a hollow tube and the second has a massive structure. Bamboo´s structure consisting of cellulose fibers, vessels, parenchyma and a silica outer layer provides its characteristics which are comparable to steel wherefrom the denomination vegetal steel is derived. In order to design and build with bamboo, it is crucial to understand how its structure affects the efficiency of the material. Bamboo is an anisotropic meaning that the properties depend on the direction relative to the fibers (Widyowijatnoko, 2012). For materials such as timber and steel, one can rely on data based on a grading system. However, for bamboo no such tables is available, hence the material properties need to be derived from test results. A designer/architect needs to apply a limit state design procedure or work according to local practices (Janssens, 2000).

Bamboo´s microstructure exists of vascular bundles within a parenchyma matrix imbedded by supporting cellulose fibers that act as reinforcement. The amount of cellulose fibers increases towards the outside going from 10% to 60% outward. It is the density of these cellulose fibers that gives bamboo its main mechanical properties (Javadian et al., 2019; Yap et al., 2017). The greater the mass per volume, the heavier and denser the material. Janssen notes that in general the density for bamboo is about 700-800kg/m^3, varying between the different species. Density can be used to derive other mechanical properties. For example, bending stress at failure (N/mm^2) is presumed to be 0,14 times the mass per volume (kg/m^3) for an air-dry bamboo and 0,11 times for a green bamboo. For compression this ratio to mass per volume is 0,094 for dry and 0,075 for green bamboo and for shear it is 0,021. These ratios can be helpful when one is on the field without access to laboratory test facilities. Obviously these values are not exact and have to be applied with care (Janssen, 2000). It is obviously better to design with species-specific values if these are known. De Vos (1995) describes in his research that both Moso and Guadua possess similar bending strength properties equal to dark red Meranti. If Moso and Guadua were to be ranked to a strength class for timber, they would respectively belong to strength class C16 and C35.

Although there has already been done much research on the mechanical properties of bamboo, the results obtained often vary a lot impeding a straightforward comparison. Either different bamboo species have been researched, diverse testing methods or codes have been followed or divergent aspects or parts of the bamboo culm were tested (RWTH Aachen, 2002). Even though most research refers to the ISO22157 (2004) standards, some studies are based on other codes such as the Colombian NTC5525, the Indian JG/T199-2007 or even to the ASTM standard which is to test small specimen of timber. Also the applied methodology affects the interpretation of results (Kaminski et al., 2016). For example, the ASTM 143 standard prescribes a longer sample leading to lower compressive strength values (Sánchez et al., 2019). In this regard, it is important that researchers proceed from the same standards to enable a comparison of test results. The renewed international ISO22157 standard seems the most appropriate for it describes exactly how bending, compression, tension and shear must be determined.
Table 3.1 to 3.4. are a synthesis made by the author of various studies on compressive, tensile, shear and bending strength. Besides the fact that test results fluctuate because of the research method applied, there also exists a wide range in mechanical properties as bamboo is a bio-based material with a natural wide variety in specimen quality. Timber shows a similar variability in its mechanical properties. Multiple factors such as species, density, age, diameter, and moisture content, position along the culm, site/soil and climate conditions play a role. These inequalities in properties are encountered in longitudinal, radial as well as tangential direction (Javadian et al., 2019; Yap et al., 2017; Sánchez et al., 2019). Bamboo´s anisotropy is stronger than that of timber as almost no radial fibers are found within the culm. Additionally, the ratio between longitudinal and lateral strength is also higher than that of timber, respectively 30:1 and 20:1. This causes bamboo to more likely crack than timber (Huang, 2019).

In theory, equal to timber, the type of **species** strongly influences the mechanical properties. Dixon (2016) however examined three different bamboo species and found that density is of a greater influence for the modulus of rupture (MOR) than species. As the fibers contribute 60-70% of the weight of the total culm, the density of a culm depends on the quantity and distribution of fibers around the vascular bundles, the diameter and cell wall thickness. The density of bamboo can be assumed 0.5 - 0.9g/cm (Hidalgo-López, 2003).

Denser bamboo has a higher concentration of cellulose fibers. Density of the culm wall increases from the bottom towards the top of the bamboo and it has been observed that this increase is accompanied by an increase in compressive and tensile strength. In radial direction, fiber density increases from the inner towards the outer part of the culm (Yap et al., 2017; López & Trujillo, 2016). In general, it can be stated that bamboo with a thicker wall has better mechanical properties (Janssen, 2012). Correal and Arbelaez (2010) found that there exists a significant correlation between density, age, moisture content and the compressive strength. Also De Vos (1995) noted that Guadua is denser than Moso, probable caused by its higher moisture content.

Although the optimal **age** for harvesting varies according to species and location, the best mechanical properties are generally achieved when aged between 3 to 5 years old. Very young culms (1-2 years) possess less starch and are less dense therefore they are more brittle. Too old bamboo culms (>5 years) show a decrease in starch content hence become increasingly brittle. However, because of this decrease in starch, the culm becomes naturally pest resistant. Situations that do not require high material properties and could benefit for the natural immunity to pest attacks, older bamboo culms can be applied (e.g. decorative elements, fences, etc.). In nurseries, new shoots are labelled in order to identify the accurate age of culms. Yet for bamboo extracted from wild sources, there are no exact parameters to establish the age of a culm. Outer colour and presence of mold is good indicator. Also measuring the surface temperature appears to be a successful indicator. In many studies, there is only reported vaguely on the factor age or conveniently within the recommended age, which does not help to establish clear conclusions (Sánchez et al., 2019; Janssen, 2012).

Small diameter bamboos demonstrate a higher compressive strength, modulus of elasticity (MOE) and shearing resistance in relation to their cross section as the same amount of fibers are extended over a greater surface diminishing its amount per mm² (RWTh Aachen, 2002). The combination of the **diameter** and density can be used to predict the MOR and MOE values of 3m long specimen, although it cannot be extrapolated too much as the diameter and density also vary along the culm (Gnanaharan et al., 1995).

Bamboo and timber differ in **moisture content.** Green bamboo usually has higher moisture content than wood but decreases significantly after harvesting. The fiber saturation point (FSP) of bamboo is mostly between 13-20% while that of timber lies between 28-30% (Huang, 2019). Moisture content has a strong influence on the strength of both timber and bamboo therefore it is important to measure it (Javadia et al.; Chung & Yu, 2001). According to Janssen (2012), bamboo with low moisture content demonstrates better mechanical properties in comparison to wet bamboo. This is confirmed by Awalludin et al. (2017) as they researched compressive and tensile strength after 1 and 5 months. The compressive strength of the studied bamboo specimen increased due to the decreasing moisture content. Tensile strength showed more stable outcomes. The moisture content differs with age, outside temperature/relative humidity and culm diameter/wall thickness. For example, a higher outside temperature and relative humidity results in higher moisture content (Yap et al., 2019). In a study by Javadian et al. (2019), it appears that when exposed to relative humidity variations, large culms are more stable in comparison to small culms with thinner wall sections due to the fact that smaller diameter culms have a higher fiber density and a lower percentage of lignin.

The **position along culm** refers to the three parts a bamboo culm is often separated in; base, middle and top. There exist conflicting results where some report an increasing value from base to top, especially for compressive strength and MOR (Gnanaharan et al. 1994; Chung & Yu, 2001)while others report a decrease in MOR and tensile MOE values from base to top (Gnanaharan et al., 1994; Ghavami & Marinho, 2005; González et al., 2007) and whereas other research notes no difference in compressive strength values attributed to the specific culm part (Ghavami & Marinho 2005; Correal & Albeláez 2010; Sánchez et al., 2019).

3.2.1 Compressive strength

Compressive strength is the capacity of the bamboo culm to resist longitudinal pressure or compression. The harder the fibers and larger the area of fibers, the greater the resistance will be to compression. This means that the compression strength increases vertically from bottom to top and horizontally from the inner part to the outer part of the culm. According to Janssen (2000), the compression strength is determined by the amount of lignin present in a bamboo and not by its percentage of cellulose. Buckling failure of a bamboo culm under compression always happens in the internode and never happens in the node because of the presence of the diaphragm. The fact that bamboo is a hollow tube complicates the execution of a reliable compression test (Widyowijatnoko, 2012). In this context, Janssen points out that compression implies a longitudinal shortening which consequently impacts the lateral strain. This lateral strain can be impeded when the two steel plates compressing the bamboo are keeping the specimen together by friction, thereby giving a false impression of its compression strength. It is important when executing a compression test that the steel plates are provided with a friction-free surface. The values listed in Table 3.1. are average values. Differences in vertical direction, nodes or internodes, age or moisture content are not specified. Test results are difficult to compare due to the fact that bamboo is a natural varying material which is reflected in the test results. Nevertheless, the average compressive strength of bamboo can be situated between 20 and 70N/mm². Compared to most timber species this is two to four times higher (Schröder, 2020).

Compressive strength Comparison of different sources on the compressive strength of several bamboo species						
Species	**σ (N/mm²)**	**E (N/mm²)**	**M.C. %**	**Age**	**Diameter**	**Source**
Dendrocalamus *Giganteus*	70		8,02 %	2 years	12 cm	*Naik, N.K. (2000)*
Dendrocalamus *Asper*	60,23 - 68,05		18,32 - 20,83 %	air-dried 1-month		*Awalluddin D., Mohd Ariffin M., Osman M., Hussin M., Ismail M., Seung Lee H. & Abdul Shukor Lim N. (2017)*
	53,08 - 73,65		15,85 - 18,44%	air-dried 5-month		
	68,67		11,3 %		9,25 cm	*Bounsong S., et al. (2013)*
Guadua *Angustifolia*	22,86 - 45,90	9500 – 20319		3–6 years	10 - 12 cm	*Sanchéz L.C., Guerra, A.F. & Lozano J.E. (2020)*
	58	18480		2-5 years	11 cm	*Lorenzo R, Godina M, Mimendi L. & Li H. (2020)*
	36,50 - 43,06	3650 - 9600		6 years	10 cm	*Bedoya M., Mendoza O., Garcia, B. & Preciado C. (2019)*

Guadua *Angustifolia*	28,65 - 38,16	9739 - 24496	5-21%	3-5 years	6,9 - 10 cm	*Philco P. & Garcia I. (2018)*
	41,60		26 %	5 years	12 cm	*Camargo J.C. & Suarez J.D. (2014)*
	19,10 - 23,60	8100 - 10560	12-19%	3 - 6 years		*Luna P., Lozano J.E., Takeuchi C.P. & Gonzalez, M. (2012)*
	28,60 - 41	16400 - 17200	56,2-65,2%	green 2-5 years	10 – 13 cm	*Correal J. & Arbeláez, J. (2010)*
	32,87	9082	87 %	green		*Lozano, J.E. (2010)*
	54,80 - 56,30		10-12%	dry		
	29,48	12580		3 years	7,96 cm	*Marinho A.B & Ghavami K. (2005)*
	63,60 - 86,30	15190 - 18900		1-7 years	10 - 14 cm	*RWTH Aachen (2002)*
	56	18400	15 %			*Eicher S. (2000)*
Phyllostachys *Pubescens*	54	11930		3-4 years	8,5 cm	*Lorenzo R, Godina M, Mimendi L. & Li H. (2020)*
	69,10	10560	7%	dry	12,4 - 16,8 cm	*Dixon P. & Gibson L. (2014)*
	40,1	4013		1-6 years	12 cm	*Berndsen R, Klitzke R.J., Batista D., Mauro do Nascimento E. & Ostapiv F. (2013).*
	108,19			>3 years	7,7 cm	*Sakaray H., Togati N., & Reddy I. (2012)*
	48- 114	3600 - 11000	<5%			*Chung K. & Yu W. (2002)*
Unspecified species	47 - 93,60	2067 - 5185	60%	1-3-5 years green		*Li X. (2004)*

Table 3.1. Comparison of different sources on compressive strength of different bamboo species. 2020.

3.2.2 Tensile strength

Bamboo's tensile strength is astonishingly high (Widyowijatnoko, 2012). Bamboo can resist more tensile than compression forces. Inside the silicate outer skin, there are axial-parallel fibers which are extremely elastically with a tensile strength up to 40kN/cm³. For comparison, wood can resist a tension up to 5kN/cm³ and steel´s ultimate stress limit is 37kN/cm³ (Aachen, 2002). According to Arce-Villalobos (1993)there exists too much information about tensile strength of the bamboo, although often very little account is given on the procedure followed to measure this quality, nor enough data included in reports or textbooks on the matter (Widyowijatnoko, 2012). When discussing tensile strength, it has to be described whether the culm or the fibers were tested for fibers themselves can resist higher tension. Generally, tensile strength is lower at the nodes (Bornoma, et al., 2016). Bamboo´s tensile strength properties from different sources and species are listed in Table 3.2.

Tensile strength Comparison of different sources on the tensile strength of several bamboo species						
Species	**σ (N/mm²)**	**E (N/mm²)**	**M.C. %**	**Age**	**Diameter**	**Source**
Dendrocalamus *Giganteus*	177		8,02 %	2 years	12 - 39 cm	*Naik N.K. (2000)*
Dendrocalamus *Asper*	193 - 340	18140 - 28230	12 – 15%		8 - 15 cm	*Javadian A., Smith I.F.C., Saeidi N. & Hebel D.E. (2019)*
	200,75 - 232,80		18,32 - 20,83 %			*Awalluddin D., Mohd Ariffin M.A., Osman M.H., Hussin M.W., Ismail M.A., Seung Lee H. & Abdul Shukor Lim N. (2017)*
	96 (node)	52000 - 70200	11,3 %		9,25 cm	*Bounsong S., Vallayuth F., Piyawade B. & Waranyu R. (2013)*
	358,33 (internode)					
Guadua *Angustifolia*	42,50 - 56,58	9425 - 19486	12-19 %	3 - 6 years	10-12 cm	*Sanchéz L.C., Guerra, A.F. & Lozano J.E. (2020)*
	143,13			6 years	10 cm	*Bedoya M., Mendoza O., Garcia, B & Preciado C. (2019)*
	37,10 - 41,40	6080 - 6990		3 - 6 years		*Luna P., Lozano J.E., Takeuchi C.P. & Gutiérrez, M. (2012)*
	86,96	14590		3 years	7,96 cm	*Marinho A.B. & Ghavami, K (2005)*
	135,3 - 327,3	14000 - 24100		1 - 7 years	9 - 13 cm	*RWTH Aachen (2002)*
Phyllostachys *Pubescens* *(Moso)*	144,81	16570	15 %	3-4 years	9,55 - 11,14 cm	*Liu P., Zhou Q., Jiang N., Zhang H. & Tian J. (2020)*
	289	14900 - 39800	7 %	dry	12,4 - 16,8 cm	*Dixon P. & Gibson L. (2014)*
	125			>3 years	7,7 cm	*Sakaray H., Togati N., & Reddy I. (2012)*
	482,20	33900	12,5 %	4 years		*Shao Z., Fang C, Tian G., Huang S. (2010).*
	115,30 - 309	9000 - 27400	9,7 %	4-6 years	7 - 9 cm	*Yu, H., Jiang Z., Hse C. & Shupe, T. (2008)*

Table 3.2. Comparison of different sources on tensile strenght of different bamboo species. 2020.

3.2.3 Bending strength

Bamboo is known for its high elasticity capacities, which makes it especially useful as building material in areas with high risk for earthquakes. The presence of fibres and nodes protect the culm so it can resist the bending forces. The bending strength of bamboo varies along the culm, with higher values reached at the upper part,where the percentage of fibres is greater (Hidalgo-López, 2003). Bending strength has a direct influence on the behavior of a structure. The bending strength of most bamboo species varies between 50 and 150 N/mm2 (Table 3.3.), the lower values are for green bamboo and higher values for air dry bamboo (Schröder, 2019). Janssen (2000) questions whether bending strength is determined by bending stress or by shear? In his opinion, several researchers have drawn wrong conclusions as they are unaware of this fact. He points out that in case of a short free span, bamboo acts as an arch resulting in less deformation. In order to determine pure bending stresses, it is necessary to run a four-point bending test over a long freespan. Besides, there also exists a direct correlation between the cross section and modulus of elasticity (MOE) of bamboo. When the diameter of a bamboo increases, the MOE decreases. Yet, when a bamboo diameter is too small, it also shows a decrease. The higher the MOE, the higher its quality (RWTH Aachen, 2002). Guadua has a significantly higher MOE than Moso, and shows even better results than dark red meranti or Norway spruce. Both Guadua and Moso have a similar bending strength (MOR) equaling that of dark red meranti (De Vos, 1995). Gnanaharan et al. (1995) noted a similar behavior for the modulus of rupture where the highest MOR was obtained for specimen with a lower diameter (6,9 cm) and the lowest MOR with the largest diameter (9,7 cm).

Bending Strength **Comparison of different sources on the bending strength of several bamboo species**						
Species	**MOR (N/mm²)**	**MOE (N/mm²)**	**M.C. %**	**Age**	**Diameter**	**Source**
Dendrocalamus *Giganteus*	193	16373	8,02 %	2 years	12 cm	*Naik N.K. (2000)*
Dendrocalamus *Asper*	121 - 209	9375 - 14279	12 - 15 %		8 - 15 cm	*Javadian A., Smith I.F.C., Saeidi N. & Hebel (2019)*
	83,67	59533	11,33 %		9,25 cm	*Bounsong S., Vallayuth F., Piyawade B. & Waranyu R. (2013)*
Guadua *Angustifolia*	21 - 72,82	9500 - 14933	12-19 %	3 - 6 years	10-12 cm	*Sanchéz L.C., Guerra, A.F. & Lozano J.E. (2020)*
	103,5 - 147,2			6 years	10 cm	*Bedoya M.A, Mendoza O.A., Garcia, B & Preciado C. (2019)*
	41,7 - 47,44	15300 - 18910	5 - 21 %	3-5 years	6,9 - 10 cm	*Philco P. & Garcia I. (2018)*
	35,30 - 40,8	13670 - 14160	12 - 19 %	3-6 years		*Luna P., Lozano J.E., Takeuchi C.P. & Gutiérrez, M. (2012)*
	15,19 - 18,9	13600 - 32500		1-7 years	9 - 13 cm	*RWTH Aachen (2002)*
	93,4 – 98,50	16900 - 17400	56,2 - 65,2 %	green 2-5 years	10 – 13 cm	*Correal J. & Arbeláez, J. (2010)*

Guadua *Angustifolia*	130	10560	7 %	dry	12,4 -16,8 cm	*Dixon P. & Gibson L. (2014)*
		15000		>3 years	7,7 cm	*Sakaray H., Togati N., & Reddy I. (2012)*
	51,7 - 56,2	7160-7565	round, short specimen		6,4 -9,7 cm	*Gnanaharan R., Janssen J. J. A., & Arce O. (1995).*
	72,6	17608	round, long specie		6,4 -9,7 cm	
	79,1 – 122,8	8689 - 12335	split specie			
Phyllostachys *Pubescens*	167	13719		1-6 years	12 cm	*Berndsen R, Klitzke R.J., Batista D., Mauro do Nascimento E. & Ostapiv F. (2013).*
Unspecified species	110,3 - 186,2	7770 - 13410	60 %	1 – 3 – 5 year old green		*Li X. (2004)*

Table 3.3. Comparison of different sources on bending strength of several bamboo species. 2020.

3.2.4 Shear strength

Table 3.4. gives an overview of bamboo´s shear strength properties attained from different research results. Bamboo is stronger in shear than wood because the latter has rays which are mechanically weak. However, as bamboo is hollow, this advantage is nullified (Janssen, 2012). When bamboo culms are used in construction by making joints, it is important to consider the shearing resistance. The distance of the shearing surface decreases with the growing length of the shearing surface. Bamboo with a wall thickness of 10mm demonstrates a lower shear strength than a culm with a 6mm wall thickness. Probably this is caused by the distribution of the high strength fibers per cross section surface. Nodes appear to have a considerable higher shear strength than internodes (RWTH Aachen, 2002). More research with longer lengths in shear are needed to imitate real construction situations.

ShearStrength Comparison of different sources on the bending strength of several bamboo species					
Species	**τ (N/mm2)**	**M.C. %**	**Age**	**Diameter**	**Source**
Dendrocalamus *Giganteus*	10,60	8,02 %	2 years	12 cm	*Naik N.K. (2000)*
Dendrocalamus *Asper*	9,37 - 9,80	11,33 %		9,25 cm	*Bounsong S., Vallayuth F., Piyawade B. & Waranyu R. (2013)*
	7,30 - 7,90	56,2 - 65,2 %	green 2-5 years	10 – 13 cm	*Correal J. & Arbeláez, J. (2010)*
Guadua *Angustifolia*	3,08	26 %	5 years	12 cm	*Camargo J.C. & Suarez J.D. (2014)*
	14,7 - 23,10		1-7 years	9 - 13 cm	*RWTH Aachen (2002)*
	12		2-5 years	11 cm	*Lorenzo R, Godina M, Mimendi L. & Li H. (2020)*
Phyllostachys *Pubescens (Moso)*	29,12		>3 years	7,7 cm	*Sakaray H., Togati N., & Reddy I. (2012)*

Table 3.4. Comparison of different sources on shear strenght of several bamboo species. 2020.

3.2.5 Conclusion

Architects, designers and engineers need to have information about the mechanical strength properties of bamboo if to be used more widespread (Sánchez et al., 2019). There are still some issues identified in this regard.

Firstly, when applying recommended values, one should take into account substantial safety factors (RWTH Aachen). This is necessary because of the variety in quality and because of the often contradictory findings in studies. Kaminsky et al. suggest a safety factor of 1,5 for limit state design, which is based on the Colombian NSR G-12 and ISO22156 (Kaminski et al., 2016).

Secondly, Sánchez et al. (2019) noted that several mechanical properties are understudied such as impact energy, toughness and compression perpendicular to grain. The latter is the weakest point of bamboo culms. Although bamboo is capable in taking great compression stresses parallel to its fibers, it is much weaker to take strain caused perpendicular to the fibers because this occurs between the fibers (lignin) (Janssen, 2000).

Thirdly, the applied testing methodology has an effect on the results, but also published data can be misleading when the strength values are not clearly stated (e.g. characteristic, average, ultimate, design, allowable) or the samples tested are not described clearly (age, top versus bottom parts, moisture content, etc.). Care hence has to be taken when comparing results.

Furthermore, the moisture content of bamboo is an important variable because a lower moisture content generally leads to better mechanical properties. This should be considered when building with bamboo.

Finally, yet to a lesser extent, strength properties vary between the different species although they do not deviate much from the average values (Sánchez et al., 2019; Kaminski et al., 2016).

It is hence clear that additional research is still necessary before bamboo can become a widespread building material. Nevertheless, studying the mechanical strength more in detail, it became clear that bamboo has a good mechanical performance for various structural applications, such as columns, space frames and other structural systems that rely on tension. It is hence a material with a lot of potential.

3.3 **Standards and building codes for bamboo**

3.3.1 Standards and codes

Bamboo buildings are primarily designed and built based on tradition with little or no reference to design codes. Such traditional practices are generally limited to low-scale housing types, and therefore inadequate to extrapolate to more ambitious projects. In large parts of the world, bamboo is consequently still perceived as a poor man´s material (Trujillo, 2013). For bamboo to gain a greater acceptance as a primary construction material standardization is needed. A fundamental aspect of any standard or design code is the determination of material properties (e.g. strength and stiffness) and by extension treatment requirements, design values as well as to provide a reference frame to the user. Bio-based materials such as timber and bamboo vary greatly in strength, size, thickness, etc. in comparison to industrialized materials such as steel, aluminum or concrete. Data from comparable tests can contribute to reliable and statistical analyses, which in turn will lead to further refinements and more confidence in the material. Such acceptance, coupled with advocacy, can lead to broader social acceptance of previously marginalized vernacular construction methods (Trujillo, 2013; Harries et al., 2012). Table 3.5 lists which specific elements each code or standard discusses. Janssen (2000), whom led the initiative to develop international ISO standards for bamboo, emphasizes on such need by stating that the omission of bamboo from national building codes is a constraint for the development as an efficient engineering and building material. The efforts from INBAR guided by amongst others Janssen, Ghavami and Sands led to the first three international bamboo standards being published in 2004 by **the International Organization for Standardization (ISO)**. The **ISO22156** (ISO, 2004a) focusses on the structural design with bamboo (round, split and glued laminated bamboo). It is sequenced by the **ISO22157** for the determination of physical and mechanical bamboo properties. Part 1: Requirements (ISO, 2004b) provides the testing methodology used to obtain properties necessary for establishing design values. Part 2 serves as a laboratory manual proposing testing methods and methods on data collection (ISO, 2004c). These standards are comparable to ISO timber standards such as the EN:384:1995 and the EN:1995-1-1 Euro code 5 (Sharma, 2010; Gatóo et al., 2014). An adverse consequence to the setup of these ISO standards is that as they address a modern limit states design approach while still recognizing traditional design and practices in rural areas, it becomes inadequate for both objectives. A limit states approach requires specialized engineering knowledge whereas the traditional approach is unable to rely on ultimate limit states, particularly in extreme situations such as earthquakes (Sharma, 2010). Other handicaps are the fact that the tests in the ISO22157 lack the determination of tensile strength test methods perpendicular to the fiber, the shear tests are under discussion and many tests cannot be practically implemented in the field (Harries & Sharma, 2016; Harries et al, 2012). In short, these ISO standards remain too limited and further improvement is necessary (Gatóo et al., 2014). Janssen underlines that when the development of national bamboo standards is handled by the respective national authorities, it will result in a wide diversity of standards. However, when instead an international model for national standards is designed by an international body in consultation with the national entities, the position of bamboo would be strengthened considerably (Janssen, 2000).

In 2015, INBAR launched a Bamboo Construction Task Force named ISO/TC165 to act as an incubator with as task to coordinate international research institutes and commercial companies actively working in bamboo construction to update the existing ISO bamboo standards. The first, ISO19624 (ISO, 2018) was published in September 2018 and provides basic principles on grading of bamboo poles. The second ISO22157 (ISO, 2019) was published in August 2019 and elaborates on the previous one dating from 2004. It describes various methods to test physical and mechanical bamboo properties. In short, two mechanical tests were added and one physical test was removed (shrinkage). Moreover, a greater consideration was given to the procedures to ensure adequate accuracy and precision and attention was given to align better to existing timber testing standards. Besides these current developments, there also exist plans for the near future to adapt the ISO22156 in a similar way as the ISO22157, with a greater coherence between this code and other bamboo and timber standards. The idea is to modify it from a code about design philosophy to a technical specification that provides design guidelines for bamboo structures. This could play a particularly important role in promoting bamboo for the use as a primary construction material in buildings. In addition, new standards on glued laminated bamboo and parallel strand woven bamboo products are to be developed (Inbar.int/bamboo-standards-2019, 2019).

Multiple countries worldwide have already adopted these ISO codes. Predominantly those countries with local bamboo resources such as China, India, Colombia and Ecuador have adapted the ISO standards or had/have already set up their national standard or building code (Harries & Sharma, 2016; Gatóo et al, 2014). Next, a short overview of the most relevant ones is given.
The **Colombian bamboo codes** existed first as a part of the national seismic design code **NSR-98 Chapter E.7** which was published as an addendum in 2002. The name of this chapter E.7. can be translated into "cement-rendered, one and two-story ´bahareque` houses" (Trujillo, 2013). This construction technique, similar to wattle and daub, consists of a load-bearing bamboo structure (full culms) with woven bamboo walls finished off with a cement mortar for weathering protection and structural integrity. These bamboo structures are generally "self-build" or built by bricklayers and carpenters with little training, because it is simple and does not require complex tools. The Colombian codes address mainly these types of bamboo constructions as they are the most common in this region (AIS, 2002; van Drunen et al., 2015). Between 2006 and 2009 additional standards were

set up such as the **NTC5300 and 5301** for harvesting, drying and preservation of Guadua, the **NTC5404** regarding the vegetative propagation, **NTC5407** for structural joints, the **NTC5525** concerning methods and tests to determine physical and mechanical properties of Guadua and the **NTC5727** about the terminology applied to Guadua and its processes (ICONTEC, 2006; ICONTEC, 2007; ICONTEC, 2008; ICONTEC, 2009; Minke, 2012; Gatóo et al., 2014). The most complete and detailed regulation is arguably the **Colombian NSR-10 code** from 2010 which includes a chapter (Chapter G12) specifically on structures built with Guadua Angustifolia Kunth (AIS, 2010; Gatóo et al., 2014). It contains some visual grading guidance, factors of safety, a process to derive characteristic values, mechanical properties, design procedures for beams and columns, some design values for connections, and, by linking it to the chapter E.7, shear wall strength values. Chapter G.12 is not without fault or omission, for example, the procedure for the determination of connection design values is opaque and the listed moduli of elasticity values are peculiar, nevertheless, it is arguably the first standard in the world that allows a user to structurally design a bamboo building (Trujillo, 2013). The code was set up after an earthquake in 1999 where most bamboo buildings suffered only minor structural damage whilst 60% of the conventional concrete buildings collapsed. Since this incident, research on the mechanical qualities in Guadua and its suitability for construction increased significantly which resulted amongst others in this seismic-resistant code (Archila & Walker, 2012).

Besides Colombia, also **Ecuador and Peru** have embedded bamboo in their national building codes. Both Ecuador and Peru have used the Colombian NSR-10 code as a template as the bahareque construction technique explained above is also common here. In Ecuador, the general building code included a chapter (Chapter 17) on the utilization of Guadua in construction in response to a devastating earthquake in 2016, similar as had happened in Colombia. This **INEN2011** addresses the processing, selection, construction and maintenance of bamboo. It describes the process in general and is also an elaborate code similar to the Colombian. Nevertheless, it does not include any design guidance or calculations (INEN, 2011; Gatóo et al., 2014; van Drunen et al., 2015). The Ecuadorian standard INEN42 (INEN, 1976) highlights the qualities of bamboo in construction but neither includes any design guidance (Gatóo et al., 2014). Also the **Peruvian national building code E.100** includes a section on bamboo (ICG, 2012). It focuses on the design and construction with bamboo for seismic-resistant structures. It refers mainly to the Colombian code and the ISO standards on bamboo construction. Modified versions of construction design calculations from the Colombian and Ecuadorian codes are included, although not as detailed as their original source (Gatóo et al, 2014).

In **Brazil** several academics active in bamboo research such as Prof. Ghavami, K. and Prof. Barbosa, N. have drafted a standard based on the Brazilian norm ABNT NBR7190 from 1997 for timber structures, the ISO standards and the Colombian NSR-code. This standard has been entered for approval in 2019, however has not yet been published.

Section 3B of the **National Building Code of India (NBCI)** (BIS, 2016) describes strength limits on three classes of commonly found bamboo species in India. Although it provides examples of jointing and connections, further detailing on dimensions and capacities of such joints is not addressed. NBCI refers to previous Indian Standards (Sharma, 2010). India was one of the first countries to set up standards for bamboo construction. The IS6874 (BIS, 2008) dates from 1973 and provides test methods for round bamboo in order to determine its physical and mechanical properties. The IS8242 (BIS, 1976) from 1976 describes testing methods for split bamboo. In 1979 the IS9096 (BIS, 2006) on the preservation of bamboo was drawn up and the IS15912 (BIS, 2012) from 2012 provides minimum requirements for structural design and serves as a code of practice (Marçal, 2018; Gatóo et al., 2014).

The **Chinese standard JG/T199-2007** for full bamboo culm construction provides guidance for material and mechanical testing. It is mainly based on the ISO22156 with the difference that the ISO standard uses the full culm for mechanical tests, whereas the JG/T 199 uses sections of the culm wall for compression, shear and flexure tests. Additionally, it uses separate tests to obtain the modulus of elasticity. The JG/T199 provides a correction factor utilizing the empirical equation for moisture content in the test elements to obtain strength and stiffness values (Gatóo et al., 2014).

In **the US** there does not exist a code or standard for bamboo construction. However, in 2013 laminated veneer bamboo was included in the **ASTM D5456**, a standard specification for structural composite lumber products. It is the first country to recognize laminated bamboo veneer as a structural product and considers it equivalent to structural composite lumber products. It discusses manufacturing standards and test methods (Gatóo et al., 2014).

Overview of existing standards and codes

	Standard	Code	Grading of bamboo	Harvesting, drying and preservation	Mech. and phys. properties	Lab testing	Structural design e.g. joints	Seismic resistance	Maintenance
INTERNATIONAL	ISO22156 (2004a)		X				X		
	ISO22517 (2004b)				X	X			
	ISO19624 (2018)		X						
	ISO22517 (2019)				X	X			
COLOMBIA		NSR-98 Code Chapter E.7 (2002)			X		X	X	
		NSR-10 Code Chapter G12 (2012)	X	X	X		X	X	X
	NTC5300 + NTC5301 (2008)			X					
	NTC5407 (2006)						X		
	NTC5525 (2007)				X				
	NTC5727 (2009)								
PERU		Norma Construtivo E.100 (217)		X	X		X		
ECUAD		Ecuadorian construction norm INEN 2011: chapter 17 (2013)	X	X			X	X	X
	INEN42 (1976)			X	X		X	X	
BR	ABNT/CE-002:126.012	PN 002:126.012-001/1 – Estruturas de Bambu			X	X	X		

INDIA		NBCI; section 3 Timber and Bamboo (2005)		X	X		X		
	IS6874 (1973)				X	X			
	IS8242 (1976)				X	X			
	IS9096 (1979)			X					
	IS15912 (2012)						X		
	JG/T 199 (2007)				X	X			

Table 3.5. Overview of existing standards and codes. 2020.

3.3.2 Conclusion

Standards, building codes and norms contribute in ensuring good quality constructions by giving guidance on testing methods, limit state design, minimum requirements, etc. To date, these however do not exist in most countries. Bamboo is hence not considered as a certified construction material. In consequence, local authorities need to give case specific approval. Although regulations from other countries can serve as a base, in most cases permission is only given based upon laboratory testing of the individual bamboo stem or load bearing tests (Minke, 2012).

INBAR is currently working on technical specifications that provide design guidelines for bamboo architecture. These recent efforts of INBAR together with bamboo experts worldwide show that, intensified by the climatological changes and greater public awareness on the environmental impact of construction materials, bamboo is on the verge of being accepted by the mainstream public. These efforts predominantly focus on defining the physical and mechanical properties of bamboo, while also attention should be given to the structural design, e.g. jointing techniques, structural systems, etc. to provide a practical guidance for architects, engineers or designers that want to use bamboo.

Maintenance is moreover also lacking in current standards although it is an important parameter. In order to ensure a durable quality of bamboo constructions, maintenance should be included as basic principle in the structural design.

The learnings from this section will be integrated in the evaluation framework (chapter 8) as it is imperative for the user to be aware of the existing standards/codes and subsequently, needs to question himself, which one is applicable to his/her particular case/project.

3.4 **Overview of structural systems in bamboo**

In bamboo architecture, there are several ‘types’ of structural systems that appear to be applied worldwide. In literature however, there does not exist any type of classification system grouping or ordening the different possible structural systems as opposed to for jointing systems (chapter 3.4.) where several authors have already set up such classification system. Therefore, a new classification system is introduced in this dissertation as attempt to group different structural systems according to their level of ‘orthogonality’. In this regard, bamboo construction can be classified in at least five subcategories going from ‘organic’ or curvilinear architecture to more orthogonal architecture; organically woven structures, curvilinear architecture, truss-architecture, spaceframe structures and orthogonal architecture as is represented in Figure 3.2.

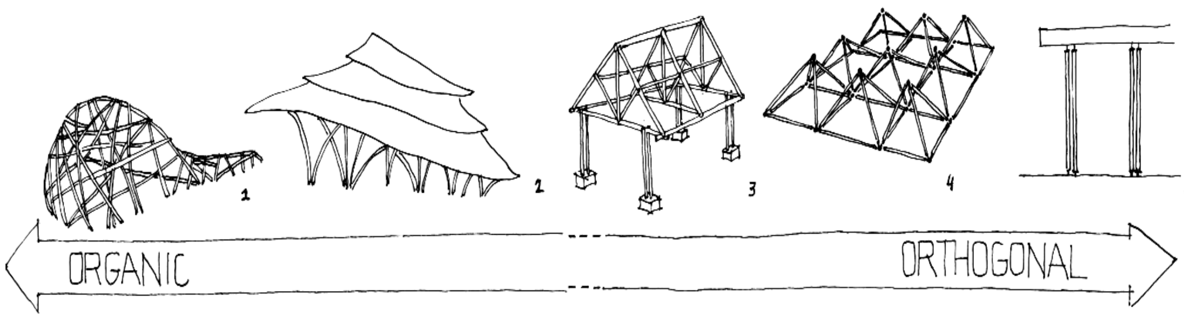


Figure 3.2. Different types of structural systems going from organic to orthogonal. 2020.

In practice, these subtypes may overlap, for example truss-architecture is often applied as main support in architecture that uses curves (here named curvilinear architecture). A common strategy that various bamboo architects adhere is to make a scale model of their bamboo buildings, stating that if you cannot build a model, it probably cannot be build. Although this practice certainly has its credits, some caution should be taken. Small wooden sticks or bamboo strips used for model making do not perform in the exact similar way as tubular hollow bamboo elements of a large diameter do. These tiny sticks are much easier to bend, making the designer believe that this is a feature which can be easily repeated on a large scale. Furthermore, this way of thinking can also exclude certain structural forms. When a particular joint cannot be made in small scale, the designer will no longer consider it as an option. Finally, model making appears to be a substitute for actual mathematical calculation of structures, which it is clearly not. Although it is advisable as a form-finding method, can never replace actual stability calculations and/or computer aided design. When bamboo is to emerge as a material, the practice of model making should not be recommended as the single or best method to design a building for it simply excludes structural options and diminishes the need for modularity, rationalism and calculations. Nowadays, several software programs can be used to calculate a bamboo structure such as GSA analysis (by Oasys-software), SAP2000, Scia Engineer or more 'intuitively' Grasshopper, a plugin on Rhino (by Autodesk). Bamboo properties have already been added as a pre-defined material in all of the above-mentioned programs. Other finite elements analysis programs i.e. Buildsoft or Tekla (by Timble) can most likely be used in a similar manner.

3.4.1 Organically woven, freeform architecture

Digital design tools and computational design thinking allows designers to explore the parametric variability and pursue eccentric freeform shapes. Frank Gehry and Zaha Hadid are pioneering avant-garde designers in the application of freeform architecture. In design practice, any kind of freeform shape requires a translation of the shape into rational elements that allow for fabrication (Wang et al., 2017). Despite the fact that bamboo in its raw form is not easy to bend, when split bamboo is applied in a load-bearing structure, a curved shape is unavoidable (Dunkelberg, 2000). Bamboo cut into strips is very flexible, lightweight and can be woven in an arbitrary manner or in a geometrical pattern. Frei Otto, a German engineer-architect who gave a series of lectures (IL31) at the University of Stuttgart on his expertise on tensile and lightweight structures in bamboo, referred to these woven structures as ´basket shells' (Dunkelberg, 2000). Frei Otto refers to these structures as basket shells because the same weaving techniques are applied for weaving a basket. The art of bamboo weaving is in decline as it is complex and requires local craftsmen (Hidalgo-López, 2003). Known examples in this classification are the bamboo hostel in Baoxi, China by Anna Heringer (Figure 2.10) (Heringer, 2019), the bamboo pavilion in the Fengyuan district, Taiwan by ZUO Studio (Figure 3.3) and the bamboo dome ´Love in Shodoshima` by Wen-Chih Wang on Shõdo Island, Japan (Figure 3.5)

The challenges in freeform architecture with bamboo are to tackle bamboo´s material irregularities and to create a replicable jointing technique. Systematic and algorithmically parametric 3D modelling can be used in the creation process (Wang et al., 2017). Both methods (arbitrary or geometrically woven) are difficult to calculate and the first method is without doubt the most difficult, and in some cases even impossible because this structural system is conceived in an intuitive manner where its final form is shaped on site without a pre-calculated model. Baboom, a Belgian company active with bamboo structures for the events sector, resolved the difficulty in calculating its tarantula-shaped freeform bamboo structure by providing a simple and calculable bamboo base structure while weaving the tarantula shape around it afterwards (Figure 3.4).

Organically woven structures are primarily temporary constructions as the main design criteria for bamboo, such as weather protection and a solid protection against insects, fungi and humidity, are commonly not pursued (Padovan, 2010). Freeform structures often lack a proper roof covering, roof overhang and have direct contact to the floor such as the example of the bamboo pavilion in the Fengyan District in Taiwan demonstrates (Figure 3.3). Without constant maintenance, these structures have considerable short life-time expectancy.

Figure 3.3. Bamboo Pavilion in Fengyuan District Taiwan designed by ZUO Studio. 2018. Retrieved from https://www.archdaily.com/905690/bamboo-pavilion-zuo-studio (25/03/2020). Copyright Shih-Hong, Yang.

Figure 3.4. Tarantula - a bamboo dance temple at Tomorrowland designed by Baboom. 2014. Retrieved from https://www.baboom.be/tarantula. (25/03/2020). Copyright Baboom.

Figure 3.5. Love in Shodoshima designed by Wen-Chih Wang at the Setouchi Triennial Japan. 2019. Retrieved from www.setouchi explorer.com/setouchi-triennale-2019-part-one-shodoshima. Copyright Yun Koo.

3.4.2 Curvilinear architecture

The word curvilinear literally means "*consisting of or containing curved lines*" (dictionary.cambridge .org, 2020). Curvilinear forms are mainly designed through form-finding. By bending small bamboo sticks, one can intuitively design a firm structural system. Although the previous structural system (organically woven freeform) is established in a more organic manner, it can arguably be said that it is this structural system that is most associated with the term 'organic' architecture. It was Frank Lloyd Wright (1867-1959) whom introduced the term organic architecture in his essay entitled *´The Language of Organic Architecture*`. The term comprises a harmonious relation between a building and its environment (franklloydwright.org, 2019). Yet, the term organic shape has a slightly different meaning, referring to how materials, shapes and patterns found in nature can be used as inspirational source. Organically inspired structural systems typically exhibit aesthetic qualities that are not necessarily intuitive. Adaptations of natural forms usually generate irregular geometries (Nurdiah, 2016). Curvilinear architecture is a form-active structure meaning that the loads are taken by the form or shape of the structure. Whereas form-active structures can only withstand axial forces, tension or compression, non-form active structures (e.g. trusses) can additionally withstand bending moments (Nurdiah, 2016). Bamboo is almost always applied under compressive or bending stresses; bamboo under tensile stress is rarely found (Widyowijatnoko, 2012). Form-active structures can be divided into 4 subcategories; cable, tent, pneumatic and arch structures. In bamboo architecture, predominantly the latter is applied. On its turn, arch architecture can be subdivided into three types; circular form, pointed arches and parabolic arches depending on the shape of the arch and the floor plan (Archistudent.net, 2009). When curving bamboo to span a width through compression stresses, attention has to be given to prevent the arch element from tilting or behaviour in the lateral direction and is therefore best anchored by fixed base connections restraining it. Another method is placing bamboo members transversely to the arch (Dunkelberg, 2000).

In order to obtain curved bamboo, multiple bending methods are possible. In general, only the lower half or lower third of the natural length of a bamboo cane is used to provide load-bearing elements of a structure. However, these lower parts of the bamboo cane are practically rigid and cannot be bent. Bending is best applied to the upper sections of the canes with their relatively small diameter and wall thickness (Dunkelberg, 2000). In a bamboo bush or grove, also naturally curved bamboos on the outside perimeter of the grove can be found. Often these bamboos can be sourced at low cost or even for free for these bamboos lack economic value to the producer (Janssen, 2000). However when curves need to be fiercer and the natural curvature of bamboo is inadequate, mechanical bending is required. Besides bending bamboo canes by a local application of heat or immersion in lukewarm water to soften the fibers, also bundling small diameter bamboos in a curve or splitting bamboo into strips are commonly used techniques as seen in Figure 3.6 (Nurdiah, 2016).

Figure 3.6. Bending and bundling of split bamboo. Retrieved from The potential of bamboo as building material in organic shaped buildings (p. 37) by E.A. Nurdiah. 2016. Procedia.

The most prominent example of curvilinear architecture is the Green School in Bali (Figure 3.7). The organic shape of the building is defined by the roof which is a form active structure. The main hall is arched with wide span arches stabilized by roof rafters to form the curved shape roof. Long roof eaves provide a good protection from sun and rain. The main building has a nautilus shell shape. The associated firm IBUKU continues to produce similar architecture at the Green Village in Bali, such as the Sharma Springs Residence. Their design process always starts by creating a scale model with bamboo sticks in order to conceive aesthetically remarkable designs. Thereafter, the model is replicated in a 3D software program enabling the engineers to make stability calculations (Ibuku.com, 2019). Some of the works designed by Vo Trong Nghia also belong in this category such as the Nocenco Café in Vingh City, Vietnam (Figure 3.8).

Figure 3.7. The Green School. 2019. Retrieved from ibuku.com/heart-of-school/ (27/03/2020). Copyright Ibuku.

Figure 3.8. Nocenco Cafe in Vingh City, Vietnam designed by VTN Architects. 2018. Retrieved from vtnarchitects.net/bamboo-properties-1/nocenco-cafe. (27/03/2020). Copyright Trieu Chien.

3.4.3 Truss architecture

Truss architecture is structurally the most firm and logic system of the different structural categories for it transfers forces to the ground in the most efficient manner. Similar plain geometrical triangulation systems can also be found in timber and steel structures. When no bending is required in a structure, the bamboos are rarely split because the raw hollow tube members demonstrate a better performance in resisting forces (Widyowijatnoko, 2012).

Most works by Simon Vélez can be placed in this category. A special mention should go to the ZERI pavilion for the Expo in Hannover in 2000. This pavilion was conceived as a ten-sided polygon with a peripheral overhang of seven meters wide, consisting of 2.150m² floor area on two levels (1650m² ground level and 500m² first floor). The structural system was a truss framework. Ten pairs of framework-beams supported on two pillars and cantilevers, arranged in a circular shape such as the drawings in Figure 3.9 illustrate. The purlins pass their load to 40 radially arranged girders. Every second grinder is not directly supported, but transfers its loads to the adjoining girders. At the end of the pillars, there is a ring-shaped framework foreseen which distributes the horizontal loads. On top, the trusses are additionally connected by a ridge ring, an eave ring and purlin rings. The large protruding eaves which are typical for Velez's work prove the strength of triangulation (Pauli, 2012; Lindemann & Steffens, 2000; Rohrbach & Gillmann, 2001).

Also in the other works by Vélez this spatial order generated by the layout of the structure can be found. The modular system based on the interval between the columns derives from the structural system of the roof and the way the bamboos reach the ground. Although his floor plans are very simple, the cross sections are complex giving the structure its dynamic. When analyzing the cross-section, they always reflect a geometric order that responds to efficient transmission of loads to the ground (Salazar Ocampo, 2018).

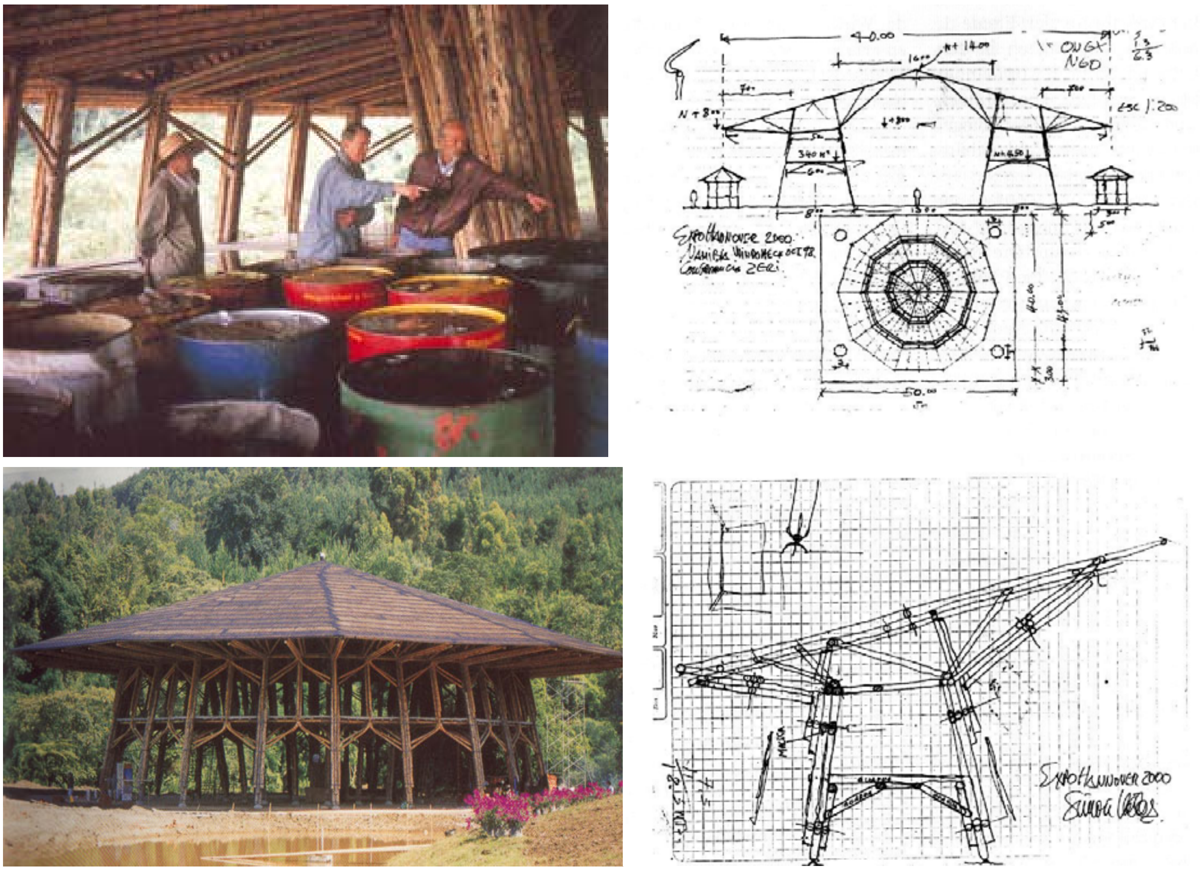


Figure 3.9. Load testing, sketches and 1:1 scale model of the Zeri Pavilion in Manizales, Colombia designed by Simón Vélez. 2001. Retrieved from https://bambus.rwth-aachen.de/eng/reports/zeri (27/03/2020). Copyright D. Rorhbach & S. Gillmann.

Figure 3.10. Mungpoo frame test. Retrieved from Performance based design of bamboo structure: Mungpoo frame test (p.7) by B. Sharma, K. Ghavami and K. Harries. 2011. International Wood Products Journal.

The PUC University of Rio in collaboration with the University of Pittsburgh tested a portal frame truss structure based on the truss used for a housing project in Mungpoo, India. The columns were each composed of four bamboos with a doweled and grouted Vierendeel connection to form a simple portal frame. For the laboratory testing setup, it was chosen to test in a two-dimensional plane on a 1:2 scale (Sharma et al., 2011). However, in a real construction, the truss connection would be three-dimensional with wind braces and consequently the load this particular truss can withstand would be higher. Figure 3.10 illustrates the test set up (left) and the result after the test (right). It was found that the load capacity of the bamboos was satisfactory and that behavior was comparable to a similar wooden frame construction. Another remarkable fact was found; the pull-out strength test indicated that the bond between the grout and the internal bamboo wall was considerably high, preventing pull-out failure when tensile loads are applied, even more so when the grout passed over more than one internal bamboo node. This signifies that in tension, a grouted joint can be considered as one entity and does not function as a cemented 'cork' (Sharma et al, 2011).

3.4.4 Geometric structures

This category comprises those structural systems that are based on mathematical calculation and principles to become geometric structures. Although relatively few bamboo buildings have been erected using this structural method, it is probably one of the most promising and apt ways to work with bamboo. Beneficial to this structural system is its capacity to foresee large free spans with a relatively light own weight. Normally, this construction system is provided in steel or aluminum components that are industrially manufactured at millimeter precision. However, bamboo could offer an advantage as it has many ecological benefits over steel and aluminum and it allows for (small) error in precision. The capacities of bamboo are similar to that of steel and aluminum and it can be as simple as replacing the steel or aluminum tubular elements by bamboo canes. The jointing method could even remain the same. Although bamboo culm ends are more vulnerable and care has to be taken to avoid cracking when transferring loads to the connector pieces (Saevfors, 2012).

3.4.4.1 Space frame

A space frame is a rigid and lightweight, truss-like structure constructed from interlocking struts in a geometric pattern. It is assembled of linear elements arranged as such that forces are transferred in a three dimensional manner (Lan, 1999). Self-supporting bamboo space frame structures have already been studied since 1999 by Prof. Ghavami at the PUC laboratories in Rio de Janeiro (Moreira & Ghavami, 2015). Figure 3.11 illustrates the space frame examined by Moreira et al. (2018) where flexible joints with polypropylene textile cables tightened with tourniquets were applied. Even though this type of jointing method is beneficial in areas of poor resources and/or with high seismic risk, it was found that there occur displacements in the joints and occasional crushes at the end of the canes due to these tourniquets. Arguably it would be more beneficial to make use of fixed jointing elements. A challenge is to design connector pieces where multiple members can meet at one point for a reasonable price (Moreira et al., 2018).

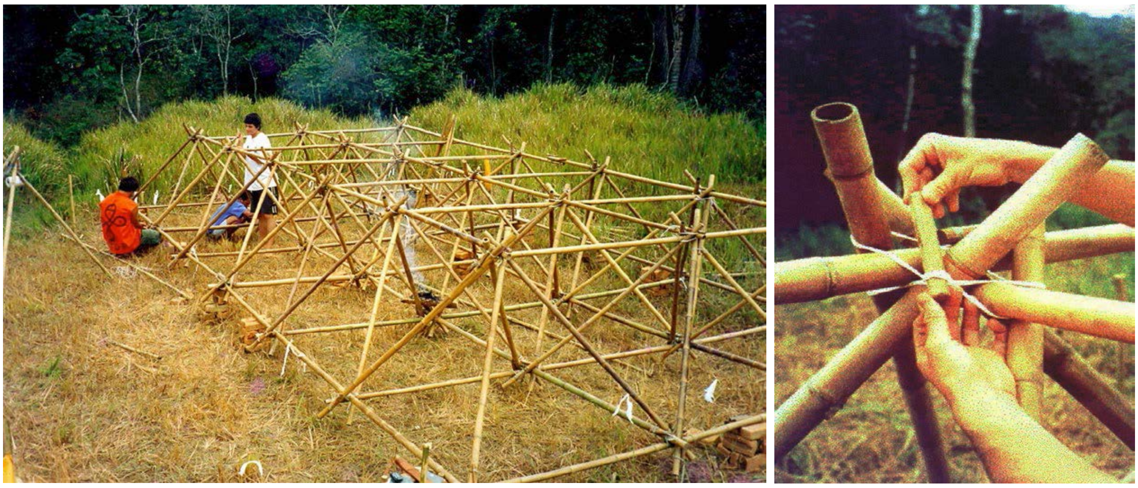


Figure 3.11. Bamboo spaceframe structure. Retrieved from Self-supporting bamboo space frame structure with flexible joints (p.393) by L.E. Moreira, M. Seixas, J. Bina & J. Ripper. 2018. Copyright Materials Research Proceedings.

Another example of a bamboo space frame is the 157m² Amana Key summer school aula in Cotia, Brazil designed by Leiko Hama Motomura from Amima Architects (Figure 3.12). This three-dimensional spaceframe bridges a 16m span with locally sourced Phyllostachys Heterocycla of 10cm diameter. The joints are made with metallic connector pieces that permit for the curvature of the roof (Amima Arquiteture, 2019).

Figure 3.12. Amana Key Summer school in Brazil designed by Amima Arquitectura. 2000. Retrieved on 27/03/2020 from www.amima-arquitetura.com.br/projetos/institucional/amana-key-saladeauladeverao.Copyright Amima Arquitetura.

3.4.4.2 Grid shell

A grid shell can be defined as a spatially curved load bearing structure consisting of a grid or lattice, often deriving its strength from its double curvature. In IL31 (2000) inspired on Frei Otto's lectures, Dunkelberg mentions the Russian engineer Shukov whom already pioneered in 1896 with the first grid shell structures at the All Russia Exhibition in Nizhny Novgorod, Russia. The technique has evolved since into different kinds of configurations, hereafter shortly discussed;

- A **hyperbolic paraboloid** is a doubly-ruled surface meaning that every point on its surface lies on two straight lines across the surface. Horizontal sections are hyperbolic in format and vertical ones are parabolic (Dunkelberg, 2000). The Mexican architect Felix Candela, well-known for his light structures, once mentioned that of all the shapes that can be given to a shell, the easiest and most practical to build is the hyperbolic paraboloid because it has the advantage that the double curved anticlastic surface can be formed from straight elements (Seixas et al., 2017). Consequently, it is a structural system that is frequently applied in bamboo architecture, not only in smaller or temporary pavilions but also in larger constructions., such as for example the great hall of OBI designed by Widyowijatnoko (Figure 3.13). It contains an oval shaped, floating roof deriving from a rhomboid section. At the end of this roof, the entrances are hyperbolic parabolic shaped. The construction was prefabricated in modules which were assembled on site. The repetitiveness and parallel assembling of the modules minimized error and created time-reduction (Widyowijatnoko & Aditra, 2018).

- A combination between spatial trusses and a **pantograph grid shell** was designed by Seixas at the PUC-university of Rio (Figure 3.14). This modular self-stabilizing and self-deployable structure was conceived without the application of screws or nails, only with textile moorings to make a hinged handcuff (clove hitch knot). The Finite Element Method (FEM) software was used to calculate the structure from the initial studies on. The structure could be completely prefabricated and after pulleys and ropes were used to lift the structure until equilibrium. Each module was separately anchored, cantilevered and stabilized before a following module was mounted. Beneficial was that the entire structure could be assembled on site without the use of electrical machinery. The structure can easily be dismounted and mounted again on another location. The roof is covered by a tensioned PVC canvas. (Seixas et al., 2016).

- The term **diagrid** comes from ‘diagonal grid’ and is a framework of diagonally intersecting beams. The ZCB bamboo pavillion by the Chinese University of Hong Kong, School of Architecture is a long-span and form-active gridshell structure of approximately 350m² folding down into three hollow columns. The poles were bent and hand-tied with metal wire by Chinese craftsmen based on ancient scaffolding techniques (Architizer.com 2015).

- A **geodesic dome** is a very popular grid structure for temporary pavilion structures. Geodesic bamboo domes are based on aluminium and wooden ones conceived and coined by Buckminster Füller in the nineteen fifties. It is a hemispherical thin-shell (lattice shell) structure consisting of many geodesic polyhedrons. These triangular elements make the structure rigid and distribute forces in a logic and equal manner throughout the structure. Therefore they can withstand heavy loads in comparison to their size (Dunkelberg, 2000). A Belgian company called Bebamboo rents out bamboo domes in multiple sizes going from 5 to 14m diameter (Bebamboo.eu, 2020).

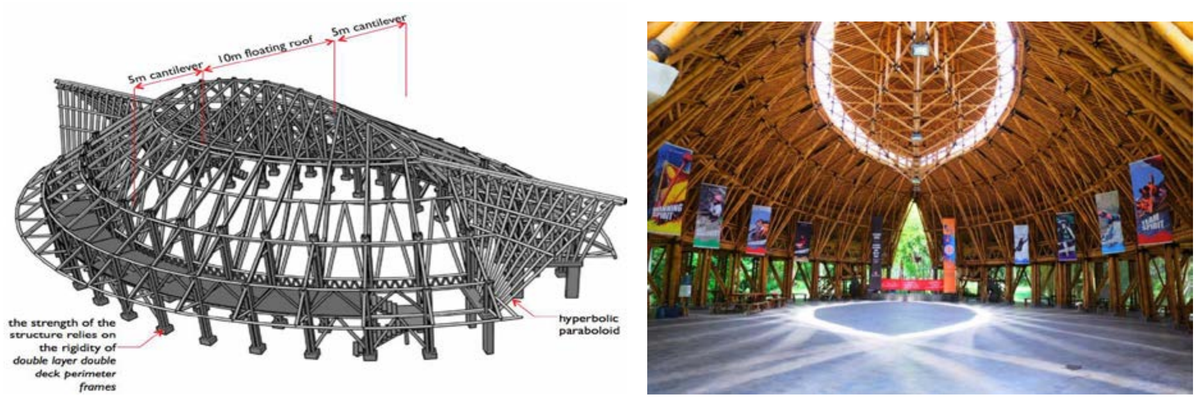


Figure 3.13. The Great Hall of OBI in Bali designed by Widyowijatnoko.2018. Retrieved from Architectural design Great Hall of Outward Bound Indonesia. Proceedings by A. Widyowijatnoko & R. Aditra. World Bamboo Congress.

Figure 3.14. Pantograph grid shell structure. 2016. Retrieved from: Prefabricated bamboo structure and textile canvas pavilion (p.183, 186) by M. Seixas, K. Ghavami and J. Ripper. Copyright Journal of International Association for Shell and Spatial Structures.

3.4.5 Orthogonal bamboo architecture

The term 'orthogonal architecture' might be the least obvious one, but this term is meant to describe architecture wherein bamboos are merely employed in either a horizontal or vertical manner or a combination of both such as beams, columns or in an orthogonal framework. Because of its specific straight structure, it is easily associated with modern architecture. Curvatures or diagonal use of bamboo poles does not appear in this category. Also the jointing technique is addressed in an orthogonal manner.

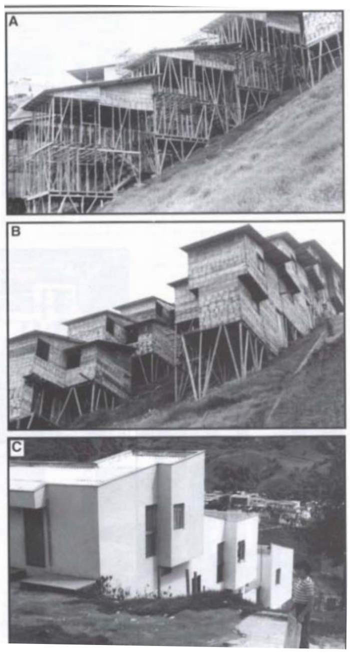


Figure 3.15. Malabar Project designed by Jorge Archila. Retrieved from The Gift of the Gods (p.380) by Hidalgo-López. Colombia.D´vinni Ltd. 2003

An example of orthogonal structures are modern **Bahareque** constructions based on the traditional bahareque method common for Latin American countries such as Colombia and Ecuador where horizontal bamboo strips are tied or nailed to both sides of a bamboo post. As this is a very simple and cheap technique, it is often applied by poor people who has resulted in a negative connotation. Hidalgo-López (2003) quotes in this matter the Malabar social housing project in the Holanda Neighborhood of Manizales in Colombia built in 1982 where modern baharaque techniques were employed in this project. Manizales has a long and rich history of traditional bahareque houses. Whereas the traditional bahareque technique uses an earth mixture as plaster, nowadays a wire mesh is put on top of the bamboo framework finished off with a cement plaster also called ´baharaque encimentado` (Padovan, 2010). A cement mortar is preferred over an earth mixture for it provides a better protection to the exterior walls (Gutiérrez, 2000). Due to the cement covering, the quality of the houses was improved considerably. Moreover, bamboo poles were only visually present in the foundations. Both factors aided in enlarging the acceptance of the poor families that were housed here (Padovan, 2010). Bahareque walls plastered with cement mortar form structural walls with a high strength and stiffness (Hildago-López, 2003). According to Gutierrez (2000), the fact that the frame and mortar works together duplicates the mechanical behaviour compared to the separate frame elements acting alone. The structural entity thus formed transmits in plane shear horizontal forces that earthquakes and wind can produce.

Another example of this logic and straightforward way of providing structural frames can be found in **modern or minimalistic bamboo architecture.** In this subcategory**,** bamboo canes are deployed as beam or columns. Other materials than bamboo are added as they serve better as structural elements such as floors, walls or roof cladding, much like steel frame structures where steel is rarely used for other structural elements other than the load bearing structure itself. In this category, bamboo is regarded upon as a replacement for a steel or wooden frame, while maintaining the same constructional logic of steel or wooden constructions. It was researched by Moreira et al. (2019) that the effective lightness of a bamboo bar is superior to steel by 83% and 145,5% to wood. In other words, bamboo structures, for a similar load and volume, are lighter than steel or wooden structures. In the same way, the absolute efficiency of bamboo, defined as the product of effective lightness to the critical load capacity, is 81,4% superior to steel and 112,9% to wood. However, the strength of steel is confined to a smaller volume, which makes that it takes up less volume during transport or placement. It can therefore be concluded that when weight, price or ecological footprint are most relevant, bamboo gains the preference. However, if the volume occupied is most relevant, steel pipes are preferred (Moreira et al., 2019). Modern orthogonal bamboo architecture is applied in the Son La Restaurant by Vo Trong Nghia in Figure 3.16 below. The columns could undeniably be more slender when provided in steel, but serve the same purpose. Bamboo columns are used in the most efficient manner when the forces are transferred straight to the ground. Nevertheless, the slenderness of a bamboo stem can cause deflections (Dunkelberg, 2000). It is for that reason that most bamboo columns consist of multiple canes.

Figure 3.16. Son Lo restaurant in Vietnam. 2017. Retrieved from http://votrongnghia.com/ projects/restaurant-son-la-complex (28/03/2020). Copyright Hiroyuki Oki.

In Figure 3.17, a bamboo column consisting of four culms is shown. The column was designed by the author for his former house in Ghent, Belgium and supports the weight of a green roof. Bamboo columns can be composed in a plethora of ways, and not merely by combining more than one pole to form a column. Although this might be the easiest method, also cables (steel, nylon, vegetal,..) could be attached to the bamboo culm to enlarge its middle section thereby reducing possible deflection in this area. The tent rental company Atawa in France designed a bamboo tent (Figure 3.18) where deflection of the mast is countered by adding smaller diameter bamboos in a similar method as it would do with cables (Atawa.com, 2018), which is possible due to the tensile capacities of bamboo.

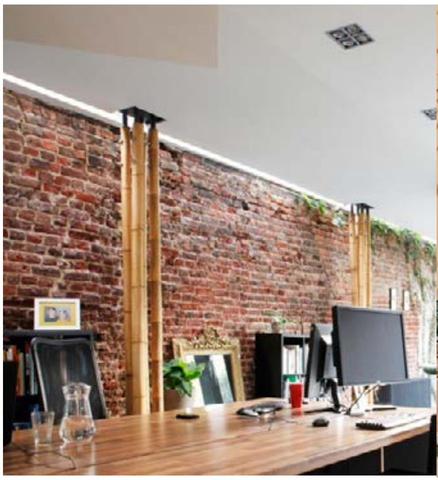


Figure 3.17. Bamboo column in the bamboo house in Ghent, Belgium designed by Sven Mouton. 2011. Copyright Sven Mouton.

Figure 3.18. Tent with middle beam in bamboo. Retrieved from https://www.atawa.com (25/11/2018). Copyright Atawa.

Figure 3.19. Bamboo mast. Retrieved from bamboo mast for lightweight architecture (p.6) by Moreira,Da Silva & Rodrigues. 2014. Key Engineering

Figure 3.19 illustrates a bamboo mast designed and tested at the Federal University of Minas Gerais in Brazil. Four cables were attached at a certain distance to a culm. The study showed that cables needed to be prestressed in order to prevent creep of the bamboo used as column. In addition, a considerable increase in load capacity of the bamboo poles was perceived. Using arms of the bamboo bracing, this limit load increased even more. Another bamboo mast (column) was researched as well without any cables but with interposed spacers composed of four bamboos, achieving a 48kN load in 5.5m high columns without any buckling. Additionally, 4 to 5cm diameter bamboos fastened together with steel shackles (without pins/wire rods) were researched and here it was found that the higher friction of the tension bands elevated the load-bearing capacity (Moreira et al., 2014).

3.4.6 Conclusion

Although the structural system itself does not have a direct impact on the quality of a bamboo construction, it does affect the way forces need to be directed to the soil, how and if a construction can be prefabricated and the way jointing needs to be addressed. As this dissertation focuses on sustainable, low-cost and innovative bamboo prototypes, the structural systems from the orthogonal spectrum are favored due to the fact that these can be designed in a modular manner, are easy to prefabricate and require a lower quantity of bamboo culms compared to curvilinear structures. A bending process weakens the bamboo stem (section 3.5) and therefore a higher quantity of bamboo culms is required to intercept the loss in mechanical properties. The curvilinear structural system is presumably the most expensive structural method, not only because bending is a time- and energy consuming process, but also because forces are not directed to the soil in an axial manner causing greater moment-forces that need to be solved. Another consideration that needs to be made is the way a specific structural system exposes or protects the bamboo culms from weather conditions. For temporary constructions this is not a very important factor. However, a good protection (both by treatment and design) prolongs the service life of bamboo constructions considerably. This is an essential aspect which should be taken into consideration from the start of the design process e.g. when defining the structural system. The recommendations in Figure 3.20 by Kaminski et al. (2016) for detailing bamboo structures to protect them against rot and insects should be adhered as much as possible despite the specific structural system that is chosen. It is in fact based on good practice timber detailing.

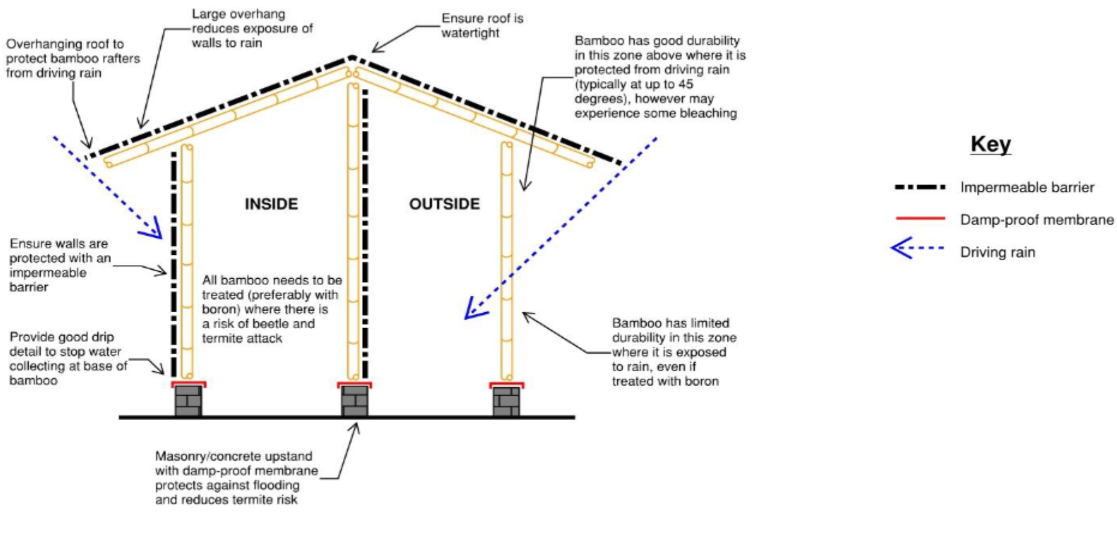


Figure 3.20. Detailing of bamboo structures. Retreived from Structural use of bamboo. Part 2: Durability and preservation (p. 6) by Kaminski, S. , Lawrence, A. , Trujillo, D. and King, C. 2016. The Structural Engineer.

3.5 **Joint design**

In bamboo architecture, the joints determine a construction´s structural behavior and inherently also its strength, success and visual quality. Using bamboo as a structural material is challenging. The lack of a joining system to accommodate its strength makes the application uneasy. Where two decades ago, there only existed little literature on this topic, nowadays there exist multiple qualitative studies on this specific subject with the PhD of Widyowijatnoko (2012) as most relevant research on joints and the classification thereof. Whereas Janssen (2000) classified joints in a theoretical manner, sometimes describing joints that are not really relevant in bamboo architecture in order to be complete, Widyowijatnoko focused on practically relevant joints and on the tensile aspect of joints. Bamboo structures as well as joints are rather loaded with compression than with tensile forces. However, in lighter structures this could be easily inverted, especially when the building is loaded with higher wind- or other forces (e.g. earthquakes). Some structural systems such as spaceframes are designed to use tensile forces within the joints. Considering the greater performance of bamboo in tension than compression, it is recommendable to optimize the use of tensile forces within any type of structural system. The following sections discuss the different classifications for joints, followed by an overview of the joints from the case studies and finally main design requirements for a designer to develop his or her own (safe and qualitative) jointing system and possible joint failure.

3.5.1 Classification of joints

For many years, the main work of reference regarding the classification of bamboo jointing systems was the INBAR report by Prof. Janssen (2000). In order to be complete, Janssen provides an overview of every type of jointing ranging from (very) low-tech to elaborate joints, however many of them are unsafe or unusable for architectural goals and more adequate for furniture. Before the INBAR report by Janssen in 2000, Arce-Villalobos already extensively discussed joints in 1993 in his PhD-research (Arce-Villalobos, 1993) and many of his findings can be found in the work by Janssen. A few years later, Jayanetti and Follet (1998) also provided a comprehensive description of connections that can be possibly made in bamboo, moreover mentioning which joints would only serve for furniture or very low-tech dwellings. They made a subdivision into four main categories; 1- sliced, 2-orthogonal, 3-angled and 4-through (Jayanetti & Follet, 1998). Widyowijatnoko (2012) produced a classification system in his dissertation which continues on the premises of these former classifications, yet reaches to be a more relevant system for modern constructions. Nevertheless, additional elements can still be found to complete Widyowijatnoko´s classification system as other research can be found on different subparts. An interesting subdivision could be found in the paper by Stamatis & Gangyi (2019) on the Area X project in China, where the authors classify joints according to the amount of ‘modern products’ used. Vernacular joints would use only 10% of ‘other’ materials than bamboo, ‘affordable joinery’ such as the fish mouth connection would use 80% bamboo and 20% steel/mortar, whilst ‘modern joinery’ such as steel wire spaceframes or nodal Mero joints would use 65% bamboo and 35% steel/mortar. Even though questions could be raised to the correctness of such arbitrary statement, it more or less indicates the difference between the jointing types (Statamatis & Gangyi, 2019).

Whilst a simple subdivision can be made between traditional (artisanal) and modern jointing systems, neither Janssen nor Widyowijatnoko did so, for the simple reason that this would not add to the clarity. The latter group would be more extensive and indistinct given the fact that only few traditional joints are really safe enough to be used in larger buildings where loads are higher and artisanal knowledge cannot always be counted on. Modern bamboo architecture constitutes predominantly of bolted joints fixated with mortar. According to Hidalgo-López (2003), the recommended proportion for the grout in a joint is 1:2 cement-sand, without the addition of gravel (López, 2003). The NSR-10, the Colombian code for bamboo construction however, mentions to use the proportion 1:3, along with a plasticizer to ensure the viscosity and fluidity of the mix (Harries & Sharma, 2016). It is important that the mixture has the exact viscosity; too wet would cause detrimental shrinkage, whilst too dry would complicate the practical application. The PhD researcher recommends the usage of the proportion 1:2. Although less cement will lower the cost and chance of cracking through shrinkage, it also lowers the strength of the grout which in cases of high loads is essential. It might be wise to propose different proportions for different structural load cases as is the case for reinforced concrete. The NSR-10 also mentions a minimum bolt diameter of 9,5mm, made of structural steel that has a yield strength higher than 240 MPa, with holes for bolts drilled 1,5 mm larger than the bolt that is to pass through it (AIS, 2010). Caution has to be taken in tropical climate conditions where standard galvanized steel will corrode over time as was the case in the case studies. In tropical climates it is recommended to apply corrosive-resistant steel which is used in the maritime sector. NSR-10 furthermore specifies that spacing between bolts should be no less than 150mm separated from each other, with an internode between each of the bolts. 150mm should also be foreseen from the lowest bolt until the end of the bamboo element when a bolt is placed perpendicular to the bamboo, 100mm is allowed when only compression is applied (Minke, 2012; AIS, 2010). When grout cannot be injected from the end of the bamboo, a hole should be drilled lateral to the internode where the injection is needed, usually with a funnel, requiring the grout to be of a sufficient viscosity to pass through the mouth of this funnel with ease. Hitting on the side of the bamboo stem with a rubber hammer or such will aid the concrete to settle slowly by the caused vibrations (Hidalgo-López, 2003; Padovan, 2010). Hidalgo-López (2003) reports furthermore that some interesting conclusions were noted on the grouting of joints during the tests done for the ZERI pavilion by Velez in 2000. It was noted that the allowable force augmented proportionally with the amount of internodes filled with grout and that bamboo was always more resistant than any connector piece used. At the FPMPA Laboratories of Stuttgart, Germany, tests also pointed out the danger of concrete shrinkage leaving empty spaces between the grout and wall. When this occurs in joints were bolts are tightened, it could locally produce rupture (Padovan, 2010). However, in practice, this does not form an essential problem for bolts are never screwed tight until the end as this can cause damage to the outer bamboo wall even if the grout completely occupies the cavity without air-pockets. When the natural nodes were not punctured, one only needs to fill these internodes with grout where the connection is made (small volume). Rarely other filling materials other than grout/cement are used, even though experiments are being made with resins in several academic and non-academic institutions as this could be beneficial to the environment (bio-resins) and for the adherence to the wall making a stronger attachment (Widyowijatnoko, 2012). Cost and availability however pose an important restriction to a wider-scale application of this technique.

The application of mails and screws in bamboo joints should be avoided because they induce splitting in the culm. Only when a small hole is drilled beforehand, screws can be used. Nevertheless, the usage thereof is not recommended. Bamboo connections do not take moment forces very well, and it is difficult to design a moment resisting capacity in the jointing element. Harries and Sharma recommend to consider connections as pin-connected, allowing none or little moment transmissions (Harries & Sharma, 2016). In general, it is best to foresee the joints near a node in the bamboo stem because fibers near the node are no longer uni-directional such as in the internode and therefore a 50% higher resistance against shear forces can be found here (Padovan, 2010). Despite the fact that bamboo jointing techniques requires a connection method which cannot simply be derived from other materials such as wood or steel, even though these can serve as an inspiration, a plethora of variations exist on the conception of these joints. Janssen (2000) determined the classification of joints based on three questions. Widyowijatnoko (2012) agreed with Janssen hereon.

1. When two whole bamboo culms are to be joined, this can either be done by contact between the full cross-sections or by collecting the applied forces from this cross-section to a joining element (separate joint)

2. There are three ways to collect and join the forces applied to an intersection of bamboo stability elements; by using the inside or hollow cavity of the stem (e.g. by filling this with concrete that contains a joining element such as a rebar), by using the cross-section or wall from the bamboo itself or by placing a jointing element on the outside of the stem. Or shorter said, from within the stem, from the wall of the stem itself or from outside this wall of the bamboo stem.
3. The joint can either run along the direction of the fibers (parallel) or perpendicular to it.

These main questions allowed Janssen to come up with a theoretically complete set of 8 groups that can classify any joint that there can be found; group 1; full cross section, group 2; from inside to a parallel element, group 3; from inside to a perpendicular element, group 4; from cross-section to a parallel element, group 5; from cross-section to a perpendicular element, group 6; from outside to a parallel element, group 7; from outside to element perpendicular & group 8; for split bamboo (Janssen, 2000).

As Widyowijatnoko rightfully noted, three of these groups have little to no relevance when it comes to modern jointing; group 3 and 7 have nearly no application and group 8 is outside the scope of this (and his) research for it refers to the field of processed or laminated bamboo (2012). The lack of relevance of these categories was presumably also felt by Janssen as they are less elaborately discussed. Besides above-mentioned joints that have less relevance, Janssen also discusses joints with little other usage than for furniture-making (2000). Widyowijatnoko, who elaborated on Janssen´s classification, comprises only the most relevant issues and therefore his categorization will be used as basis for the classification discussed in this research, completed by other relevant research. Widyowijatnoko also uses another emphasis regarding the distinction of the way forces are transferred; compression along the fibers or perpendicular to the fibers (also in tension, friction, shear and bearing stress) and the position of the joint/connector (inside or outside the poles). Another nuance or addition Widyowijatnoko (2012) made is the distinction of what a connection consists of. Whereas Janssen defined a joint as a connection between two bamboos, Widyowijatnoko views a joint as a connection between a bamboo and its connector or supporting base (Widyowijatnoko, 2012). This apparent semantic difference however does make a difference, especially in modern joint design. A connection method between two bamboos can for example exists out of more than one type of joints. Joints rarely belong merely to only one category; they are often a combination of connection principles from various groups.

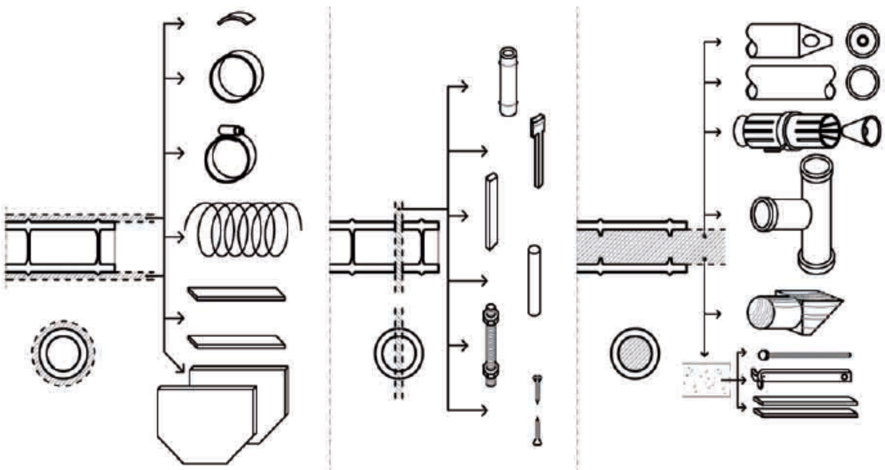


Figure 3.21. Possible locations of connectors; outside bamboo stem (left), perpendicular to fibers (middle), or inserted inside (right).Retrieved from Traditional and innovative joints in bamboo construction (p.33) by A. Widyowijatnoko. 2012. PhD Dissertation at RWTH Aachen.

In short, the classification system is based on the positioning of the connector on the bamboo; on the outside, perpendicular to the fibers or on the inside of the hollow internode of a bamboo stem, as seen in Figure 3.21 (Widyowijatnoko 2012). Widyowijatnoko (2012), departing from the theoretical possibilities of three conceivable locations of the connector piece, can re-classify the eight groups from Janssen into six groups that are slightly altered in emphasis. Five groups were maintained and one was added as can be seen in Figure 3.22. Traditional joints as discussed and classified by Jayanetti and Follet (1998) are not retained in this dissertation as they do not suffice for modern bamboo architecture.

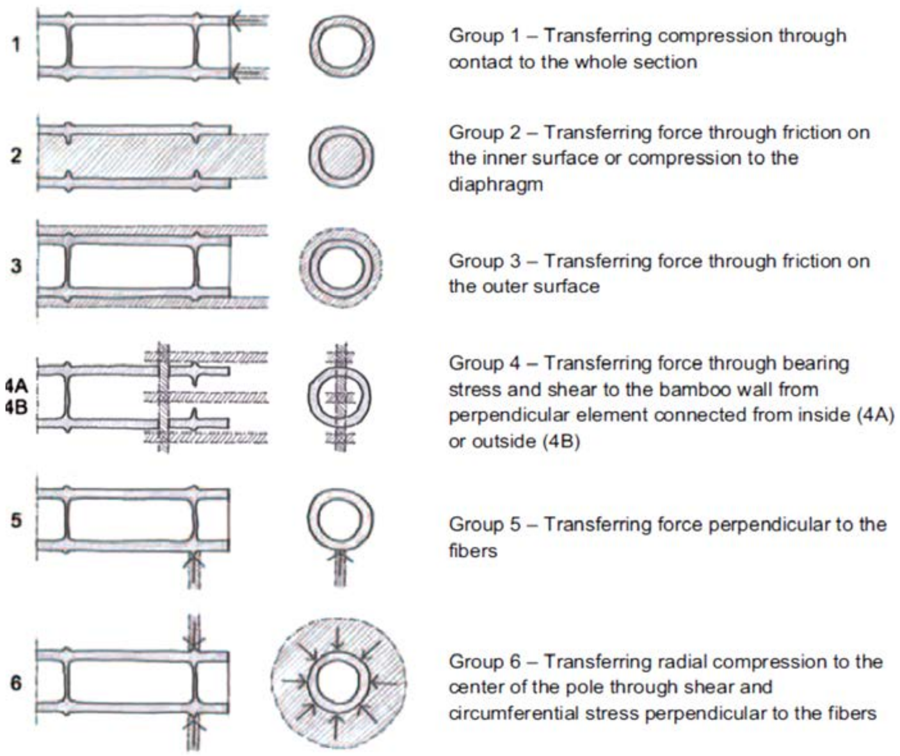


Figure 3.22. Main categories of the bamboo joint classification. Retrieved from Traditional and innovative joints in bamboo construction (p.34) by A. Widyowijatnoko. 2012. PhD Dissertation at RWTH Aachen University.

3.5.1.1 Group 1 – Transferring compression through contact to the whole section

This first group is the most common applied jointing method for it is the strongest possible connection against compression forces, which is the most prevalent force in construction (Janssen, 2000). The joining members can be positioned in a vertical or horizontal manner, such as in a column or beam but also in any other angle as long as the compression forces are transferred by contact of the full cross-section of a bamboo culm. Lashings used to keep bamboo in position are part of this category (Janssen, 2000). Another typical connection of this group is the connection of a column to a concrete foundation. In order to protect the stem from upward moisture, the culm needs to be lifted from the ground. Such articulated joint is predominantly done by embedding a metal rod about 10 to 20cm into a concrete foundation while extending for 20 to 40cm, onto which the bamboo stem can be glided over fixating the bamboo culm in position by filling it with grout. Also other solutions using a wooden plug, a steel or metal cone or an epoxy mortar cone can be applied to produce such a joint. Figure 3.23a is a simple yet elegant pin connection developed by Christoph Tönges for a pavilion near Milan, Italy. A solution by Marcelo Villegas implants the steel cones in a concrete sphere (Figure 3.23b). Minke himself puts the bamboo canes in a bucket filled with sand, without using cones or other metallic elements. If one of the canes transfers more loads than another, it will penetrate deeper into the sand until all bamboos transfer the same forces (Figure 3.23c) (Minke, 2012).

Figure 3.23. Potential solutions for bamboo foundations. Retrieved from Building with bamboo (p. 48,49) by G. Minke. 2012. Copyright Birkhauser.

Whilst the classical 'fish mouth' connection also has one member (the member which has a fish-like cut in it) that is part of this group, the 'receiving' bamboo is part of group 4A. The fish mouth connection is one of the most used joint in bamboo architecture and is often favored in the literature, for example in the Colombian NSR-10 code (INEN, 2011). Tests done by the Princeton University in collaboration with the PUC-Rio show that this is indeed a very strong connection. The weakest point appears to be the steel bolt and not the bamboo nor the connection method. These tests also emphasize the importance that the joint is positioned close to the node as the samples with nodes failed in compressive loads at a value around 18kN while samples without a node already failed around 4kN. A possible failure is the splitting and crushing of the culm (Michiels et al., 2017).

A fish mouth joint can be made with a simple manual hand- or hacksaw or an electric drill with a large diameter hole saw. The fish mouth form cut out the bamboo needs to be carefully smoothened in order to ensure an adequate fit (Minke, 2012). An often overlooked problem is the inattentive execution thereof in practice. Whilst in theory it is a good jointing method which successfully transfers the load through the entire section of the bamboo using all the fibers, in practice the result can be different. A mere lop-sided or crooked cut for example prevents the loads from transferring equally onto the entire surface. When such a partial transfer is not foreseen in the safety-coefficient of the calculations, ruptures can appear. Although tension bands placed near the connection itself can avoid this problem of rupture, the placement of tension bands is often overlooked. They are forgotten, unknowingly not placed or omitted for aesthetical reasons. One can also resolve incorrect adhesion of both surfaces by filling the abyss with a mixture of wood glue and bamboo sawdust. However, this does not admit the same rate of force transfer as the original fibers. It is essential to produce a cut as exact as possible. In practice, such perfection will prove to take a great amount of time, even when done by trained artisans. Figure 3.23 (left) shows how a hook is located behind the perpendicular bolt. When this hook is screwed tight, the fish mouth joint is pushed against the 'receiving' bamboo and the joint is secured. Section 3.5.2. discusses in detail the fish mouth connections made by the PhD researcher in the community center.

Low-tech variants on the above-described fish-mouth connection are illustrated in Figure 3.24 (right), made with lashing and/or with bamboo pins. For the latter, small long strips of bamboo (around 0,5cm by 20cm long) are cut with a machete from a bamboo and (carefully) hammered inside a pre-drilled hole in the connection that has to be joined. The pin is often slightly tapered. Hence when hammering inside the hole, it yields a little friction, tightening the joint. Even though it is an extremely low-cost and simple technique, care has to be taken in constructions that receive considerable loads. Improper execution could cause the joint to loosen which can jeopardise overall stability (Widyowijatnoko, 2012; Harries et al, 2016).

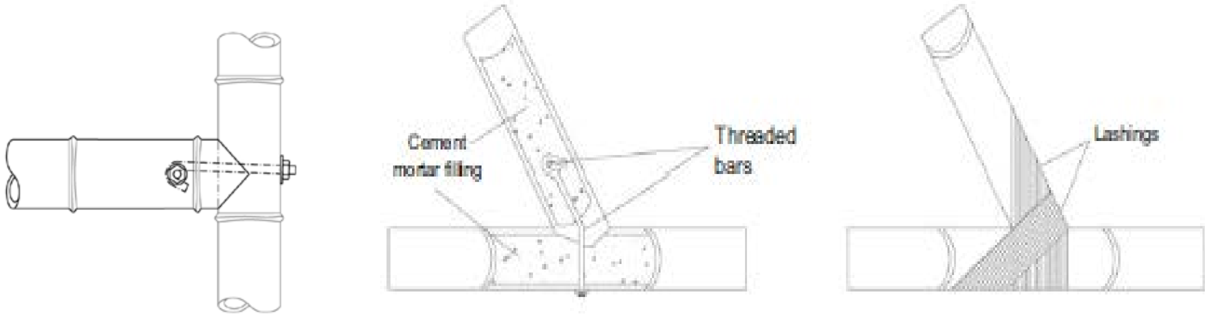


Figure 3.24. Typically angled connections. Retrieved from Non-conventional and vernacular construction materials. Characterization, properties and applications (p.421,425) by K. Harries & B. Sharma. 2016. Copyright Woodhead Publishing.

3.5.1.2 Group 2 – Transferring force through friction on the inner surface or compression to the diaphragm

The second group is also a very common method to connect bamboos to each other or to other structural elements. The cavity of a bamboo stem is a place that eases the practicality of connection for it can be filled without many complications. In this group there is a connector piece placed inside the bamboo culm and as a result the bamboo culm can be attached to other materials. Compared to the previous group, the transfer of loads is less direct because it is first transferred to the 'filler' inside the bamboo. Because the connection is hidden inside, a visually clean joint can be made. This kind of connection is in most cases made by inserting a steel rod, a metal tube or a piece of timber of a smaller diameter inside the bamboo end and thereafter fixated with a cement mortar or a glue/resin (Widyowijatnoko, 2012).

The connector pieces by Hamura Shoei Yoh in Figure 3.25 and by Vitor Marcal in Figure 3.26 are exemplary of how a metal tube connection can be used inside a culm (Minke, 2012). Another exemplary joint was designed by Leiko Motomura for the Amana Key Summer School in Brazil (Figure 3.27). In most cases, the cavities around the steel or timber plug need to be filled with a cement grout in order to secure this external element to the bamboo culm and to transmit the forces applied. However, there exists a possibility of shrinkage of the grout thereby leaving a space between the concrete and the inner bamboo wall (Janssen, 2000).

When using a timber connector piece with the exact size of the inner diameter, the stem itself is reinforced which makes it less likely to occur splitting, crushing or cracking? The internal distribution of shear stresses is changed because of the net second moment area in the region of the connection and bending stresses are diminished for the contact area is enlarged. When closed off well with a glue or resin, it also forms a good protection against insects (Meyers, 2013, Arce-Villalobos, 1993). Figure 3.28 demonstrates a wooden plug connection by Bamboo Forest in Peru (Forestbambu, 2020). Beneficial to the application of a wooden connection is that is also can be used for connecting to normal construction materials. The difficulty is to achieve the precise diameter of the inner bamboo culm. Jansen (2000) describes two methods to fit a bamboo around a timber piece. First, by widening the inside diameter of the culm with the help of a drill in order to obtain a standardized and unified diameter. Secondly, the wooden piece is glued while kept tight with a hose clamp. To make this possible a slot should be sawn in the bamboo (Janssen, 2000).

Figure 3.25. Connector piece by Hamura Shoei Yoh. Retrieved from Building with bamboo (p. 45) by G. Minke. 2012. Copyright Birkhauser.

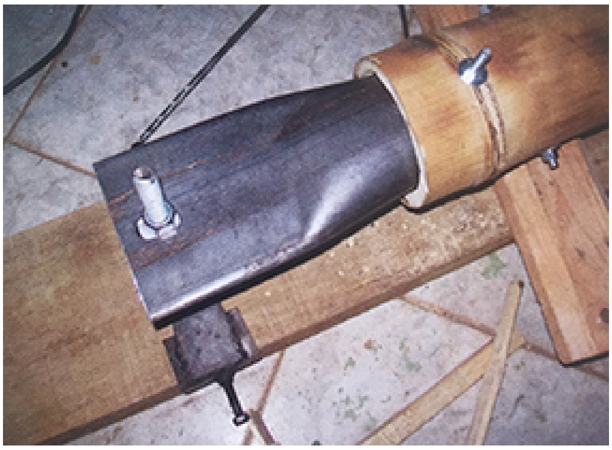


Figure 3.26. Connector piece by Vitor Marcal. Retrieved from Building with bamboo (p. 45) by G. Minke. 2012. Copyright Birkhauser.

Figure 3.27. Connector piece by Leiko Motomura. 2000. Retrieved from http://www.amima-arquitetura.com.br /projetos/institucional/amana-key-saladeauladeverao/ (27/03/2020). Copyright Amima Arquitetura.

Figure 3.28. Wooden connector piece by Y. Barnet & F. Jabrane of Forestbambú Perú. 2019. Retrieved from https://www.forestbambu.com/noticias (05/04/2020). Copyright Forest Bambu.

In Figure 3.29, the principle of a wooden plug is illustrated. In essence, it can be compared to the cork of a wine bottle. When applying this principle, a real hazard exists that the connector piece can also be pulled out like this cork when tensile forces are applied. Widyowijatnoko provides as solution to this problem to provide a node at or near the end of the connection to avoid that this 'cork' effect as Figure 3.30 demonstrates (2012). In practice, it is however very difficult to maintain the final diaphragm intact when a plug as described above needs to be inserted, because the bamboo culm has to be glided over this plug without breaking these rather fragile diaphragms. Widyowijatnoko mentions that in an experiment by Farbiarz the difference between tensile forces on a connection with and without the usage of a node at the end was tested. The results show a difference of 2kN for a connection without a node compared to 10kN with the node intact at the end of the culm (Widyowijatnoko,2012). Instead of providing a node at the end of the bamboo which secures the grouted 'cork' in tensile force, another possible method to prevent this pull-out effect is to diminish the end diameter of the bamboo culm by cutting/slicing the bamboo with 5 to 10cm cuts along the fibers to enable a tension band, steel wire (wounded several times) or jubilee clip can be fastened. Very often spaceframes are provided this way as this structural system typically has high tensile forces. Due to the concerns stated above, this joint is often combined with a connection from group 1, such as multiple examples designed by Simon Vélez show (Widyowijatnoko, 2012; Janssen, 2000).

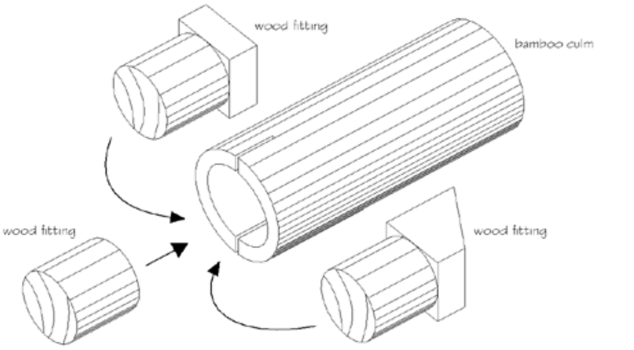


Figure 3.29. Principle of a wooden plug. Retrieved from Fundamentals of the design of bamboo structures (p.79) by A.O Arce-Villalobos 1993. PhD Dissertation at TU Eindhoven University.

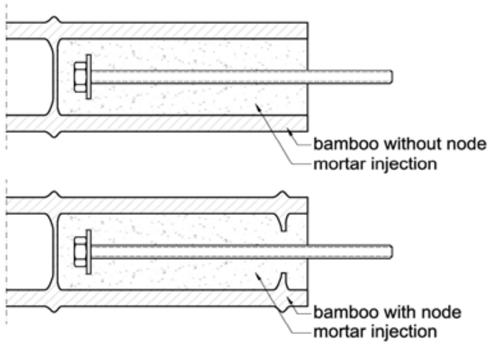


Figure 3.30. Difference of a node - no node near the end to secure a rebar. Retrieved from Traditional & innovative joints in bamboo construction (p.37) by Widyowijatnoko. 2012. PhD Dissertation at RWTH Aachen University.

Another well-known example in this category is the joints designed by Heinsdorff for the German-Chinese pavilion at the Shanghai Expo in 2010. Some of the joints used in this pavilion are based on friction by the insertion of a smaller metal connector piece. Figure 3.31 illustrates two different joints. Concrete to secure the metal connector piece was poured into the hollow section at the end of a culm. The results were studied by the University of Technology in Munich. In order to improve the adherence, sanding the inner wall of the cane without an extra PU-layer was tried first. However by removing the wax-like inner layer, the wall allowed for water uptake during the drying process of the grout, weakening the bamboo and also the concrete composition. A PU-seal resolved this problem for it came to form a frictional and watertight seal on the inner surface of the bamboo. A single-component resin was used for it has a simple processing. This polyurethane resin (Viapal Beckoplast VPU 6072/38 LG) was placed in several layers. After the first was dried, a second layer was placed containing sand-granules of 1-2mm diameter in order to ensure later bonding with the grout. The concrete mix applied had to fulfill various objectives; a good frictional bond was to be formed after placing the steel connector piece, easy processability (through correct viscosity), a low water content preventing the bamboo to absorb excessive water content, reduce the chances of corrosion (through carbonization) of the steel connector pieces, minimal deformation through shrinkage or expansion, sufficient mechanical properties (stability) and finally a sufficiently beneficial ecological content (lowest possible Portland clinker content). One way of doing so was to add a content of Fly Ash (HVFA) to partially substitute the clinker content and also prevented undesirable shrinkage and creep deformation. High-efficiency plasticizers were also added afterwards to ensure a good mixing process (Heinsdorff, 2011). Although this jointing technique obtained good performance results, the technique is costly and time-consuming to repeat for small scale constructions.

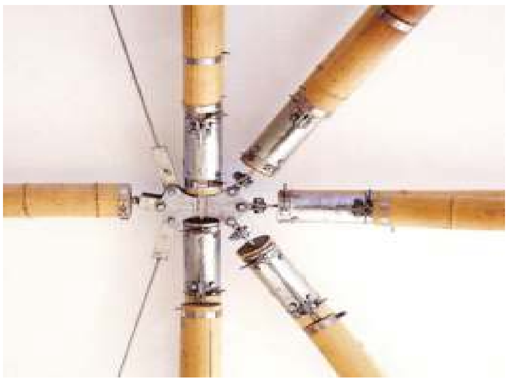


Figure 3.31. Internal metal connector pieces (Group 2). Retrieved from Design with nature (p.81,82) by M. Heinsdorff. 2011. Copyright Hirmer Publishers.

3.5.1.3 Group 3 – Transferring force through friction on the outer surface

A connector piece that makes use of the hard outer silica skin of a bamboo culm to transfer loads is categorized in this third group of jointing techniques. In comparison to connections on the inside, a connection on the outside has the benefit that the fiber density (and therefore strength) is much higher (Janssen, 2000; Widyowijatnoko, 2012). The most used example in this group is the lashed joint. Because of the round form, friction is more easily applied on the outer surface of a bamboo than for example on a square-like form. Friction is evenly applied in a round shape, whereas in a square shape the highest friction would be concentrated on the four corners when the lashing is screwed or tensioned tighter (Widyowijatnoko, 2012). Lashed joints can be found in bamboo structures designed by Vo Trong Nghia (Figure 3.32), Elora Hardy from Ibuku and in Brazil by Bambutec (Figure 3.34). Lashed techniques are especially applied in bamboo scaffolding for its rapid (dis)assembly. Although lashing is a popular connection, it does not provide adequate stiffness for structural bamboo design. Lashings allow significant displacement because they do not adequately hold the culm (Arce-Villalobos, 1993) and the variability of lashing connections diminishes the ability to verify the strength and adequacy of the field connection. When high wind, snow or water loads are placed on the structure and afterwards taken away, this temporarily caused higher friction slightly loosens up the lashed connection, becoming more loose every time (Janssen, 2000). The author moreover noted that in tropic areas the chances of rotting behind the rope are very high. This was the case in the community center (chapter 6.6) were a colouring of the sisal ropes used as an aesthetic finishing was perceived. After removal of these lashings, the area behind the rope was wet and rotting had already set in. This can possibly be remediated by applying a resin on the bamboo in advance or by using polyester ropes instead of a natural material. Lashed connections are also more prone to vandalism than for example a bolted connection. Where the lashed joint can be reached, there exists the possibility of someone making a knife cut in the lashing which could endanger the constructions´ stability. Clearly, when steel wire is used, this problem poses less. Arce-Villalobos (1993) recommends the ''Delft Wire-Lacing Tool'. A tool that winds steel wires around a tubular object i.e. bamboo. As such, the steel wire becomes tensioned and is safe to use as the wire can no longer slip from the stem. Yet, care has to be taken for there exists danger of crushing the stem under this higher tension.

Figure 3.32. Son La Restaurant in Vietnam. 2017. Retrieved from http://vtnarchitects.net/bamboo-properties1/son-la-restaurant. Copyright H. Oki.

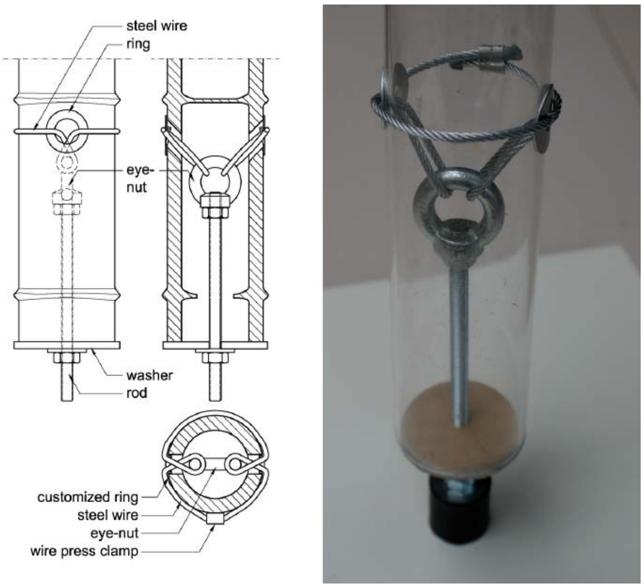


Figure 3.33. Design of a bamboo joint with eye-nut rod. Retrieved from Traditional and innovative joints in bamboo construction (p.92) by Widyowijatnoko. 2012. PhD Dissertation at RWTH Aachen University.

Traditional, vernacular, temporary and lightweight constructions usually have less free span, therefore they are not as susceptible to the danger of failure or loosening of lashings (Arce-Villalobos, 1993). Neither Janssen (2000) nor Widyowijatnoko (2012) objected the use of lashings as a jointing method. Widyowijatnoko even developed in his dissertation a firm, tensioned lashed joint by twisting a (steel wire) lashing into a pre-tension joint (Figure 3.33). This joint is especially designed for structures with high tension forces such as tensegrities or spaceframes (Widyowijatnoko, 2012).

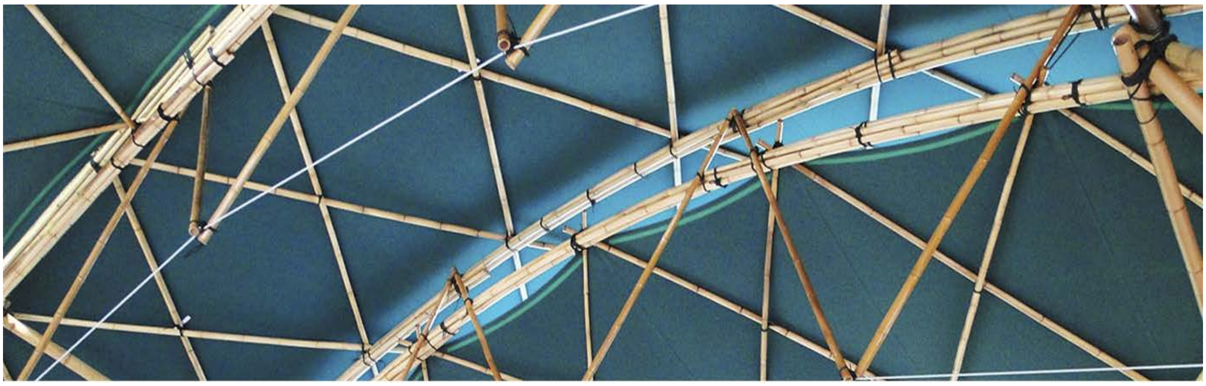


Figure 3.34. Clove hitch knot by Mario Seixas. 2016. Retrieved from https://bambutec.com.br/en/empresa/ (05/04/2020).

Seixas (2017) from Bambutec demonstrates that lashings can be an interesting and fast working method to mount/dismount temporary lightweight constructions, more than bolted connections. The main reason for this is that bolted connections often favor shear forces in structural members due to the torsion caused during assembly which can produce cracks. The bamboo constructions designed by Seixas make use of hinged lashed connections using textile polyester ropes. The constructions were calculated in software for Finite Element Method (SAP 2000). It was concluded that the proposed structures with lashed connections were several times stronger than required for expected strong winds, overload and self-weight. Seixas notes that safety for these structures does not lay in the difficulty of feasibility of a structural analysis, yet in material selection, joint detailing, design and most importantly execution, with as major disadvantage the sliding of the connections along the canes (for this specific structure) and the stability of the system due to displacements of the joints (Seixas et al., 2018). Flexible joints on the other hand decrease the stiffness of the structure, increasing its natural frequency of vibration allowing it to compensate dynamic forces. Seixas used in the amphitheater at PUC Rio (Figure 3.34) hinged handcuff connections based on the clove hitch knot, which has as most important advantage that the bamboo culms do not need to be perforated, thereby ensuring a low mechanical damage during assembly whilst attaining a fairly strong connection due to the tensioning system of the handcuff method (Seixas et al., 2016). Whilst considered more apt for temporary constructions, it should be noted that this amphitheater, a lightweight pantographic grid shell construction, which was pre-stressed by acrylic membranes and braced by self-stressed active bending beams, already stands since 2014 (Seixas et al., 2017).

Besides lashings, also other materials can be used to make connection joints from group 3. In practice, these are predominantly steel connections. In a paper by Yazdi et al. (2015) from Iran, it was researched whether bending a galvanized steel plate round the end of a bamboo, fastened by tension bands or clamps and then drilled with two perpendicular bolted pins, could transfer loads in a satisfactory manner. In this case, the connection was suggested as such in order to make a structural member for a spaceframe structure with a Mero joint (Figure 3.35). The galvanized steel plate is used to transfer load to the bamboo stem by making use of friction, similar to lashings, whilst the steel screws prevent the plate from sliding while the clamps are being closed. At the end of the galvanized steel plate, holes are drilled to allow for a hinge-like connection element which can be attached to a Mero node (Yazdi et al., 2015). One could discuss the benefit vs the negative impact of these screws, especially when they only serve to keep the steel plate in place whilst closing the clamps. It was found by Yadzi et al. (2015) that using friction on the outside of the cane as a connection principle was particularly beneficial to bamboo within spaceframe structures as this kind of structural system produces in its connections little shear resistance to the node. This conclusion was also found in 1988 at PUC-Rio where one of the first bamboo spaceframe structures with steel joints was developed. During the tests at the PUC laboratories, it was observed that the conic geometry and axial irregularities transferred considerable amounts of tension to the connection and the bamboo, causing shear, mainly during assembly and disassembly (Harries et al., 2016).

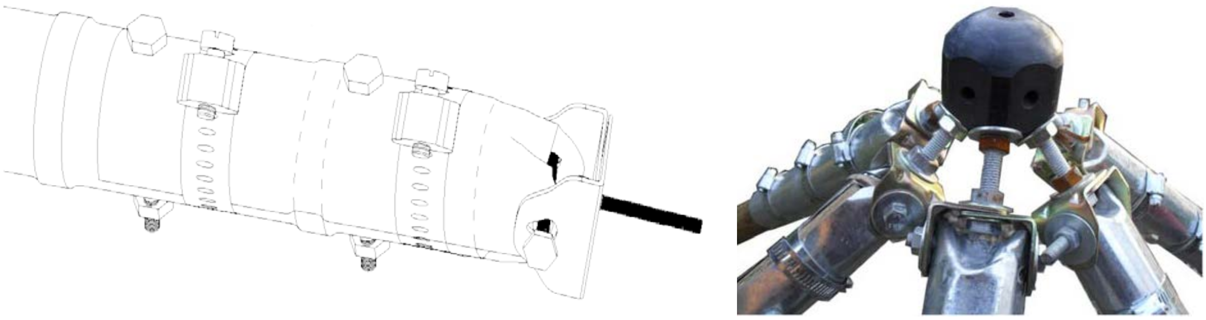


Figure 3.35. Usage of a galvanized steel plate around the bamboo end connecting in a Mero joint. Retrieved from Construction of space frame structures with bamboo. Using innovative pin-joint connections (p.7 & 8) by M. Yazdi, V.B. Moorjani & M. Golabchi.2015. Copyright University of Teheran.

In this regard, also Heinsdorff (2011) should be mentioned for he took the 'high-tech' bolted joint one step further. He applied technical solutions that, even if somewhat exaggerated in complexity, gave bamboo construction a completely different visual than what one would expect from a low-tech ecological and traditional material. Figure 3.36 shows the joint where he adheres a steel plate on the outer side of the bamboo and connects them to each other by steel pins (Heinsdorff, 2011). The use of tension bands is not very common, despite the fact it can be beneficial for it reduces most of the risk of splitting/ cracking. A tension band emphasizes the circular form of the bamboo and keeps it together by pressing the fibers equally towards the inside.

Figure 3.36. External metal connector pieces (Group 3). Retrieved from Design with nature. The bamboo architecture (p.47,55) by M. Heinsdorff. 2011. Copyright Hirmer Publishers.

3.5.1.4 *Group 4 – Transferring force through bearing and shear stress to the bamboo wall from a perpendicular element*

Widyowijatnoko (2012) describes these joints as those where forces are transferred parallel to the fibers until meeting a perpendicular connection element and from there on the load is transferred onto another element, mostly through shear and bearing stress. The distinction is made whether the perpendicular element is connected from the inside or the outside. The use of a gusset plate is a good example of a perpendicular connection positioned on the outside. In steel architecture this is a commonly used connection type, where force is transferred from one element to another without eccentricity because the axes of each member point to one point within the gusset plate. In bamboo architecture, this perpendicular gusset plate element is connected through bolts inside the bamboo, inflicting shear force and bearing stress. A well-known joint applying gusset plates is designed by Renzo Piano illustrated in Figure 3.37. This joint was presented at a building workshop in New York in 1997. Even though this joint is discussed in group 4, it is a combination of group 2 and 3 as well (Widyowijatnoko, 2012). In a paper on trusses with low-cost high-ductility joints by Sassu et al. (2012), gusset plates were also employed according to the principles of this classification group. The ductility which is a benefit in earthquake prone areas was found to be higher using plywood plates instead of steel. In Figure 3.38 the high ductility joint uses a plywood plate and steel nails whereby the bamboos are placed in a relative angle of 60°. Although the use of plywood permits high ductility, this method is less beneficial in areas where there are no earthquakes or high wind-loads.

Figure 3.37. Bamboo joint designed by Renzo Piano. Retrieved from Traditional and innovative joints in bamboo construction (p.57) by A. Widyowijatnoko. 2012. PhD Dissertation at RWTH Aachen University.

Figure 3.38. High ductility joint. Retrieved from Bamboo trusses with low cost and high ductility joints (p. 230) by M. Sassu, M. Andreini, A. De Falco & L. Giresini. Copyright Open Journal of Civil Engineering.

A relevant variant to the gusset plate is the solution studied by Masdar et al. (2019) viewed in Figure 3.39. The researchers sought a solution to tackle the problem of the perpendicular bolt crushing the bamboo stem when screwing tight. Perpendicular bolt connections are common in bamboo architecture, and where grout is applied inside the internode where the bolted connection is made, there exists little to no danger of the bolt crushing the wall. However without the grout, the risk is considerably higher because there is only a small contact area between the bolt and stem which takes all the stresses. Masdar et al. (2019) proposed to provide a wooden clamp in between the bolt and the bamboo stem to reduce the possibility of crushing the stem by dividing the stresses over a larger surface. This is a good solution when the designer seeks to apply joints without the use of grout to enable an easy assemble-disassemble. Vélez has designed a similar type of joint for the Contemplation Pavilion in Arles (Figure 3.40).

Another solution for detachable joints was found by Phanratanamala (2014) at the Kyushu University in Japan. He researched a bolted connection that could be retracted from the grout inside by placing a steel tube inside the grouted internode where the bolted connection can pass through. This joint was tested with and without grout in the internode and it was found that in this specific set up both joints produced the typical failure of a longitudinal crack from the joint to the end of the culm, however as can be expected, it occurred faster for the non-grouted (1,66 kN) than for the grouted connection (3,7 kN).

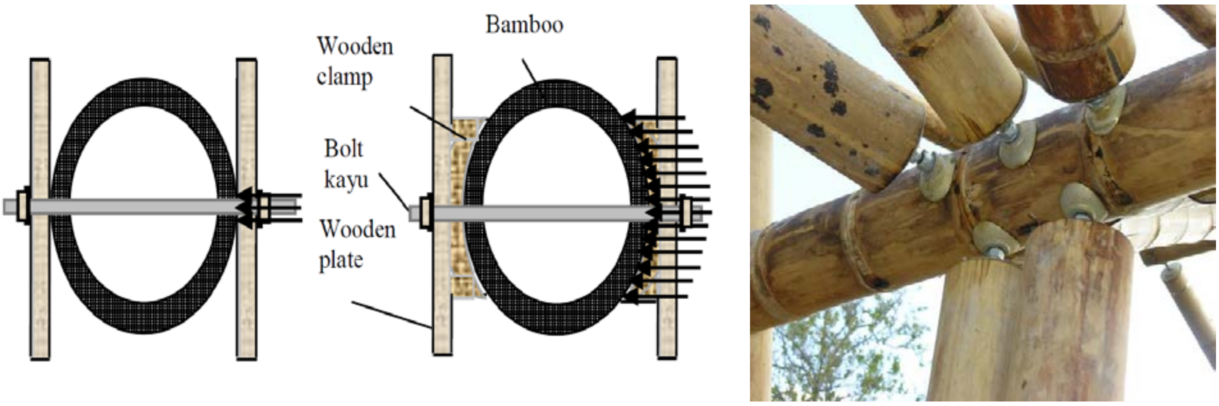


Figure 3.39. Force distribution from bolt and wooden plate to bamboo stem; (a) direct force to bamboo stem (b) forces acting through wooden clamp and an example hereof. Retrieved from Elastic behavior of connection system with the addition of wooden clamp on bamboo truss structure by A. Masdar, B. Suhendro, J. Sulistyo, S. Siswosukarto & Noviarti. Copyright International Journal of Recent Technology and Engineering.

Figure 3.40. Joints at the Contemplation Pavilion designed by Simón Vélez in Arles. 2018. Retrieved from https://contemplation.art/pavillon-simon-velez (07/04/2020). Copyright Simón Vélez.

3.5.1.5 Group 5 – Transferring force perpendicular to the fibers

This load-transferring principle is as straight forward as it seems and is used whenever two bamboos are bolted together when crossing each other. It is a simple joint that should be used with some caution because of the round shape of bamboo that allows only for a small contact area. The stress that is induced on both bamboos due to this restricted contact area produces a certain 'flattening' of both surfaces in order to transfer the loads over a larger surface. Widyowijatnoko (2012) warns for the use of such connections, especially whenever these have to carry heavy loads. Also the risk is flattening and deflection of the bottom bamboo is much higher when a bamboo stem is applied as a beam while laying another bamboo on top according to the principles of this group.

Despite the above considerations, it is an useful technique due to the speed and low-tech of its solution and the effect on the connecting surfaces can be reduced by providing the connection close to a node as the risk of flattening in the middle of an internode is much higher.

3.5.1.6 Group 6 – Transferring radial compression to the centre of the pole

This classification group was added by Widyowijatnoko (2012) to the joint classification defined prior by Janssen (2000) in order to determine a specific joint he was investigating in his doctoral thesis. Through shear and circumferential stress perpendicular to the fibers, Widyowijatnoko (2012) introduced a lashing-based joint where a tension cable was inserted in a hole made in the stem that could tighten the lashing 'squeezing' the poles together using radial forces (Figure 3.31). This joint can offer a benefit in tensegrity structures. Even though in a tensegrity structure the structure's stability is ensured with compression and tension members, it is difficult to avoid large deformation, especially in bamboo. Therefore, Widyowijatnoko (2012) proposed this lashed structure that is able to withstand this deformation. However, due to the specificity of this joint and the fact that tensegrity structures are marginally used in permanent constructions, this jointing method will not be retained in the general classification system used for the evaluation framework of this thesis.

3.5.1.7 Combination of classification groups

Although the joints are discussed in separate groups, most joints consist of a combination hereof. Several noteworthy joint combinations are given as non-limitative examples. Predominantly the inside of the bamboo cavity is used (group 2) in combination with a transversally placed screw, a metal cone or a rope on the outside (group 3).

Amongst nodal joints, the mero joint is the most popular (Figure 3.41). In spaceframes this mero ball is used to connect up to eight bamboos which has a bearing surface at 45°, 60° or 90° angles. To connect multiple bamboo members to a relatively small node, the members have to be conical at the ends. The members are connected via high tensile bolts. The bolt has a dowel pin which is screwed into the node via a sleeve. Compression is transmitted via the sleeve, stresses via de bolt. The dowel pin should be part of the bamboo member whereas the bolt should serve to connect to the nodal joint (Widyowijatnoko. 2012).

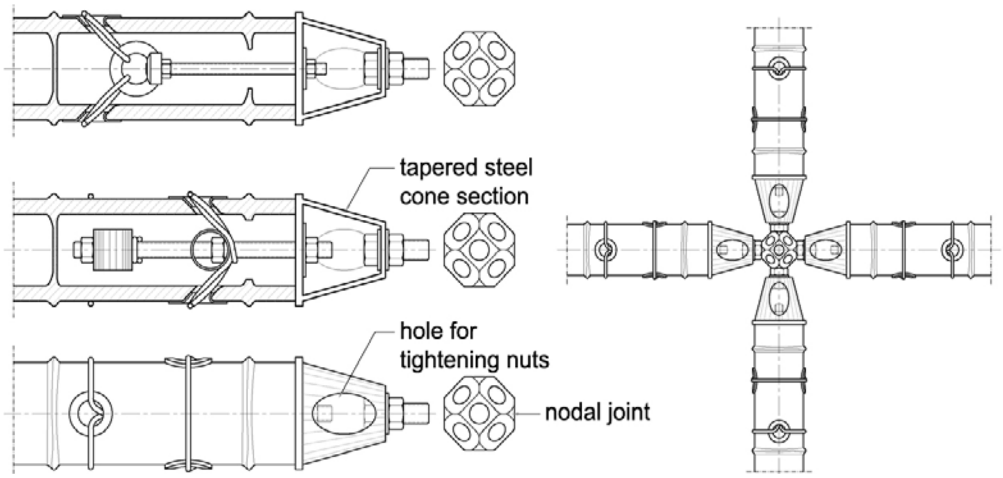


Figure 3.41. Conceptual application of a nodal bamboo joint for space structures. Bamboo joint designed by Renzo Piano. Retrieved from Traditional and innovative joints in bamboo construction (p.140) by A. Widyowijatnoko. 2012. PhD Dissertation at RWTH Aachen University.

Figure 3.42a is a bamboo joint designed by Duff (1941) were a cone-shaped wooden plug is inserted in a tapered bamboo end, tightened with a rope or a steel ring holding the connector inside through friction. A nut and washer are placed on the bamboo end to transfer compression by contact to the whole section. Spoer (1982) and Hidalgo-Lopez (2003) both designed a joint according the similar principle yet without a wooden plug and inserting mortar, respectively Figure 3.42b and Figure 3.42c.

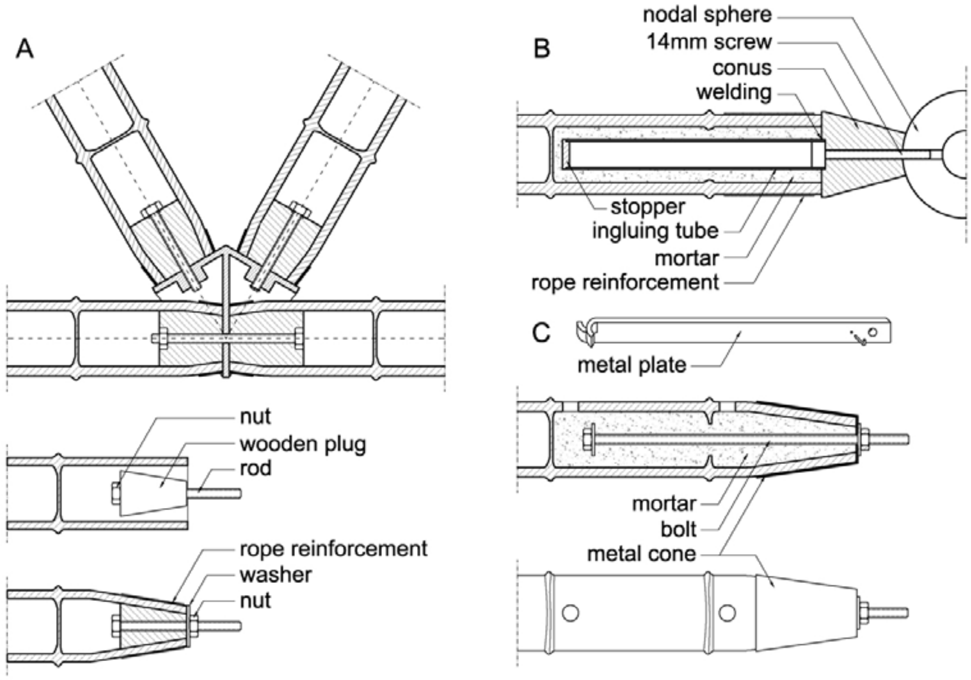


Figure 3.42. Bamboo joint by Duff with a wooden plug (A). Spoer (B) and Hidalgo-Lopez (C) both with a mortar injection in order to provide for a clean type of joint. Retrieved from Traditional and innovative joints in bamboo construction (p.49) by A. Widyowijatnoko. 2012. PhD Dissertation at RWTH Aachen University.

Another interesting joint has been developed at the TU Eindhoven (Netherlands) in 2016 in the search for a joint capable of taking tensile loads and that would be simple to make with ready available materials at the same time. Friction on the out- and inside of the bamboo stem is used as a connection strategy. Inside the bamboo stem, a wire rod with a washer and bolt is placed to converge with the inside diameter. With a handsaw a lateral cut is made so the end diameter can be reduced by means of a standard issued clamp or tension band preventing the inside ring to be pulled out. By adding another washer and bolt on the outside of the bamboo stem, both bolts can be screwed together making a tensioned and pre-stressed connection. These tensioned joints were tested with favorable results ranging from 14 to 24kN in compression, and 5 to 10kN in tension (Blok, 2016). The test setup is demonstrated in Figure 3.43. The bamboo section used for these tests (60-70mm) were considerably small in comparison to the usual diameters used in bamboo architecture (100-120mm), making this an even more interesting setup. As the author demonstrated in several case studies, that the use of smaller diameters could possibly be very beneficial for they grow more widespread, even in 'western' colder countries.

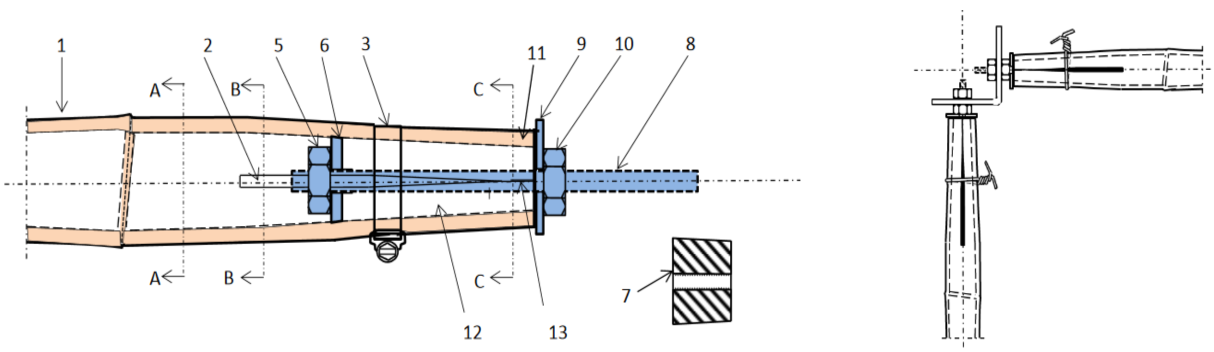


Figure 3.43. Poster session of a simple clamped connection for bamboo truss systems designed by R. Blok. Presented at the Red Cross Human Shelter Congress in Berlin, Germany. 2016. Retrieved from https://pure.tue.nl/ws/portalfiles/portal/51664288/RijkBlokShelterBerlin2016.pdf.

3.5.2 Discussion of the joints from the case studies

In addition to the above-mentioned examples retrieved from literature, a series of enriching joints which were applied by the author in the case studies are described hereafter. They are organized in chronological order as executed, illustrating the evolution the author made in joint design, starting from the most classical fish mouth connection to joints using wooden connector pieces. Having worked with most types of connections, it was found that artisanal executed joints are not always the most easiest nor economical method to provide joints in a construction.

3.5.2.1 Community Center in Camburi, Brazil - 2005/2006

Fish mouth joint (group 1) and Vierendeel or cross-connection joint (group 5): When starting to work with bamboo for the first time, most architects or builders make use of the most commonly known joints in bamboo architecture being fish mouth joints and simple cross-connections. Nonetheless, it was perceived that making fish mouth joints was time consuming and required a certain level of expertise. Figure 3.44 and Figure 3.45 show both techniques. On the left, a cross-connection joint is shown where four horizontal bamboos are secured and bolted with wire rods onto four vertical bamboos from the column. This way the connection itself serves as a wind brace similar to the fixed joint designed by A. Vierendeel for steel frameworks. Two rafters are attached in one direction while the lateral wind bracing bamboos are put in the opposite direction. With the aid of the wire rods with hex nuts and washers put in between each bamboo an equal distance between the bamboos can be obtained. Without hex nuts and washers in between, the bamboos would be pushed together making the column skewed. The hollow internodes of these connections were filled with grout. On the right, a fish mouth connection is illustrated. To make this connection, first a hook was bent at the end of a wire rod (size 3/8, 5/16 or 1/2 inches). Sizes above 1/2 are difficult to bend and therefore not recommended. Subsequently this hook is inserted in the bamboo stem with the fish mouth shaped cut at the end. Different angles require different shapes, and these shapes are made with a hole drill of the same diameter of the 'receiving' bamboo, in the direction of connection. Thereafter, the fish mouth shape has to be refined by hand with a chisel. Especially the latter can be time consuming as it has to be tested every time to see whether it fits perfectly or more needs to be abraded. The other end of the hook has to be put into the receiving bamboo and at the height of the hook (+/- 15cm from the end) a perpendicular wire rod is placed to secure this hook into place. After tightening the hex nut below the receiving bamboo, the joint is tensioned to receive forces. When these forces are considerable, grout has to be injected in order to prevent crushing and maintaining the hook in place.

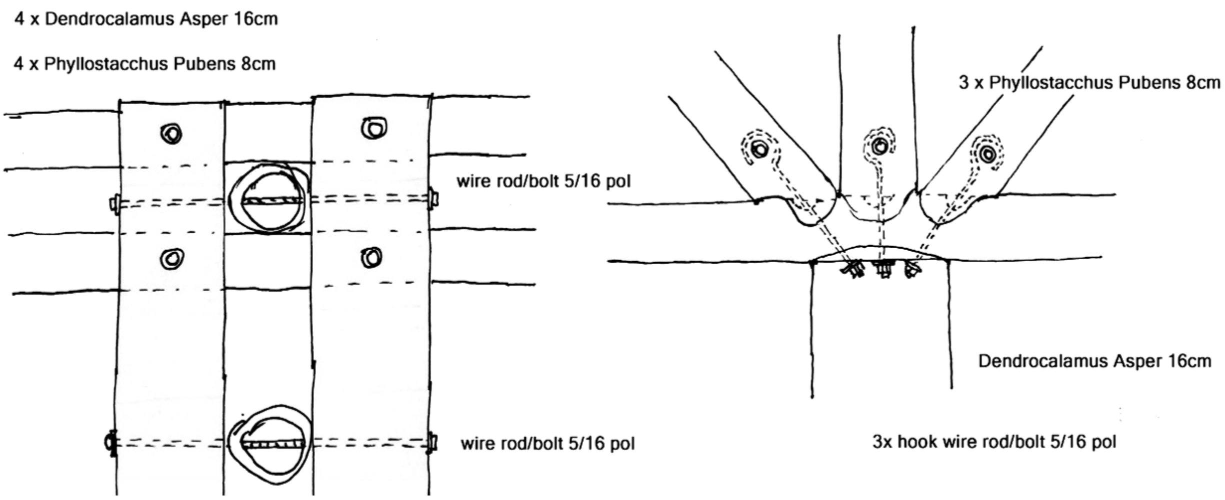


Figure 3.44. Schematic drawing of a Vierendeel and fish mouth connection.

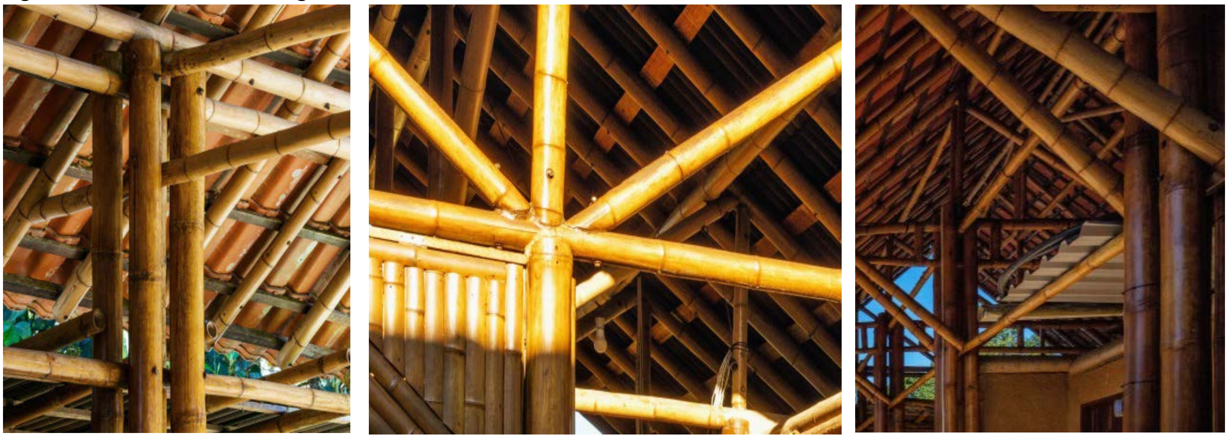


Figure 3.45. Vierendeel and fish mouth connections in the Community Center. 2006. Copyright Nelson Kon.

3.5.2.2 Residence and Architecture Office in Ghent, Belgium - 2009/2011

Steel tube internal connector piece (group 2): The author renovated his own house/architecture firm in Ghent, Belgium with two separate bamboo roofs. The first was a pitched roof made with the use of bamboo trusses. The challenge existed in connecting this non-orthogonal material bamboo to orthogonal materials such as the insulated sandwich panels and a ring beam. This was done by bolting a steel plate (15x15cm) into the wooden ring beam. Onto this steel plate, a round hollow steel tube 4x35cm is welded in the required angle, inserted for about 15 to 20cm inside the end of the bamboo stem. The steel tube connector piece is foreseen with two holes to place a perpendicular wire rod for fixation (Figure 3.46 and Figure 3.48 on the left). The roof exists of eleven similar trusses. Each truss is made with plain fish mouth connections as described before. The structure was described and calculated in a master thesis by S. Cordeel at Kaho St Lieven Belgium (Cordeel, 2010). Up to date none of these bamboos show any kind of failure and are better maintained than the bamboos from the Brazilian cases probably due to the more moderate climate and the lack of a natural presence of agents.

The second was a green roof supported by four bamboo columns. Each column takes up as much as 4 tons of weight. Each column exists of four bamboos connected to the foundation and the roof by a steel plate of 15x15cm with four extending steel tubes 4x25cm welded onto the plate as Figure 3.47 and the photo on the left from Figure 3.48 shows. Each bamboo end is bolted with two nuts to a steel tube to form a strong connection. Afterwards these connections are filled with cement. In later constructions, this type of connection is no longer filled for the weight of the roof already allows for strongly fixed connections.

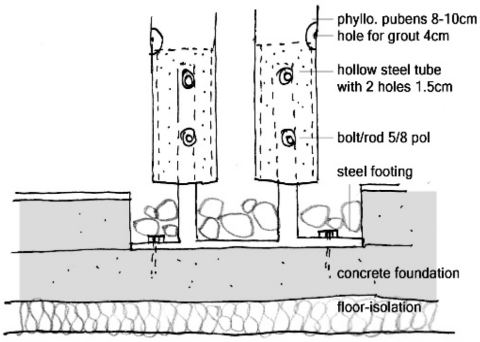


Figure 3.46. Schematic drawing of a column connection. 2020.

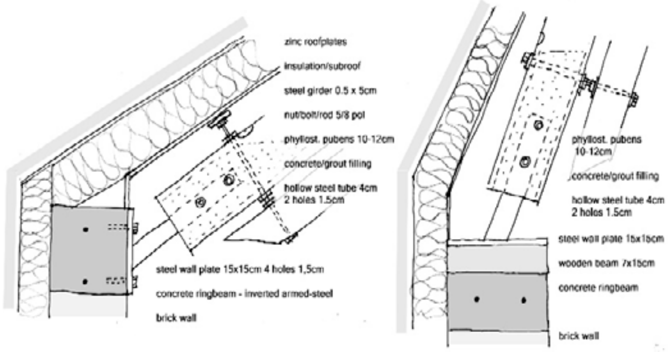


Figure 3.47. Schematic drawing of a connection to a ring beam. 2020.

Figure 3.48. Column and ring beam connections in the bamboo house in Ghent. 2011.

3.5.2.3 Art Gallery in Catuçaba, Brazil – 2016

Violin shaped joint (group 2) and an internal connector piece (group 2): In the art gallery, small diameter bamboos (5 to 6cm diameter Phyllostachys Pubescens) are used for the columns. In se, this joint is equal to the previously discussed steel tube connector joint for columns with this difference that the steel tube is replaced by a simple wire rod 5/8 and instead of filling the connection with grout; it was left ungrouted relying on the weight of the roof for the fixation of the bamboo column. By using a simple wire rod instead of a steel welded tube the building cost could be reduced significantly. A welded steel tube connector piece costs about 35 euro per piece whereas 1m wire rod 5/8 serving two or three connections costs 8 euro per piece. The difference in price can add up fast due to the large number of connector pieces that are required in a bamboo construction. In addition, working with wire rods provides greater ease of use. Only few simple construction materials are needed (a drill, a nut and a large diameter washer). Three to four short wire rod pieces (35 to 40 cm length) are drilled into a concrete foundation or into a hardwood block as was the case in the art gallery. Thereafter, a hex nut and large washer are placed at the desired height whereafter the bamboo canes are placed on top. Although the wire rod is inserted inside the cane, no grout or another type of filling is inserted to secure the wire rod. Every time the bamboos are cross connected (wind-brace, beams or rafters), the structure becomes more firm and when finally the roof is put on top and the bamboos become steadfast. In case a culm must be replaced or the height needs to be adjusted, one can simply screw down the nut/washer and take out the bamboo in question (while shoring the roof). This technique was not only used for the columns (horizontally) but also for the beams (vertically) as can be seen in the drawings of Figure 3.49.

The top of the columns are cross connected in a similar way as was done in the community centre (group 5). Bamboos arriving horizontally from two different sides become interconnected by bolting them together with a wire rod. Because the bamboo diameter used is not very thick, a wire rod size 1/2 is applied. Subtle wire rods, size 5/16, interconnect each beam formed by three bamboos while simultaneously holding up the wooden panel board from the roof. By extending these wire rods somewhat away from the bamboos, the non-orthogonality of the bamboo is averted.

For the violin joint it was envisaged to work with a hardwood connector piece which was sculpted in the shape of a violin by drawing and playing with the direction and height of the to be connected bamboo poles as vector lines (Figure 3.50). When the bamboos are placed vertically or inclined, the pressure of the roof weight cannot be used to secure them into place and therefore a wooden wine-bottle cork is inserted with a very small amount of grout. The violin shape joint was noticed by international media and it was reproduced to exhibit at the Centre Pompidou Museum in Metz, France.

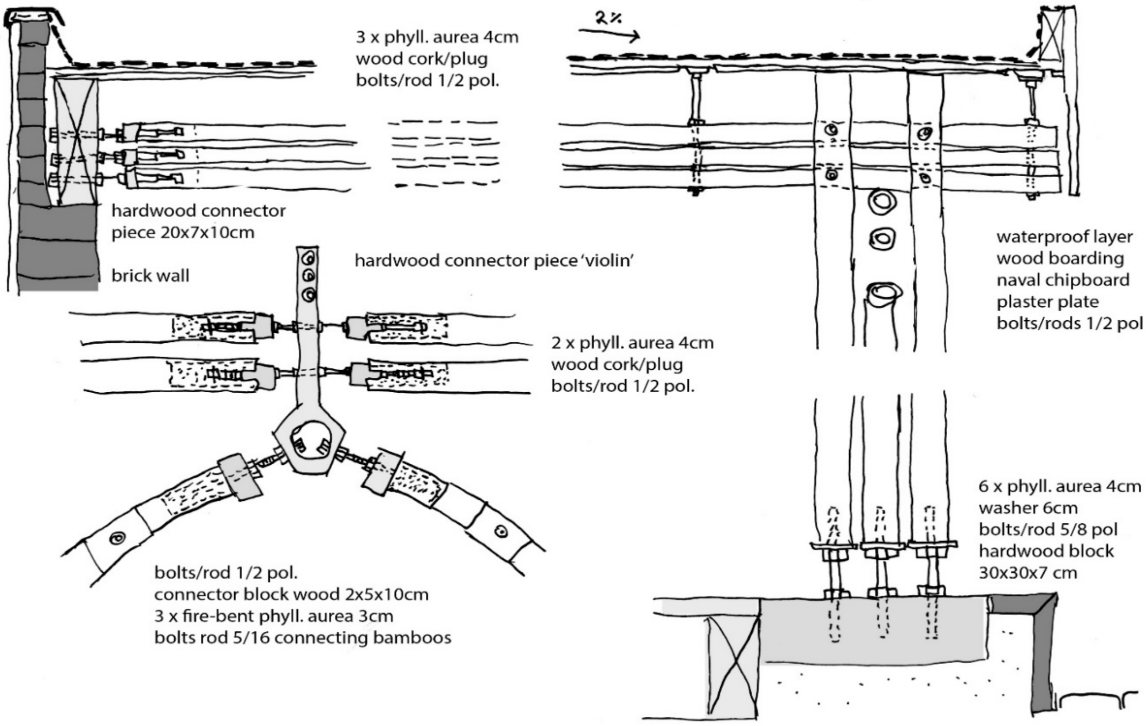


Figure 3.49. Schematic drawing of the Vierendeel, column, beam and violin connection. 2020. Copyright Arthur Mouton.

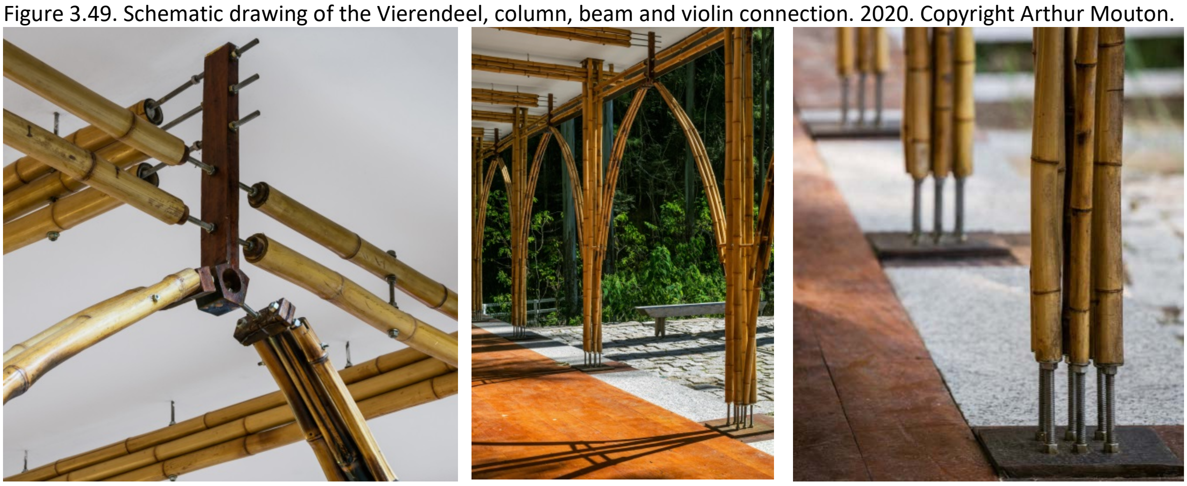


Figure 3.50. Violin connection and column connection. 2016. Copyright Nelson Kon.

3.5.2.4 Guesthouse in Picinguaba, Brazil - 2017

An inverted truss-joint (group 4) and a hardwood 'twitter-bird' joint (group 2): In the guesthouse, an 'inverted truss' was made to compensate the elastic behavior of bamboo. The drawing on the right of Figure 3.51 and Figure 3.53 illustrate this inverted truss. A wire rod is placed in the middle of the beam, extending for 35cm so that two tensioned cables going from this middle point to each outer end of the bamboo beam form a triangle. In a classic truss, the point of the triangle would point upside supporting an inclined or pitched roof, whereas in this case a 'flat' or slightly inclined green roof was used. Because the commercial size of bamboo poles were 0,6m too short for the required interdistance, a hardwood connector piece had to overcome the lacking distance. This connector piece is based on the wine bottle cork principle as discussed in section 3.5.1.2 (joint classification group 2). This method has multiple benefits. Almost no grout is needed for the wooden connector piece fills nearly the entire internal cavity until the next diaphragm. Moreover it offers support to the complete bamboo wall.

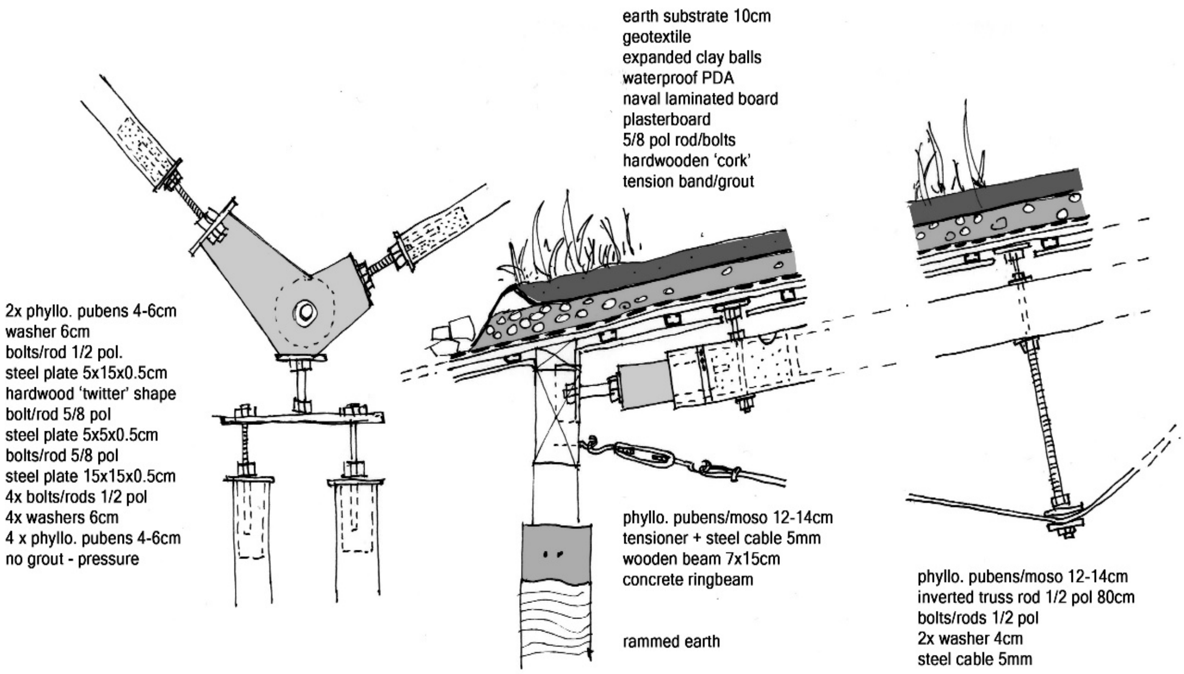


Figure 3.51. Schematic drawing of the twitter-bird connection and an inverted truss connection. 2020.

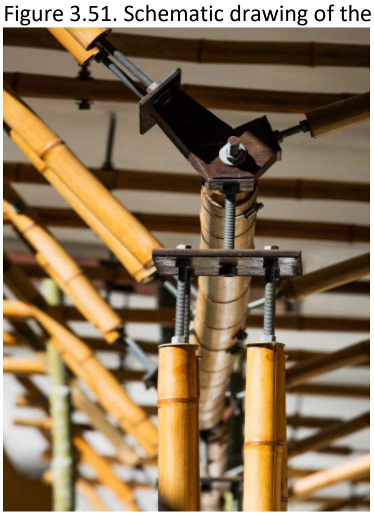


Figure 3.52. Twitter-bird connection. 2017. Copyright Kon.

Figure 3.53. Inverted truss connection. 2017. Copyright Nelson Kon.

Figure 3.51 (left) and Figure 3.52 show the 'twitter-bird` shaped joint designed for the columns on the front of the guesthouse. The hardwood connector piece was created according the same strategy as the two dimensional 'violin-shaped' joint from the art gallery, yet this connector piece is three-dimensional. In the front of this piece, two culms are connected to the beams supporting the roof while in the back a bamboo member is connected to the wooden ring beam and sideways the bamboos are interconnected serving as a wind brace. The upper bamboo structure is not interconnected. A wire rod 1/2 inches pierces the connector piece, whereafter it is bolted on both sides to secure its proper location. The connection of the bamboos in the front and back is done with the help of a small steel plate. The wind braces sideways are connected by means of a wooden plug.

3.5.2.5 Community Bakery in Camburi, Brazil - 2018

An inverted truss-joint (group 4) and an external half steel tube joint (group 3): The community bakery is a Bamboostic project that is built in annex to the Community Center in Camburi. This project is not discussed in the case studies (chapter 6) for it was designed and executed by project member and architect Reintje Jacobs, only with the assistance of the author. Atop rammed earthen walls, two wire rods are embedded every meter into a concrete inlay. A steel tube, 30cm length, is cut in half and screwed on top of these wire rods. The culms (Phyll. Pubescens) are laid into this halved tube. Deflection is not an issue as only a lightweight zinc roof is placed on top. Advantageous is the fact that the applied forces can be divided on a larger surface avoiding local crushing. The pins secure the culm into place and serve as place holders for the zinc roof at the same time (Figure 3.54). In order to avoid water infiltration, the space between the halved tube and the bamboo is closed off with a mix of glue and sawdust. Again the inverted truss principle is practiced, as discussed in the previous section, although this time the washer at the end of the middle point is replaced by a small piece of bamboo around which the steel cable is tensioned (Figure 3.55).

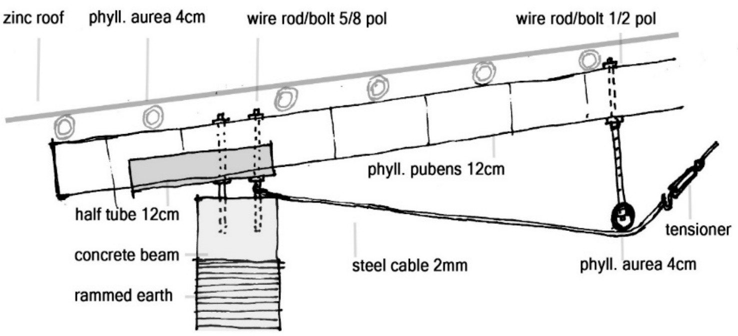


Figure 3.54. Schematic drawing of an inverted truss and half-tube connection. 2020.

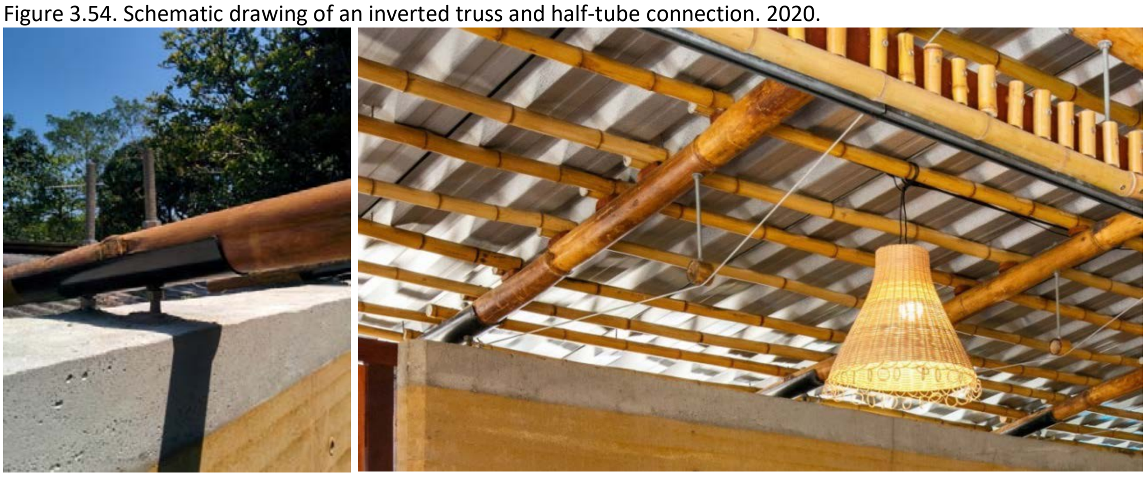


Figure 3.55. Inverted truss and half-tube connection. 2018. Copyright Nelson Kon.

3.5.2.6 *Bamboo canopy in Guaporé, Brazil - 2019*

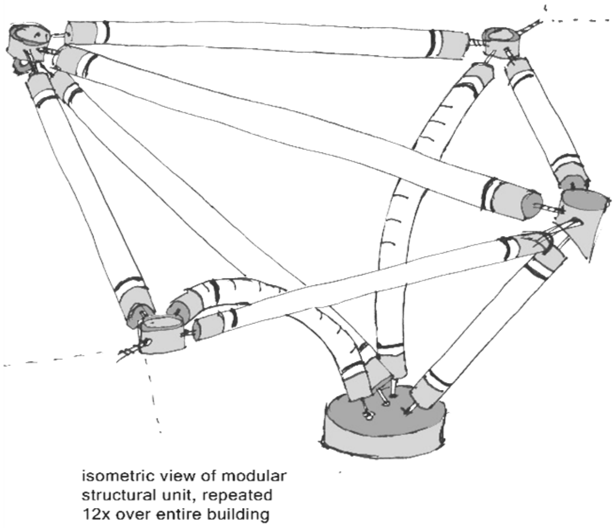


Figure 3.56. Schematic drawing of module A. 2020.

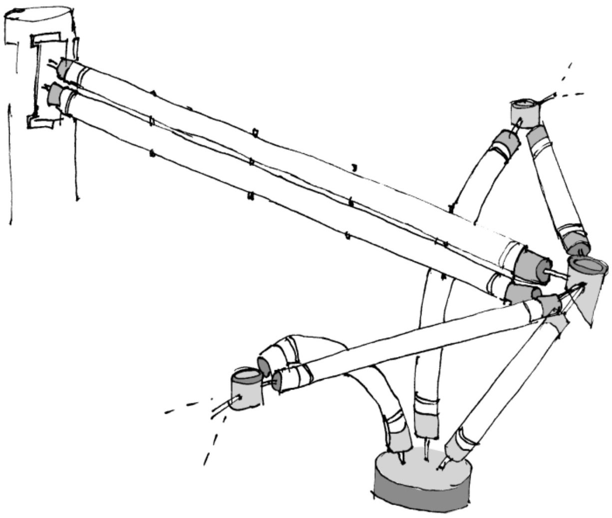


Figure 3.57. Schematic drawing of module B. 2020.

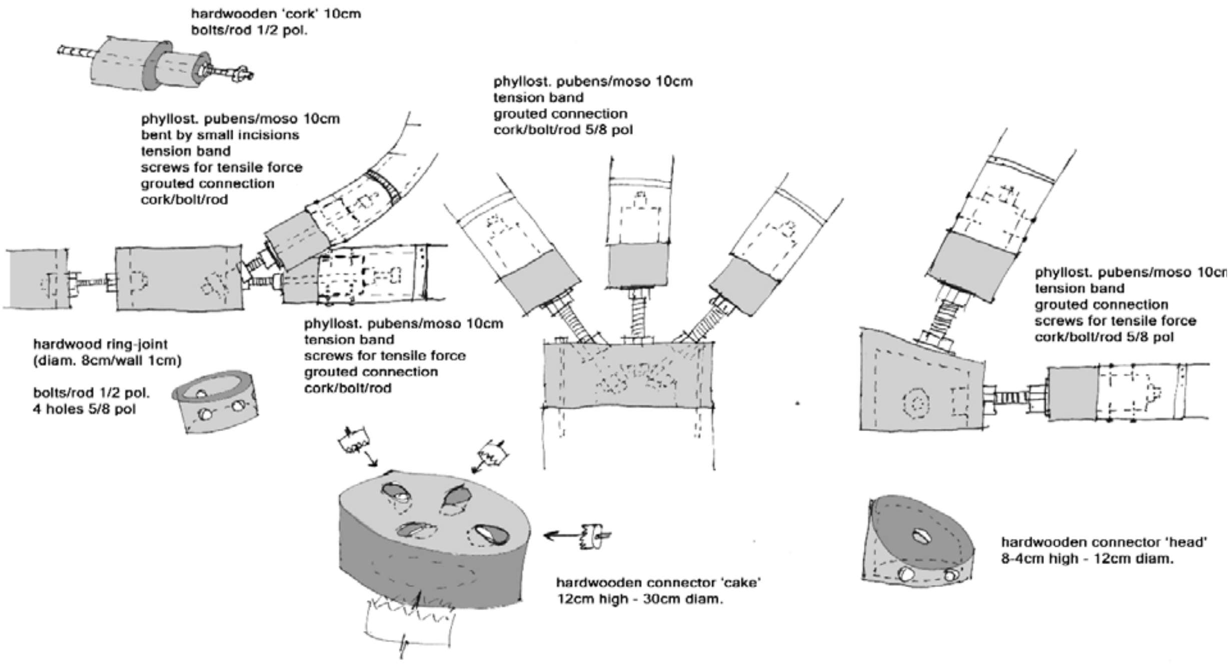


Figure 3.58. Schematic drawing of the wooden connections used. 2020.

Figure 3.59. Wooden plug connections used in module A and B. 2019.

Internal connector joints (group 1&2): For the bamboo canopy new and experimental connections were designed. The bamboo canopy exists of two modules; eight times Module A (Figure 3.56) and ten times Module B (Figure 3.57). The latter is in essence identic to the first with exception from the longer beam that is necessary to bridge the distance to the center pole. Each module is placed atop of an existing eucalyptus column. According to the principle of shaping new connector pieces by drawing vector lines of every structural member that should be connected, a connector piece abstractly representing an angel 'spreading its wings' was designed. In this case, the hardwood connector pieces were prefabricated in a carpentry shop. The construction itself was done by two men in 5 weeks' time. Each module was prefabricated on the ground before lifting into place. Module A exists of four different connections or joints (Figure 3.58 and Figure 3.59), although only the shape of the connector piece or the amount of arriving bamboos varies. The main principle is that each bamboo pole receives a wooden end plug with an extending wire rod on the outer ends. For the wooden end plug, a hardwood timber piece is provided with an equal diameter of the bamboo pole and a length of 20 cm. Over a length of 13 to 15cm about 1cm of the diameter is removed by sanding it thereby enabling a precise insertion in the bamboo end. Only 5 to 7cm is maintained equal to the diameter of the bamboo stem. A hole pierces the wooden plug enabling a wire rod, size 5/8, to be inserted and fixated with hex nuts and washers while extending for another 10cm. On each bamboo end, a tension band is placed to prevent possible cracking due to moment-forces. Different from previous internal timber joints is that in this case the entire wall of the bamboo end is supported and the loads are transferred through contact with the whole section.

The round basis that connects the module to a eucalyptus column is a hardwood piece in the shape of a cake. Holes (5/8) are drilled through this piece in a continuous line of the direction of the bamboo poles that have to be connected. The wire rods of the bamboo poles are inserted in these holes and bolted tight on the bottom side of the connector piece. The nuts are encapsulated in the wood to avoid corrosion. When several modules are finished, these are put atop of the eucalyptus columns and need to be interconnected to each other for stability reasons.

Two A modules are joined by means of a central key joint connecting four bamboos of each module. There are four such key joints as there are eight modules A. This joint is made with a prefabricated CNC-cut hardwood connector piece. It connects six bamboo beams in a horizontal plane and two in a diagonal direction. Due to the considerable large moment forces applied to this joint, it was decided to provide steel tension bands on each arriving bamboo end and the connector piece itself as well. Again, this shape was sculpted and determined by combining the directional vector lines into one central point. Figure 3.60 illustrates the principle of this central key joint.

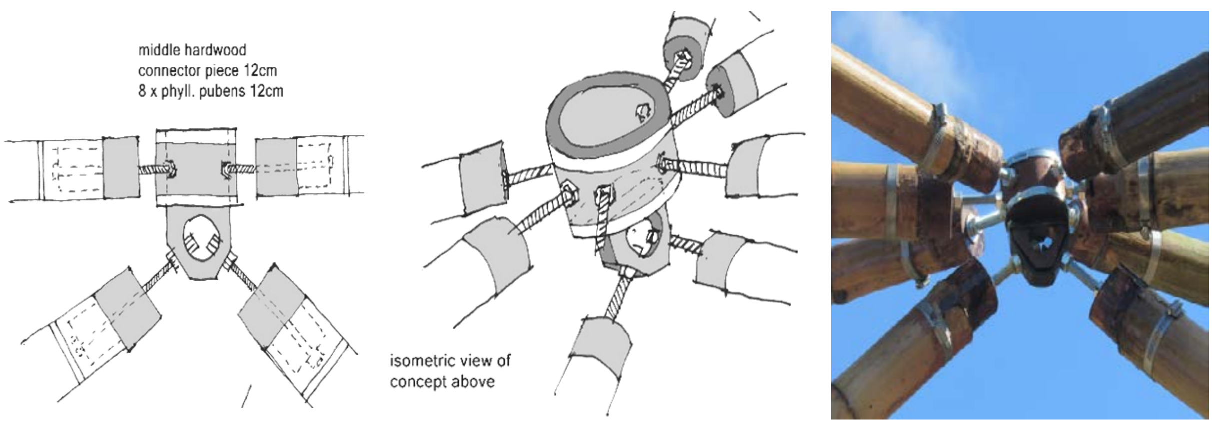


Figure 3.60. Schematic drawings and a photo of the key joint. 2020.

As already mentioned, the main difference between the A and B module is the longer beam to bridge the longer distance to reach the centrally positioned eucalyptus columns. As a consequence, the bottom and side bamboo poles are no longer necessary for stability and could be discarded. The long bamboo beam is fabricated by the placement of two bamboo poles of 12cm diameter on top of each other and interconnecting them. Because of the oval shape of the construction, these beams have a different length varying between 3,35m to 4,10m. Five of these modules B, located at each outer focal point of the oval ground plan, need to join ten bamboos of 12cm diameter on one single eucalyptus column of 30cm diameter. This would have been impossible without placing them at a certain distance from the intersection point. This problem was resolved by providing a bent steel plate onto the eucalyptus pole, as is demonstrated in Figure 3.61 and Figure 3.62. A beneficial side effect to the design is that these beams appear rays that lead towards the ‘angel-like’ components.

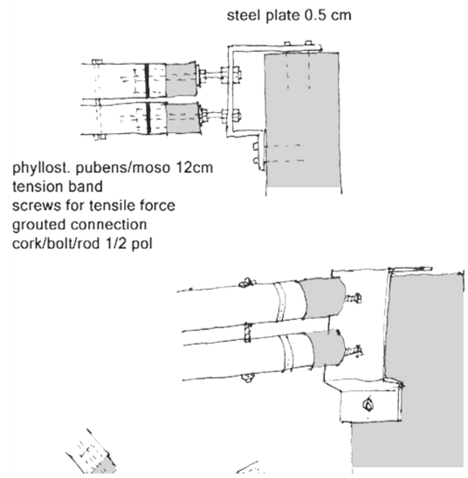


Figure 3.61. Schematic drawing of the connection of a horizontal beam to a eucalyptus column. 2020.

Figure 3.62. The connection of the beams to a eucalyptus column. 2019.

Figure 3.63. Both modules when finished. 2019.

Figure 3.63 show some modules after completion and when put into place. The modules need to be additionally interconnected to assure good construction stability. Two middle beams are placed between the two central eucalyptus poles to form a truss. Above two and below three layers of bamboo poles are needed due to the six meter length of the overspan. The poles are interrupted in order to laterally connect the A modules as seen in Figure 3.64 and Figure 3.65. The A modules are interconnected in the middle of the construction, at the height of the middle beam. These joints are similar to the discussed central key joint, although it connects fewer bamboo poles. This connector piece connects two lateral bamboo poles that are part of the middle truss and four perpendicular poles from the A modules. Figure 3.66 shows the central joint of which there exist five in this construction. After the interconnections are made, the construction becomes so firm that no movement is longer possible.

In order to enable further finishing of the roof, wooden panel boards are put on top of this bamboo structure. As bamboo poles never has the exact same diameter, it is difficult to create a plane surface. By inserting small wire rods (3/16) on multiple places atop of each bamboo pole, this uneven surface can be levelled. The panel boards are thereafter covered with a roof finishing and a wooden border plank. Since the canopy is an open space, no roof insulation material was required.

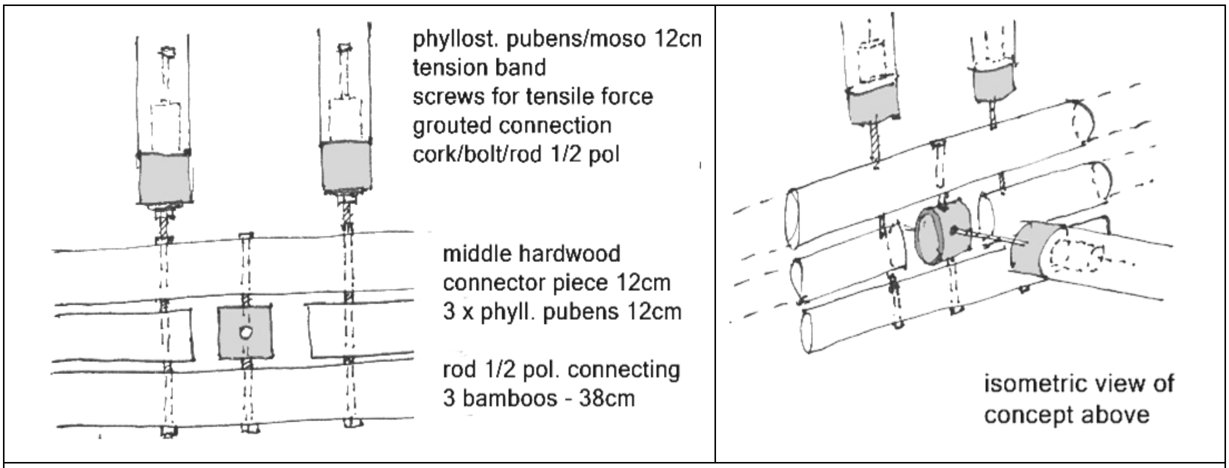


Figure 3.64. Schematic drawings of the ringbeam.2020.

Figure 3.65. Middle beam. 2019.

Figure 3.66. Central joint connecting the A modules. 2019.

3.5.3 Criteria for joint design

Despite the fact that the classification of joints (section 3.5.1.) already presents designers an overview of potential and executable joints, there still exists a great liberty for designers to design proper joints that suit the architecture of its specific building. Designers can even depart from a standardized joint or a combination thereof to design a 'personalized' joint. As Alvar Aalto already said in 1935 '*a standardized object should not be a finished projec but complemented by the designer and all individual laws controlling him*' (Domusweb, 2020). Especially joints that have a separate connection element with a wire rod protruding from the culm provide designers considerable design liberty. Form and technique are completely free, although in this and the following chapter several base criteria are given. NSR-10 specifies that a joint can be used in a repeatable manner when at least twenty standardized tests on that specific joint have been executed (AIS, 2010).

As examples of this free joint design, the joints by Markus Heinsdorff can be mentioned (chapter 3.5.1.3), but also the joint illustrated in Figure 3.67 developed by Studio Cardenas. Focusing on modularity and the wish not to perforate the bamboo stem, a multilayered connection was designed. Whilst perhaps too complex and therefore too costly, this joint allows for a pronounced acceleration in construction time as none of the bamboos need to be drilled or punctured. The effectiveness of the construction presumably makes up for the higher cost of the joint element itself. An interesting fact is that the designers of Studio Cardenas emphasize that the joint is based on the golden section as a proportional system, a visual strategy such as propagated in chapter 5 (Archdaily, 2017).

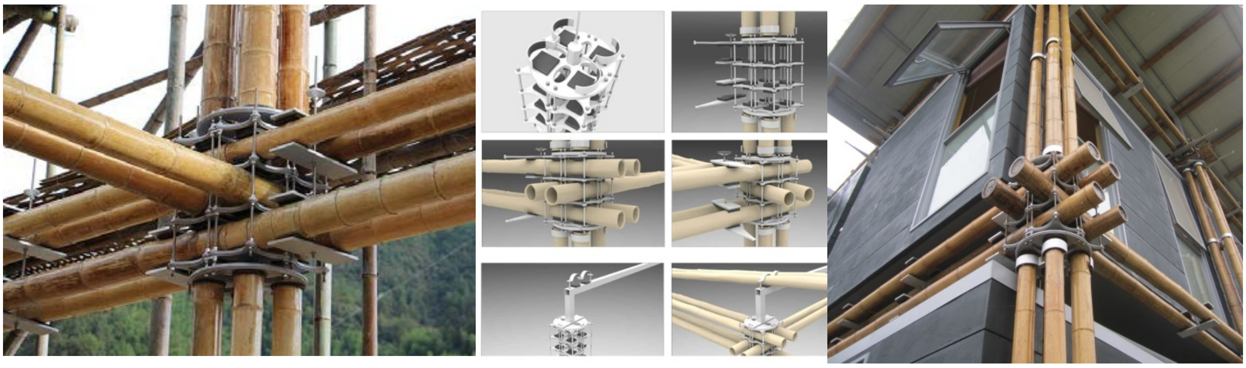


Figure 3.67. Bamboo house in the Longquan International Bamboo Commune, China designed by Studio Cardenas. 2016. Retrieved from the Archdaily website. https://www.archdaily.com/868926/enener-efficient-bamboo-house-studio-cardenas-conscious-design/58ec3742e58ece07df0000a8 (15/05/2020). Copyright LIB.

Arce-Villalobos states the following elements as key to a successful joint design (Arce Villalobos, 1993; Phanratanamala, 2014):

1. Avoid penetration by nails, screws or bolts: Despite the fact that the attachment of external connection materials by friction such as rope lashings is complicated because of the smooth outer silica layer, Arce-Villalobos recommends to avoid as much as possible puncturing in the bamboo stem for this weakens the bamboo stem (1993). The amount of holes to be drilled in one culm should be kept at a minimum and when possible foreseen at different positions, yet always near a node. Drilling holes weakens the bamboo and enlarges the possibility of cracking, especially when provided too close to one another. The joints should at least be as strong as the bamboo itself (tension, compression,…). Moreover, the holes drilled for inserting cement should not be larger than strictly needed (usually 3-4cm).

2. Avoid open ends: Because of the orthotropic character of bamboo with great strength in longitudinal direction, but considerable weakness in transversal direction, end-points tend to crack under any other than tension or compressive forces (especially moment forces). Therefore, but also to avoid biotic agents entering the bamboo stem, open ends need to be closed off. This can be done either by inserting grout/resin, inserting an end plug (wood, steel or other) or by providing a node close to the connection itself. Beneficial of a node close to the connection is that besides the end being closed off, it results in a strong point where fibers run in several directions as opposed to the fibers in an internode that run in mere axial direction.

3. Solve the problem of size variability: Size variability of bamboo remains a challenging factor for bamboos have different diameters within the stem (the bottom is thicker than the top), they are often askew and there often exist great variations between the poles. Nevertheless, Arce-Villalobos emphasizes the need for simple construction techniques, especially in areas where low technical capacity, both in skill as tools can be expected.

4. Transfer forces by axially distributing them to the fiber of the culm: The fourth observation regarding the fact that shear stress at the junction node of bamboo must be controlled, implies that designers have to convert shear stress into tension and compression in the bamboo stem (Yazdi et al., 2015). This can be done in different ways and depends on the creativity of the designer.

Some years after Arce-Villalobos, Janssen (2000) complements these design criteria and adds some recommendations. He advices designers to sketch all possible solutions on paper without discarding any possibilities in advance. Even the most dubious proposals might hold valuable ideas. All problems should be studied thoroughly and one should try to improve the best solution, yet keeping aside unused sketches in a 'reject pile' so it can be later 'dug up' in search for another idea. He also advocates building a scale model. This form-finding method is commonly used. The final advice Janssen mentions, is to keep close contact with the contractor from the beginning and to analyze the design afterwards in order to see where failures/successes can be found.

Design criteria listed by Janssen (2000):

1. Make full advantage of the good qualities of bamboo, and avoid the bad ones
2. Simplicity; in terms of skill and equipment involved in its production
3. Stability; stable in relation to time, with durability in relation to the required service life
4. Adaptability of dimensions to a modular system
5. Strength predictability
6. Cost effectiveness

It is interesting to note that in more recent literature, there is still referred to Arce-Villalobos (1993) and Janssen (2000) when addressing bamboo design criteria. This illustrates that these criteria are still relevant. Nonetheless, the author of this PhD would like to add some additional points of attention:

- Design **joints making use of materials that can be easily found** in local construction stores, welding or carpentry shops. Related to this, it is moreover recommendable to **diminish the use of skilled labor.** In some circumstances, especially in developing countries, there is little control that the contracted labor is as trained as assumed. Joints such as fish mouths are labor intensive and require trained labor whereas modular systems can provide a joint which can be prefabricated and multiplicated in short time span and in large quantities, both to make the joint as to assemble it. This can reduce labor cost significantly. Although the amount of material and the specificity thereof also play an important factor in cost and should be considered as well.
- A point of view concerning joint design which the author advocates, is to **depart joint design from mere vector lines**. A joint is a meeting point of linear elements and this meeting point can contain members coming from all directions. When designing it, it is advisable to regard upon the bamboo poles as lines without any thickness. This way the diameter size does not affect the joint solution from the start and aids the designer to determine where the lines can possibly be joined. The meeting point itself does not have to be in bamboo, it can also be in hardwood, steel or another material. It can even be given a sculpted form such as the joints from the guesthouse and the art gallery illustrate. Once this meeting point has been designed, the diameter sizes can be added at such distance required in order for the bamboo stems not to touch each other. If the joint were to be designed assuming its correct diameter from the start, this complicates the meeting point needlessly, making the designer possibly abandon a particular structural system or joint solution in advance.
- Another aspect not often mentioned in literature is the fact that in **earthquake prone areas**, it is best to **design an articulated joint in order to create a hinge** for this takes away most of the moment forces, which are the highest during an earthquake.

- **Tension bands** are an excellent and easy way to maintain the original tubular form of a bamboo stem avoiding it to crack as bamboo ends are susceptible to cracking.
- Emphasis should be laid as well on the **aesthetics of the joint.** The appreciation for the aesthetics of a bamboo construction often stands or falls with the visual aspect of the joint. Most liberty of design and 'personality' of the designer can be laid here as well. In chapter 5, on the visual aspects of bamboo in construction, emphasis is laid on the use of proportional systems in order to control the visual aspect of a building. This alone clearly will not suffice to have an aesthetically pleasing joint or construction, but it can be a tool in doing so. Studio Cardenas for example used the proportional system to design its joint, but also the art gallery and guesthouse were based hereon.

Although every joint should be tested in a laboratory setting following the codes and norms, a pre-simulation can be made with specialized engineering software such as Scia or SAP2000. In a thesis report by Ballegeer & De Boever (2019), some (simplified) assumptions were made to enter the bamboo species Guadua and Dendrocalamus as a material in the Scia software. Even though the material properties used can be contradicted by some sources, it can be a useful tool to give insight in the strength capacity of the designed joint. Table 3.6. demonstrates the values Ballegeer and De Boever (2019) inserted in the Scia software. Section 3.1. gives a detailed overview on the mechanical properties of bamboo.

Characteristics of Guadua and Dendrocalamus		
Name	Guadua	Dendrocalamus
Density	800 kg/m^3	800 kg/m^3
E-modulus	17 000 N/mm^3	13 000 N/mm^3
Poisson Coefficient	0.3	0.3

Table 3.6. Characteristics of Guadua and Dendrocalamus. Retrieved from Optimalisatie van een bamboestaal eindverbinding en stabiliteitsontwerp (p.51) by R. Ballegeer and L. De Boever. 2019. Copyright KU Leuven.

3.5.4 Joint failure

Such as many other natural construction materials, bamboo is susceptible to fungi and insect attacks, to humidity, lignin degradation when exposed to UV rays, low shear resistance and geometric imperfections. These factors, either isolated or combined, can generate cracks or splits along the longitudinal fibers of the bamboo stem. This induces premature flexure-compression failure, when subjected to compression load (Krause & Ghavami, 2009). Joint failure can express itself in various ways; local squashing of fibers, longitudinal splitting, shear or deflection of the member. Important to know is that because bamboo is a functionally [illegible]ded material, meaning it possesses an anatomical structure with different microstructures (vessels, fibers, parenchyma, and hollow cells), the aligned anatomy contributes to initiate cracks. Failure will first appear at places where stress is highest such as the joints and the center of a beam according to the typical moment diagram. It will lose its cylindrical shape yet the outer fibers will temporary maintain the structural integrity before collapse. Therefore collapse is more gradual than would be the case with steel structures for example where collapses is immediate after failure.

The most prevalent structural system in bamboo architecture is a truss system wich is usually constructed with steel pin connections and nuts/washers. Moreira and Ghavami (2015) studied joint failure in such regular bolted joint connections and established a ´Limit State Diagram´. Truss systems not only make the joint less of a hinge, but also divide the applied loads over more than one point on the bamboo stem. Nevertheless, at the contact point of this bolted connection stress is concentrated which can cause local crushing or splits/cracks that appear along the fibers. The crack propagation path depends on the pattern of the transmitted stresses. Compression stress tends to counteract the propagation and tension stress increases the crack propagation, yet both situations occur up and down the pin.

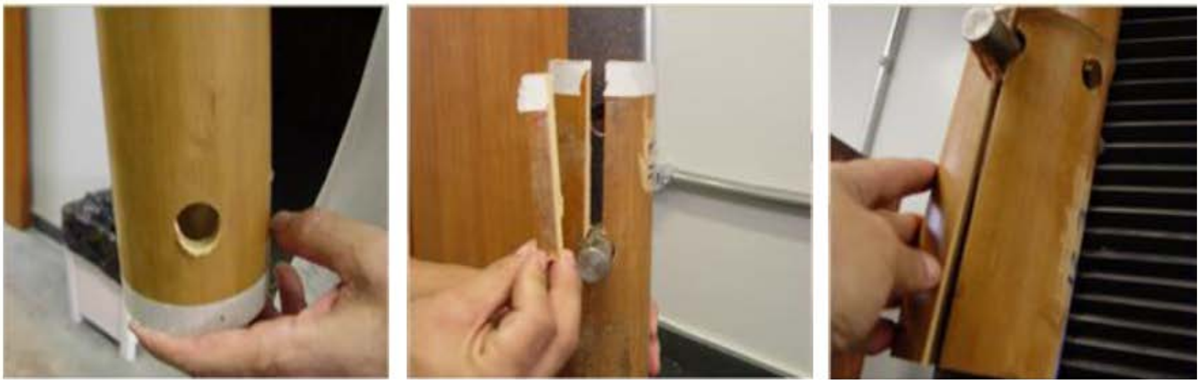


Figure 3.68. Bamboo failure modes. Retrieved from Limit state design of steel pin connections for bamboo truss structures (p.2) by L.E. Moreira & K. Ghavami. 2015. Copyright 16th Nocmat Conference.

Figure 3.68 demonstrates different failure modes; the hole where a bolted connection passes can be squashed (left), fibers can suffer shear resulting in an entire piece to crack (middle) or bamboo can split (right). The latter is the most common failure type in a bamboo due to its anatomy. Whether or not these cracks propagate, depends on the applied loads but also in the position of the bolted connections towards each other and the end of the bamboo stem (Moreira & Ghavami, 2015). The ´Limit State Diagram' (Figure 3.69. Limit State Design Diagram and Safety Region. Retrieved from Limit state design of steel pin connections for bamboo truss structures (p.2) by L.E. Moreira & K. Ghavami. 2015. Copyright 16th Nocmat ConferenceFigure 3.69) by Moreira & Ghavami (2015) can be used to determine the optimum space between two steel pin connections in order to be in the 'safe zone' regarding crack propagation. This is important for once the crack has started; it extends easily making the connection fail under relatively low loadings. Moreover, Moreira and Ghavami (2015) determined the difference between failure on axially loaded joints and joints where both axial forces and bending moments occur. Figure 3.70and b illustrate when in an element the axial tension force is equal to 20kN, the limit to compression stress is 80MPa before the squashing of the fibers starts.

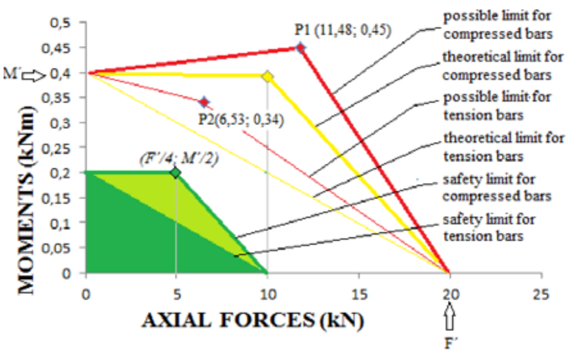


Figure 3.69. Limit State Design Diagram and Safety Region. Retrieved from Limit state design of steel pin connections for bamboo truss structures (p.2) by L.E. Moreira & K. Ghavami. 2015. Copyright 16th Nocmat Conference

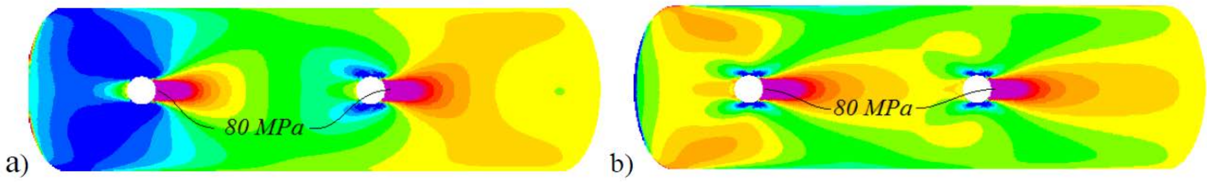


Figure 3.70. Failure mode on axially loaded joints. a) base and b) top. Retrieved from Limit state design of steel pin connections for bamboo truss structures (p. 3) by L.E. Moreira & K. Ghavami. 2015. Copyright 16th Nocmat Conference

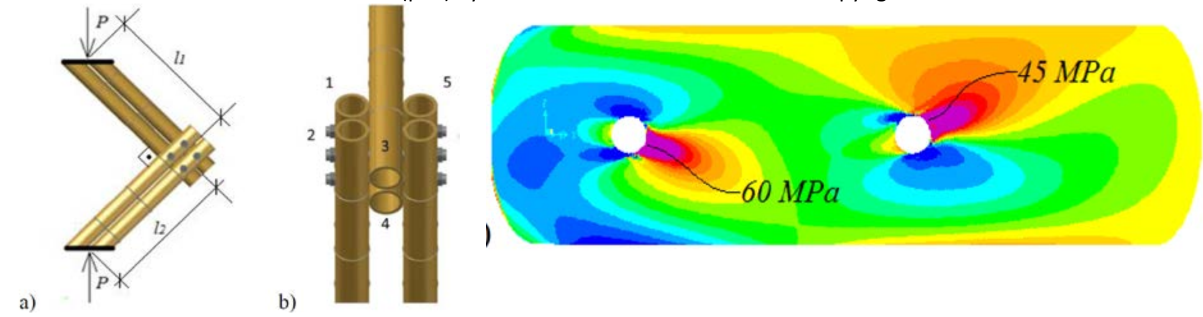


Figure 3.71. Failure mode when a moment force is applied such as in the truss on the left. Failure modes at 60MPa and 45MPa. Retrieved from Limit state design if steel pin connections for bamboo truss structures (p.2) by L.E. Moreira & K. Ghavami. 2015. Copyright 16th Nocmat Conference.

Figure 3.71 indicates the critical load in combination with moment forces (for example when a truss connection is loaded under an angle). Whereas in an axially loaded joint each pin takes an equal amount of force, failure occurs at (much) lower and different levels (45MPa- 60MPa) when the moment-force is introduced. This is an important fact to take into consideration, certainly when a truss structure is not completely axially loaded. This concern has also been integrated into the above-mentioned Limit State Design Diagram and therefore this diagram becomes a useful tool for engineers to determine whether a certain joint design is a reason for concern or not (Moreira & Ghavami, 2015). Even though the result of these tests depend on the bamboo species (in this case Phyllostachys) and the way the test case is setup, the conclusion can be extrapolated for the fact that there exists a overall reduced load-bearing capacity when moment forces are applied.

3.5.5 Conclusion

There exists a broad range of possibilities to join bamboo poles to each other or other materials. To achieve the purest load transfer from a pole to another structural element (or to another bamboo pole), it is clear that contact over the entire section of a bamboo (group 1) is preferred, even more so in compression. This is however not always the easiest solution, the most aesthetically pleasing nor the cheapest jointing method. Inserting a prefabricated connector piece inside the cavity of a bamboo culm fixated with a filler such as concrete or resin as described in group 2 and partly in group 4 is the fastest method to construct a joint. Beneficial is that this jointing technique provides the designer a wide range of possibilities to choose from and will create the most aesthetically pleasing joint due to its subtlety (the joint is partially hidden inside the stem). Using the outside surface of the bamboo wall (group 3 and partly group 4) can also be advantageous, both in terms of speed of construction as other aspects (aesthetics, strength, cost,…) as it makes use of the strongest part of the bamboo culm. It is however not simple to design a rigid connection using this type of connection in comparison to inserting a connector piece inside the bamboo (group 2).

A connection method that might be added in the future could be based on 3D printing technologies. It is not inconceivable that this technology will become cost-effective and accessible to a wider public. Even proper bamboo fibers might be used (inside a resin-filament?) to print joints designed according to the varying diameters of a bamboo culm it needs to be attached to. Although this technology is already available, it is not yet widely applied to be considered as a viable group. Students at ETH Zurich have recently made an interesting design for a bamboo pavilion (Figure 3.72). For the design-to-fabrication process they used purpose-made design tools to generate an ultralight yet complex structure. The digitally designed joints are manufactured with sub-millimeter accuracy in high-strength nylon and stainless-steel using 3D printing technology (Designboom, 2021).

Figure 3.72. 3D printed joints. Retrieved on 06/02/2021 from https://www.designboom.com/architecture/eth-zurich-digital-fabrication-bamboo-pavilion. Copyright ETH Zurich / Marirena Kladeftira.

3.6 **Bending**

3.6.1 Introduction

Bamboo is known for its elasticity, especially its flexural deflection. There is however a limit to the natural curvature and in many cases the expected curvature cannot be naturally obtained. In traditional bamboo architecture, the supporting structure is predominantly fabricated from straight canes, almost always applied under compressive or bending stresses (Widyowijatnoko, 2012). Canes under tensile stress are rarely found (Dunkelberg, 1985). Organically shaped buildings generally use form active or semi-form active structural systems that use arches or curved bamboo. To achieve such shapes, the bamboo needs bending. It is important for architects/designers to understand the consequences of bending bamboo, especially when creating an organic shaped construction (Maurina, 2015). Gutierrez et al. (2018) studied that bamboo loses strength above 150 degrees, making the often applied techniques of bending by heat possibly compromising the integrity and mechanical properties of the structural element. Cellulose and hemicellulose will start to decompose at temperatures above 150°C, and modulus of elasticity and modulus of rupture will drop significantly in value. Nurdiah (2015) establishes that when the split bamboo technique is used, the compressive strength of bamboo drops significantly and therefore a sufficient dimension proportion in the span should be foreseen to prevent deformation or deflection of the structural members (Nurdiah, 2015). Each bending technique has other implications, therefore the different techniques and their consequences to the structural bamboo elements is discussed in this chapter.

The high elasticity of bamboo is a result from the higher distribution of cellulose fibers on the outer side of the wall (60%) decreasing to the inside (10%). The higher the E-modulus of the bamboo, the higher its quality. Following elements need to be considered as well in the design of bamboo elements subject to bending; Deflection, Bending strength, Shear-parallel-to-grain strength and Bearing (Compression-perpendicular-to-grain). For example, when compression results in strain perpendicular to the fibers, and this occurs in the material between the fibers (lignin - weak in taking strain), this becomes a weak point for the bamboo. Despite the fact that the lignin is weak and the fibers are still in good condition, the coherence is lost and consequently the value of the EI drops drastically. Fortunately, once the load is removed, the cane often returns back to its original straight form, which can be advantageous in case of a hurricane or an earthquake. Bending strength can be determined by bending stress or by shear, depending on the length of the free span. If the free span is short, bamboo does not act as a beam, but as an arch and therefore the bamboo will fail in shear (transversal forces). If the free span is long, bending stresses will determine the strength (Janssen, 2000).

There exist two categories of bending methods; hot and cold-bending methods. The hot-bending method can be subdivided into the immersion or combustion technique. Slashing and bundling techniques are cold-bending methods (Maurina, 2015). The author has experience with bending as he experimented with different techniques for a social housing project for a colleague in Nicaragua as well as for the arches in the art gallery (section 6.8) and the bamboo canopy (section 6.10). The design for this particular social housing project in Nicaragua foresaw multiple bended members and because the author never bended bamboo before, several techniques that are commonly found in literature were tried. Firstly, the hot bending method where a bamboo stem is curved under the heat of a flame torch. Secondly, the cold bending method were bamboo strips are bundled or glued together into the required curvature. Finally, the cold-bending technique by making incisions on one side of the bamboo stem was tried. Bending a bamboo stem appeared to be a time intensive process and is more difficult when the curvature needs to be greater. Moreover as bamboo is an anisotropic material, it does not bend symmetrically complicating the bending process of multiple members with an equal curve design. Therefore it is only recommendable when applied aside a straight bamboo structure, when the curvature is only little or divided over a great length.

3.6.2 Hot-bending methods

Where moisture or heat (>150°C) is applied, bamboo will become softer and more flexible which facilitates it to bend. After the bamboo is cooled down, it will remain in its new form since the molecules re-crystalize, making them immovable. There exist two hot-bending techniques: soaking in lukewarm water (immersion) or applying heat (combustion) (Maurina, 2015; Wikihow, 2019).

3.6.2.1 Immersion technique

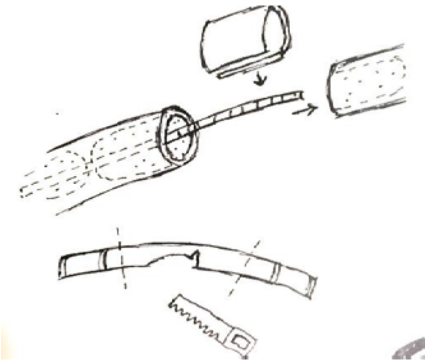
Moist bamboo is more flexible than dried bamboo as moisture mitigates the lining and hemicellulose cells in a bamboo allowing it to bend. When placing bamboo poles in a tub of lukewarm water (34,4 to 35,6°C) and let it soak overnight (or longer depending on the size and thickness of the bamboo), it can be shaped by gradually putting it in a formwork of nails or steel bars according the desired curvature. The bamboo stem needs to dry one to three days before removing the formwork. This technique results in a smooth curvature and texture (Maurina, 2015; Wikihow, 2019).

3.6.2.2 Combustion technique

Heating bamboo with a blowtorch is besides a bending method also a traditional treatment method as heating the bamboo crystalizes the minerals inside the bamboo. This makes the application of other bamboo treatments superfluous (treatment methods are discussed in section 4.1.2.1. The bamboo needs to be freshly cut, preferably at the right time to reduce already the level of minerals to a minimum. Generally, some techniques are recommended to prevent bamboo canes from splitting when applying such high temperatures. Firstly, the internal diaphragms need to be punctured with a long rebar to release the heat inside the culm since heated air expands causing the bamboo to crack. Some literature also recommended filling bamboo canes with sand. The latter was tried several times during bending tests coordinated by the author in Nicaragua. However, it appeared not to make any difference, perhaps due to the fact that the diameter of the bamboos that was bend, was relatively small (5-7cm). Secondly, a few small holes should be drilled closely to the nodes for excessive vapour and juices to escape. Thirdly, the flame is to be applied upwards following the fibers in the direction of growth, moving from the thickest towards the narrower end (Maurina, 2015; Wikhow, 2019). Before starting to apply heat to the bamboo canes, the design of the desired curvature needs to be laid out on the floor. Alongside that curvature, two rows of holes need to be drilled into the concrete floor (at least 5/8) with an interdistance of the bamboo diameter applied. These holes should be positioned according the most common distance of the nodes. Steel poles that can resist large forces should be used. It is essential that these steel poles are not placed in the middle of an internode for this part of the bamboo cracks easily. The second row with steel bars can only be put only into place after the curving is done. Principally after heating, the main bending points have to be tightened with cords or another tensioning device that marks the correct diameter of the curve (base/center point of the radius).

When starting to bend, the bamboo pole is placed between the first two lateral securing steel bars with only little tension applied by tensioning cords. A flame torch is then applied to the lowest part of the bamboo. It is necessary that the bamboo is lifted from the floor, not only to avoid damage to the floor, but also to reach the lower part of the bamboo stem when applying heat. Wooden blocks can be used to this end. The flame torch should be applied equally with a medium force, yet above boiling temperature. A too strong blue flame can blacken or burn the bamboo too fast and a weak flame would needlessly slow down the entire process. When the green colour changes into yellow, it means that the moisture content has been vaporized and that there can be continued to the following internode. Care needs to be taken that one only continues to the next internode when tension is applied to the arch. The internodes that do not need to be curved yet, should not be heated for this will solidify their position. Tension should always be applied slowly, gradually and equally, never at fast speed or suddenly greater distances for this will enhance failure at the level of the internodes. At the most curved point of the bamboo pole, it is essential that this particular internode has a support at both end parts of the pole. The second row of bars should not be put immediately. At the start of the bending, the tension needs to be able to bend away from the desired point in order to diminish the tension at the most fragile and curved piece. When the curving is finally succeeded, the bars on the other side can be put. The entire curve should be kept under heat before placing all the bars to avoid the curve to cool down and return into its natural position.

A technique to avoid cracking was developed during the experimental bending tests by bracing the part between two internodes, which appeared the weakest point, with another bamboo of a larger diameter and of approximately 20cm length. When applying this technique, it is important to break this ´bamboo brace` in multiple strips as illustrated in Figure 3.73 and Figure 3.74 in order to ensure that the forces applied when closing the brace are equally divided for a bamboo of exactly the same diameter can never be found. If this is not properly done, for example by using only two halves of a bamboo around the first one, the open spaces between the first and the second diameter can possibly lead to cracking at this particular location. It is preferred to use metal braces for tightening, yet due to the large distance to the city at the testing site such braces were not readily available and steel wire was used to close and tighten the second bamboo. The tension placed on the bamboo brace should be high and on at least three points (begin, middle, end). When there exists a great danger of deforming on a crucial point of the curve at least four or preferable five steel wires should be placed. The opening between the braces allows for the flame torch to heat the bamboo stem. When the desired curve is obtained, the bamboo first need to cool down entirely before the braces can be taken off (not before). It is advisable to keep these separate bamboo strips together to avoid time being wasted on finding matching pieces when a brace needs to be placed on the following bamboo stem. Diesel oil was applied on the bamboo stem for several reasons; ‘greasing’ up the outer fibers to facilitate bending, providing an extra treatment to the bamboo and obtaining a ‘glazed’ appearance that resembles varnish.



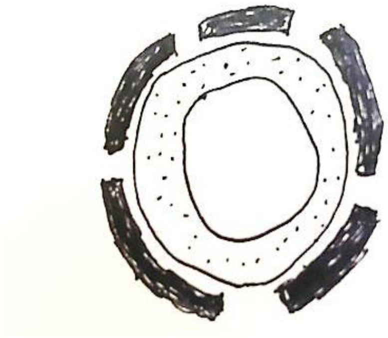


Figure 3.73. Principle of bracing. 2018.

Figure 3.74. Support and bracing between internodes for bending. 2018.

During bending, a deformation crack always occurred at the same position, meaning that the curve was too excessive for the bamboo. Changing the curvature of the arch or providing a small connector piece in between could possibly resolve this problem. Such a connector piece would involve cutting the bamboo open at the breaking point, removing the broken part and entering a curved rebar into both bamboo pieces with a grout infill. Afterwards, a bamboo with an equal diameter can be placed over the rebar to visually hide the rebar. Another possible solution would be to insert a designed and visible connector piece which would give the construction a high-tech look. In this case, the colleague in question preferred to maintain the visual aspect of one bended bamboo stem. The second arch (placed under the first) even had a minor diameter at the curve than the first one (Figure 3.75). Therefore extra bending points (steel bars) were added to the already existing ones. When bending is achieved, a rope is immediately tied from the far end to the beginning in order to maintain the exact curving. This rope is needed until the bamboos are connected with steel pins (Figure 3.76 and 3.77).

Figure 3.75. Two bamboo poles form one arch. 2018.

Figure 3.76. Securing the curvature with a rope. 2018.

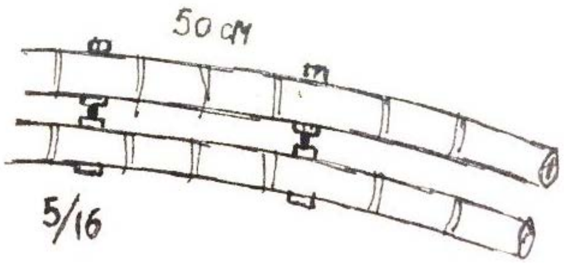


Figure 3.77. Two interconnncted bamboo arches. 2018.

Wire rods (5/16) are drilled simultaneously with a long drill bit (at least 20cm long) in order to puncture both bamboos in a straight continuous line. The drill-bit should be slightly larger than the rebar to be inserted (e.g. 1/2) to avoid tension when inserting the rebar. Shove in the rebar via the same side of the drilling. In between the bamboos, two screws are put that serve as placeholders. These screws maintain the bamboos at the accurate distance (in this case 4cm) and correct the arch when the curve is not exactly similar. Only after connecting these two bamboo members it will form a strong and tensioned arch that is capable of carrying load. Laboratory testing would be useful to know the exact load such an arch can carry. As the weight of the zinc roof that is foreseen in the design is rather low, the arches' performance will undoubtedly be sufficient in combination with other structural members.

3.6.3 Cold-bending methods

Cold-bending methods do not require adding heat to the bamboo and are therefore less time consuming. Nevertheless, they have a detrimental effect to the physical properties of the bamboo cane itself.

3.6.3.1 Slashing technique

This technique is frequently used to make furniture, for small corrections or to adjust a crooked piece of bamboo. This technique implies casting V-shaped incisions into the bamboo cane with a knife no deeper than two-thirds of the total diameter (van der Lugt, 2017). When a large inflection is required, the V-shape cuts need to be relatively narrow to each other to allow the correction whereas for a small curvature the V-shapes can be cut wider apart. In the bamboo canopy project in Guaporé (section 6.10), the arches were made according this technique. With the application of a circular saw, every 5 to 10cm, depending on the degree of the curvature, a cut was made. After the bamboo is bent, it needs to be secured into its position either by lashings, steel pins or an adhesive. The slashing technique requires little time and no special tools. Disadvantageous is that the bamboo loses substantial tensile and compressive strength and it is impossible to obtain a smooth curvature for fragments are slashed out of the bamboo cane (Maurina, 2015).

3.6.3.2 Bundling technique

The bundling technique can either be done by splitting a bamboo cane intro strips whereafter these strips are bundled together and bended or by bundling and bending multiple small diameter bamboos to form a larger structural element. The latter is a technique that Vo Trong Nghia often applies in his bamboo architecture (VTN Architects, 2019). On the other hand, John and Elora Hardy for example combine both cold bending methods where the split technique is used for the arches in the smaller masses that function as classrooms and bundling smaller diameter bamboos together is used for the large arches such as in the multifunctional hall (Ibuku.com, 2020; Nurdiah, 2015).

The author also tested the cold-bending method for the social housing project in Nicaragua by bundling and glueing bamboo strips together into an arch. Split bamboo is very pliable, yet still strong in tensile strength allowing it to be woven or bend into curved forms (Maurina, 2015). Moist fibers are also key when making bamboo strips. Contrary to the combustion bending method, laminated strips are not treated by heat. Therefore it is suggested to give a borax treatment (up front).

Figure 3.78. Process of the cold-bundling technique with glued bamboo strips. 2018.

To produce bamboo strips, freshly cut bamboo stems with a minimum diameter of 10cm and a wall-thickness of 1,5 to 2cm should be cut into strips of 5cm width. It is important that the stem has a sufficient large diameter to get a maximum of flat strips (less rounded). Adequate cutting machinery is imperative to achieve straight and equal strips. The inner sides of the bamboo strips have to be sanded as flat as possible to prevent the internal diaphragms from extending as this could form an obstacle when pressed together.

For the bundling process, first a formwork as described before should be laid out on the floor with that difference that in this case the second row of bars is not necessary. Seven to eight bamboo strips should be laid on top of each other to reach a thickness of 10cm. The bundled arch then becomes about 5x10cm. The strips can be bundled using lashings i.e. with hemp rope or as applied in the Nicaraguan project, glued together with the aid of a bamboo pin, called a pinbu-beam. When laminating the bamboo strips, the first strip needs to be attached with wire steel to the bottom of the steel bars according to the desired curve. Bamboo pins need to be cut beforehand with a proper sawing machine, size 10cm long and 0,8cm thick. Next, a hole with a smaller diameter than the pins to be inserted, is drilled every 20cm. It is essential to have sufficient tension grips present to settle the laminated beam. In the inflection itself, more grips need to be applied in order to secure it in its position (at least every 10-15cm). In the straighter parts, there can be fewer tension grips (every 20cm). Additionally, also steel wire thread is put below the first strip to later fasten all strips together as well. Bending is done gradually, starting at the beginning of the arch and placing a grip every time a part of the beam is glued together with a sufficiently strong wood-glue applied to the surface of each strip as seen in Figure 3.78. When the entire beam is glued and bent, the bamboo pins are inserted in the holes drilled in advance (not coinciding with the grips). The pins need to be sharp and inserted with force, connecting the strips with sufficient strength. This is important, for otherwise the pin has little function. The tapered pin is covered in glue to achieve more adhesion, securing them tight in such a way that afterwards load can be applied. In the most pronounced curve again more pins should be placed, yet this time in slant position in relation to each other. When the glue has dried out, the arch can be taken out of the formwork and then sanded forming a laminated bamboo arch. The success rate is clearly higher than the artisanal bend arches, but it nevertheless requires a substantial amount of effort and time in order to obtain the desired effect.

3.6.4 Natural curvature

In addition to the above-mentioned bending methods, one can also take advantage of the natural curvature of bamboo. Note that naturally curved culms are rare, especially in cultivated bamboo areas as they are cultivated and trained to grow vertically and interweaving is avoided. Also the curved bamboo are located usually have more gentle and uneven, less uniform curves. If and how much bamboo grows crooked, depends on the species, its soil condition and its environment. For example, bamboo growing near a river or water tends to have a curved pole for they grow faster and consequently have less strong fibers than under normal circumstances. Some species even grow crooked or climb to other trees such as the Chusquea Coronalis (Nurdiah, 2015). Natural curved bamboo can be additionally curved by forcing and fixating the already curved stem even further (van der Lugt, 2017). This method is amongst others utilized in the Green School to create the arches and curves. The uniqueness of a natural curved bamboo can be applied for example as a curved roof frame (Nurdiah, 2015; Widyowijatnoko, 2012). The bamboo church from Simon Vélez in Pereira, Colombia makes a great allusion to a naturally curved bamboo forest. Natural curved bamboo can also be straightened again by bending it in the opposite direction above an open fire. This is only possible if the curve is in one direction (Widyowijatnoko, 2012).

3.6.5 Conclusion

It is often a misconception that bamboo is easy to bend because of its high bending strength characteristics. Obataya et al. (2006) researched the bending characteristics of bamboo (Phyll. Pubescens) with respect of its fiber-foam composite structure. The flexural elasticity of bamboo specimens was compared to that of wood with regard to the remaining strain after the removal of load. No clear difference was identified between the remaining strains of the bamboo and wood and therefore it was concluded from this research that bamboo is not so flexible elastically but its fiber–foam combination and intelligent fiber distribution give excellent ductility. Because of this limited natural curvature, external bending methods need to be applied in order to meet the expected curvature for specific designs. This can either be done applying hot or cold-bending methods. Each technique has its (dis)advantages and issues different effects on the aesthetic, structural and construction aspects (Maurina, 2015). Table 3.7 summarizes the consequences of each bending technique. As a loss in strength may occur due to the bending, it should be applied with care. These findings will be reflected in the evaluation framework in chapter 8

Aspect	Hot Bending Method		Cold Bending Method		
	Immersion Technique	Combustion Technique	Slasing Technique	Bundling Technique with bamboo split	Bundling Technique with bamboo poles
1. Aesthetic Aspect					
Curvature	Smooth	Smooth	Not smooth	Smooth	Smooth
Texture	Smooth	Smooth	Smooth	Roughest	Rougher
Color	Not change	Change	Not change	Not change	Not change
2. Construction Aspect					
Tools	Big tub & heater	Heater	knife	Clave or splitter	-
Time	Long	Long	Short	Short	Short
3. Structural Aspect (Compared with origin bamboo)					
Compres-sive Strength	The same	The same	The same	decrese	The same
Tensil Strength	The same	The same	decrease	The same	The same
Bending Resistant	The same	The same	decrease	The same	The same

Table 3.7. Characteristics on the aesthetic, construction and structural aspects of bamboo after the application of different bending techniques. Retrieved from:´ *Curved structural bamboo element`(p. 12) by A. Maurina. 2015.* Paratyangan Catholic University. Jatiluhur, Indonesia.

3.7 **Fire Behavior**

3.7.1 Fire reaction and fire resistance

Bamboo is a combustible material and when exposed to a certain amount of heat, it presents mass loss and strength reduction. It is imperative to understand how bamboo will behave under fire. Different factors play a role. Fire reaction is associated with the ease with which a material ignites and the spread of fire under specific conditions, whereas fire resistance is a specific design consideration to minimize the risk of material failure in buildings under fire such as structural collapse (Harries & Sharma, 2016; Cramer & White, 1997). Although important, there exists little to no research on the fire resistance of bamboo. After extensive research, only two academic articles specifically on the fire resistance of the round bamboo culms were found in comparison to the extensive research that exists on fire resistance of wood, polymers, concrete, etc. In addition, several articles were found on the fire behavior of laminated, strand woven or other engineered bamboo applications. However, last-mentioned research results will not be discussed in detail as the focus of this research is limited to the structural application of round bamboo culms. Nonetheless, in both articles on fire resistance of round bamboo culms, also laminated bamboo was researched and a comparison between both materials was made. The outcome of these research results will be discussed as the comparison between both materials gives interesting insights. The lack of knowledge on fire resistance is a barrier for a widespread use of bamboo as a construction material as it is a required parameter for mid and larger constructions (Gutierrez et al., 2018). The main objective of fire resistant structural design is to maintain structural integrity during a fire for a sufficient period of time required for safe evacuation, safe fire extinction and minimized property loss. Consequently, flammability is a real concern to clients, architects, designers and engineers working with bamboo and therefore addressed in this chapter as well as in the evaluation model. The characterization of bamboo´s fire behavior is essential to predict its response in order to adequately be considered during design (Mena et al., 2012; Cramer & White, 1997).

Many (inter)national standards and codes have been developed to be able to measure and determine the period of time a specific material can withstand fire. Yet, fire resistant building has become complex because of a tangle of regulations (Cramer & White, 1997). Not only the fire resistance of the material has to be researched, also the combination of different materials matters. For example, wooden battens against a stoned wall will demonstrate a different fire behavior than wooden battens with a foil or insulation material close by. In addition, the end-use application plays an important factor as well. There also exist differences in safety requirements for roofs, floors, walls or facades. Finally, also the user function makes a difference e.g. an office, education, industry, housing, health care, etc. (Instituut Fysieke Veiligheid, 2014). An extra complexity is added, given the fact that bamboo is a naturally varying material with an irregular geometry (Madden, et al., 2018). The European NEN EN 13501-1 (2019) classifies the fire reaction of construction materials into different fire classes. Building elements and structures are tested and classified in respect of their fire separation performance and smoke tightness according to a system that indicates the properties by a letter where A is the best fire resistant and F the worst. Most wood species, such as untreated MDF, OSB, hardboard, etc., are classified as fire class D which is described as materials that are capable of resisting a small flame attack for a longer period without substantial flame spread. They are also capable of undergoing thermal attack by a single burning item with sufficiently delayed and limited heat release. Some stronger wood types are classified in the higher class C (Cramer & White, 1997; Instituut Fysieke Veiligheid, 2014; NEN - EN13501-1, 2019).

There exist several methods for a construction material to be included in a specific fire classification. First, there exists the direct application where research is done to test a particular material whereby different methods and machines according to the prescriptive norms are applied. Secondly, extended application is a prediction of research results based on other research or on the mechanical/physical properties of the material. However, for fire behavior such extended application standards are not yet available. Thirdly, Europe offers the possibility to classify a material according to a recognized fire classification such as DtS and CWFT. DtS stands for *´Deemed to Safety`*. All materials consisting of a material with an A1 classification are listed here for they are deemed to be safe. CWTF stands for *´Classification without further testing`*. Here materials are listed that at least achieve a particular classification. This list is included in the NPR 6051. Finally, a manufacturar of a certain material can appoint an independent party to write a conformity declaration of his product. This occurs when a material is applied in a situation that deviates from the normal test requirements or environment (Instituut Fysieke Veiligheid, 2014). Currently, bamboo is not included in any fire classification. Yet, it can be suggested that bamboo could be classified at least in fire class D. Similar results were the results of fire tests conducted by Wood.be and Warringtonfire. The author designed the entrance buildings including three bamboo towers for the Zoo Planckendael in Mechelen, Belgium. These fire tests resulted in class D without any treatment and a class C with a fire-resistant coating.

As these testsresults have not yet been published, the official results cannot be divulgated yet. Values reported by Gutierrez et al. (2018) on fire reduction for bamboo are similar to other lingo-cellulosic materials such as timber. Bamboo shows even less reduction in tension and elastic modulus than timber. At 100°C, the Eurocode 5 reports a 35% reduction for tensile strength and 50% reduction in the elastic modulus in tension for timber elements (Eurocode 5, 2004) whereas bamboo suffers respectively only a 25% and 10% reduction. Moreover, bamboo demonstrates almost equal yet slightly better results for compressive strength being 70% strength reduction at 100°C in comparison to 75% for timber. At higher temperatures, the compressive strength of round bamboo experiences a minor increase in its compressive strength capacity to finally drop to an 80% reduction at 250°C. The reduction in the stiffness can lead to a shift in the failure mode changing from a crushing failure to a buckling failure (local buckling in the wall thickness). All samples of Gutierrez et al. (2018) presented a failure in the node. However, this was expected due to the interruption of the fibers at this point.

Whereas Gutierrez et al. (2018) studied the compressive and tensile strength of bamboo at elevated temperatures, Mena et al. (2012) researched bamboo´s fire reaction and fire resistance according to the following parameters; fire ignition, flame spread, charring behavior and flexure strength at high temperatures. When characterizing fire performance of a load-bearing bamboo, not only the reduction of mechanical properties needs to be researched, also its burning behavior (i.e. fire ignition, charring & flame spread) plays an important role. Therefore, these parameters studied by Mena et al. (2012) are discussed hereafter.

Fire ignition requires three elements namely heat, fuel and an oxidizing agent (usually oxygen). When exposed to fire, materials develop chemical decomposition processes that facilitate gas emissions and charring of the surface. These gasses can turn into flames, which can help spread fire. Therefore, the critical ignition flux is determined. In experiments done by Mena et al. (2012), both the round culm as the laminated bamboo show a critical ignition flux of 14kW/m². A typical wood value that has been adopted by several countries for design purposes is 12kW/m². This higher critical ignition flux for bamboo can arguably be explained by the higher concentration of fibers in the outer cortex that provide an enhanced protection due to its silica content, delaying the ignition process (Mena et al., 2012).

Flame spread consists of the horizontal displacement of a flame affecting the whole element. The fire spread rate depends on the heating rate and the thermal inertia of the material. Materials with a lower inertia heat more rapidly and are most likely to develop a rapid ignition phenomenon. Mena et al. determined the critical flux to spread a flame by using a LIFT (lateral ignition flame spread test) according the ASTM E1321 standard (ASTM, 2002). The tests results show a critical flux of 5,1kW/m² for the round Guadua, 10,4kW/m² for laminated bamboo and plywood has the lowest value of 3,5kW/m². The result of the Guadua culm is similar to wood values where results vary depending of the material between 3,1 and 6kW/m². These results indicate that bamboo requires a higher heat flux, or a greater energy to propagate fire then plywood, however not as high as laminated bamboo (Mena et al., 2012).

The charring rate is the speed at which a charcoal layer is formed during the decomposition process. This is an important parameter as it allows the anticipation of material loss of an element under fire. The thickness of the charcoal layer is correlated to its exposure time. For this test, Mena et al. (2012) exposed all specimen 2 min to 425°C followed by another 2min exposure to 524°C. The charring rate of round Guadua is three times lower than of plywood however it is still within international standard code values for wood design.

Measuring **flexural strength at high temperatures** is essential in order to anticipate the flexural behavior of bamboo beams or slabs in such conditions. At extreme high temperatures, the physical and mechanical properties of bamboo changes, more particularly the fibers decrease as the temperature increases. In order to determine the effect of temperature on flexural behavior, the specimen were exposed to temperatures of 15, 100, 140 and 180° C. Round bamboo commences under normal circumstances with a higher flexure strength of 173Mpa in regarding to laminated bamboo (114Mpa) and plywood (88Mpa). Moreover, bamboo demonstrates a slower decrease in flexural strength. As plywood is commonly used in construction these results suggest that round and laminated bamboo can be designed with similar design considerations as applied for lighter wood types such as plywood made from Radiata Pine (Mena et al., 2012; Harries & Sharma, 2016).Even though the research results of Gutierrez et al. (2018) and Mena et al. (2012) are difficult to compare to one another, both studies underline the similarity to timber elements regarding bamboo´s fire behavior. Hence, it is safe to design with bamboo considering the fire resistance norms for timber, although further research is necessary to receive an official classification. Minke describes that the non-structurally applied bamboo in the façade of a car park in Leipzig had gotten, following the German DIN4102 regulations, a class B2 categorization being moderate flammable. Because bamboo canes are hollow, they represent a high fire risk, yet because of the high concentration of silicates in the external layer bamboo is not highly flammable (Minke, 2012).

Although fire behavior of materials plays an important role in determining the level of safety in a building, it is necessary to establish the fire risk by looking at the expected performance of the entire building as well. There exists a wide range of building codes that prescribe general fire protection requirements applicable to all type of buildings, regardless the materials used. Currently, building codes prescribe a combination of passive and active features to obtain fire safety. Whereas passive features focus on prescriptive measures of fire-rated building elements, active features concentrate on fire detection such as alarms or systems to suppress fire spread. Bamboo buildings should be designed as such that they meet the general fire safety requirements established in these building codes (Harries & Sharma, 2016).

Besides the natural fire resistance properties of bamboo, fire retardant treatments and coatings can offer an extra protection. The effect of boron components on wood and bamboo based materials has been extensively researched and appears to have significant results. Although borax and boric acid have different fire retardant effects during the combustion process, a synergy of both components offers a solution. Borax tends to reduce the flame spread and subsequently restrains heat release better, however it promotes charring. In contrast, boric acid suppresses glowing and shows better fire resistance performance by reducing smoking and toxic gas formation but has little effect on the flame spread. In general, heat and smoke release are significantly reduced in treated bamboo specimen with a higher concentration of boric acid and borax mixture then untreated filaments. Again here, more research needs to be done to detect if these products can provoke cancer on long-term and to research what better results exactly this coating gives in comparison to untreated bamboo and how often it needs to be applied (Yu et al., 2017).

3.7.2 Conclusion

Because bamboo is hollow, it presents a high fire risk. Nevertheless, because of its protective outer layer that contains a high concentration of silicates, bamboo is not highly flammable. Bamboo has roughly the same fire resistance characteristics as wood due to the similar chemical structure of both materials (Minke, 2012). Based on a limited number of fire tests, the charring rates of bamboo can be assumed similar to those for timber (e.g. 0.6mm/minute). Bamboo chars at a slow and predictable rate and is a poor conductor of heat, so that the bamboo behind the charred layer remains virtually undamaged. However, because of its thin wall, the culm wall loses its strength rapidly when burning (Kaminski et al. 2016). For public and larger bamboo constructions case specific fire studies need to be done. In Germany, fire tests were conducted on the bamboo for the ZERI pavilion at EXPO 2000 and for the car park building for the Zoo in Leipzig. In both cases, the bamboo stems were classified as class B2 (moderately flammable) in accordance with DIN4102 part 4 (Minke, 2012).

It can be concluded that fire is an important factor to take into consideration. Proper laboratory tests are hence recommended for larger and for public buildings. For smaller constructions, fire-escape routes and applying a fire-resistant coating can already be sufficient.

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CHAPTER 4 Component 2: Performance of a bamboo structure (Utilitas)

The idea that the earth is a finite planet in a mathematical sense was first introduced in 1972, both in the report ´Limits to the Growth` published by the Club of Rome as at the first Earth Summit in Stockholm. The building sector is accountable for a great part as buildings are major energy and resource consumers, both during construction as usage phase and additionally generate large quantities of waste. The industrialized character of the modern building sector has been destroying local and less impactful ways of building. Short-term economic profitability dominates while other factors such as environmental quality (pollution, GHG-emissions) or social questions (massive sub-contracting, job insecurity) are ignored (Floissac et al, 2009). In accounting, the triple bottom line approach (TBL) has been coined by J. Elkington in 1994 to measure the sustainability of an organization or a corporation. Going beyond the mere financial profit (the bottom line), the TBL theory also takes into account social and environmental aspects. These three pillars are also referred to as **P**rofit, **P**eople, and **P**lanet or in short the 3P´s (Designingbuildings.co.uk, 2020). Mapping these factors gives an insight whether a company is sustainable and on which particular aspects it needs to focus to improve. This threefold framework can also be applied to measure the sustainability of a certain material. Therefore this chapter provides an overview of the strengths and challenges of bamboo regarding its environmental, social and economic performance.

4.1 Environmental Performance

One of the principal reasons to consider bamboo in construction, besides its strength and affordability, is its low negative impact on the environment. In a study done by van der Lugt et al. (2005), a calculation of the environmental load for different building components in office buildings was made (Figure 4.1.) in which a remarkable 57,1 % was attributed to the load-bearing structure. Even though this percentage can be discussed as results might be susceptible to the method used for the calculation, the load-bearing structure can be considered to be the most impactful part of a building. When the load-bearing structure is provided in bamboo, the environmental load of a building can be reduced considerably. A detailed life cycle assessment (LCA) is performed in section 7 based on two different load-bearing bamboo columns from the case studies discussed in part II.

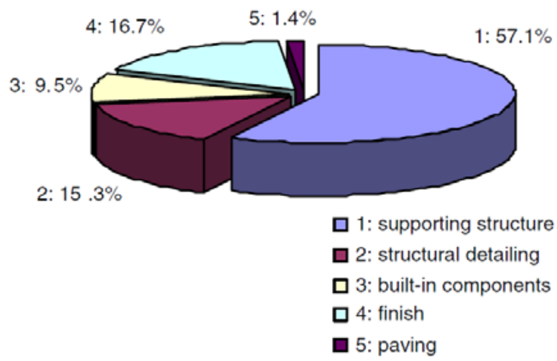

Figure 4.1. Division of environmental load of building materials in office buildings. Retrieved from An environmental, economic and practical assessment of bamboo as a building material for supporting structures (p.2) by P. van der Lugt, A.A.J.F. van Dobbelsteen & J.J.A. Janssen. 2005. Construction and Building Materials.

Because of the growing population, overconsumption and mainly linear economy, we are heading towards a worldwide material scarcity. The building industry consumes over 50% of all extracted materials and in particular the small amount of renewable energy and diminished reserves of economically viable metallic minerals such as copper, lead and zinc constitute a problem. Moreover, oil-reserves are declining, making oil-based products such as bitumen and plastics increasingly scarce. Even though the base ingredients to produce concrete and cement are still abundantly available, the production hereof requires high temperatures (often > 1500 °C) signifying high-energy consumption and CO_2 emissions (van der Lugt, 2017). Substituting techno-cycle materials by bio-based materials seems appealing. In theory, the production of wood is when planted and managed properly unlimited. However, with a predicted growing demand for bio-based materials this can also lead to depletion (Floissac et al, 2009). The wood production capacity needs to be expanded through new plantations, large-scale reforestation projects and complemented with other fast-growing plants such as bamboo but also hemp, seaweed, cork, flax, algae and fungi (van der Lugt, 2017). Bamboo is considered to offer the greatest potential as a bio-based construction material. Its environmental strengths are discussed in section 4.1 whereas its environmental challenges/points of attention are discussed in section 4.2. Plantations, transport and treatment methods need to be assessed upfront considering their possible negative impact on the environmental performance. As it is also essential to shift from a linear production scenario to a circular one in order to diminish the consumption of primary materials (van der Lugt, 2017), the principles behind circular economy are outlined in section 4.3. as well as the role of bamboo herein.

4.1.1 Environmental strengths

4.1.1.1 Rapid Growth & Renewability

One of the most known and interesting features of bamboo is its rapid growing speed. Bamboo belongs to the grass species (graminea) and not to tree species. The stems are mostly hollow and shoot from the root according a rhizome system. These rhizomes can broadly be classified either as pachymorph (sympodial) or leptomorph (monopodial). In a sympodial rhizome system, the apex of a rhizome gives rise to a shoot that grows into a culm. Such culms grow close together in a clump. In a monopodial rhizome system, the rhizome grows horizontally, making each culm to grow at a distance from one another (Janssen, 2000). It is this extensive rhizome network that anchors the bamboo to the soil and supplies it with food and water. Unlike trees, bamboo stems do not grow in thickness. The diameter of a sprouting shoot is equal to a mature stem as cell growth only occurs in vertical direction. The mother plant (first generation plant) has a small diameter and every new generation the stems thicken. Bamboo can reach up to full length (30m high) within a couple of months, with a recorded maximum of one meter growth a day (van der Lugt, 2017). The process of lignification takes four to six years depending on the species and climatic circumstances. Stems grow faster and higher in fertile and moist climates. On inclined terrain with little water, bamboos grow slower yet stronger (more fibers). Generally, it takes about five to seven years for a bamboo stem to be ready for an application in the building industry (Minke, 2012). The growth rate of bamboo is twenty times higher than the production rate of trees that are commonly used in the lumber industry and nearly three times that of the fastest growing trees. Its rapid growth implies renewability of the base material and results in a high annual yield which is particularly important as land is becoming scarce. A bamboo plant is not exctinted when harvested. On the contrary, by harvesting mature poles, the yield and quality of the bamboo plant is increased and when bamboo is not cultivated and maintained, mature stems become old and decay, blocking space for new culms to sprout (van der Lugt, 2017; Sands, 2009).

4.1.1.2 Primary Energy

When bamboo is used in its raw form and not as an engineered product, as is the subject of this research, hardly any extra energy needs to be added before application. According to Janssen, 300 MJ/m³ of energy is required to produce 1m³ bamboo in comparison to 600 MJ/m³ for wood. Steel and concrete have a heavy demand on the energy production. Table 4.1. demonstrates that bamboo has the lowest energy requirement for production (Janssen, 1981; Minke, 2012; Manandhar et al., 2019).

material	energy for production MJ/kg	weight per volume kg/m^3	energy for production MJ/m^3	stress when in use N/mm^2	ratio energy per unit stress
(1)	(2)	(3)	(4)	(5)	(4)/(5)
concrete	0.8	2400	1 920	8	240
steel	30	7800	234 000	160	1500
wood	1.	600	600	7.5	80
bamboo	0.5?	600	300	10?	30

Table 4.1. Energy, needed for production, compared with stress when in use. Retrieved from Bamboo in building structures (p. 13) by J.J.A. Janssen. 1981. Technische Hogeschool Eindhoven.https://doi.org/10.6100/IR1183.

4.1.1.3 Annual yield

Compared to other bio-based materials, the annual yield of bamboo is high. Guadua and Dendrocalamus have an average annual yield of 9m^3 per hectare and in ideal circumstances, annual yields over 20m^3 have been reported. In comparison, the average annual yield for European oak and Scots pine is 3m^3 per ha and for Meranti and Chinese fir 4m^3 per ha (van der Lugt, 2017). Where van der Lugt (2017) indicates an annual yield between 9 and 20m^3, Lobovikov et al. (2007) assume a 17m^3 annual yield of bamboo. It is estimated that 36 million hectares are covered with bamboo forests: 6 million in China, 9 million in India and another 9 million spread in other Asian countries totaling to 24 million hectares only in Asia. Ten countries in Latin America are considered to have over 10 million of hectares and although the information gathered from Africa is partial, over 2.7 million hectares was reported by six African countries (Lobovikov et al., 2007). It has to be pointed out that most of these bamboo forests are not privately owned, nor managed and thus not 100% accessible for production or cultivation. For example in Asia, 80% of the bamboo forests reported is publicly owned. Therefore, growing stock is a better indicator of the extent of commercial bamboo resources because it calculates the number of commercial species, the quantity of each and their physical and economic accessibility. Regretfully only limited and estimated data are available. Lobovikov et al. (2007) estimated in 2005 a 23.455.000 million hectares of commercial bamboo sources while Van der Lugt gives an estimation between 211 and 398 million ton bamboo stock. The amount of millions of ton yielded yearly indicate that bamboo is indeed an abundant material, nevertheless there is still room for growth. The advantage is this high annual yield is particularly important as land might become scarce in the future (van der Lugt, 2017)

4.1.1.4 Carbon sequestration

Plants that assimilate CO_2 for photosynthesis, storing it in their biomass, make an important contribution to the global climate (Minke, 2012). Measuring the carbon footprint is a commonly used methodology to measure GHG emissions during life cycle in terms of kg CO_2 equivalent. On a global scale carbon is stored either in forests, the ocean or products (e.g. building or furniture) and emissioned by the combustion of fossil fuels or released in forests by natural decay. Biogenic CO_2 is captured inside a bamboo stem during growth phase and locked inside the stem when living or harvested. Carbon is released back into the atmosphere at end-of-life phase or when discarded (van der Lugt & Vogtländer, 2015). The amount of carbon a bamboo can sequester varies from species, climatic circumstances and life cycle. Carbon mass calculation is complex and results vary depending on the method and criteria applied (van der Lugt, 2017). Manandhar et al. (2019) calculated a carbon storage between 30 to 121Mg per ha and a carbon sequestration rate between 6 to 13Mg per ha per year. Minke (2012) reports that Guadua Angustifolia Kunth can uptake 54 ton of CO_2 per ha in its first six years. In general, it can be said that the amount of carbon a bamboo sequesters is 3,5 to 7 times higher than that of a tree (van der Lugt, 2017; Manandhar et al., 2019). Carbon stockage is higher in a managed plantation where old bamboos are harvested, making space for new ones. When bamboo is planted on wasteland, poor farmland or in other degraded areas, the carbon sequestration credit is even higher. In order to determine the carbon footprint, not only carbon sequestration of the plant itself has to be taken into account, but also the carbon emission during every step in the production chain such as harvesting, treating, processing and shipping. These factors have a negative impact on the carbon footprint. For engineered products, it is the energy consumption in the country of processing which contributes the most to the carbon footprint whereas for bamboo in its natural form, the treatment method and sea transport are impactful factors. When a bamboo stem is used in the country of origin in its original form, bamboo becomes the most sustainable building material possible with a carbon footprint of 0.19kg CO_2eq/kg stem (van der Lugt, 2017).

4.1.1.5 Reforestation and restoration of degraded land

A valuable feature of bamboo is its reforestation potential. Bamboo´s extensive root and rhizome system and the numerous bamboo poles/shoots help to secure the soil, improve soil quality and restore the water table while its dense foliage offers protection against beating rains. Studies show that 80% of the roots and rhizomes are present in the upper 30cm of the soil layer and that one bamboo can bind up to 6m³ of soil (Singh et al., 2015). Unlike wood, clear-cut is not an issue as there are always new and young bamboo shoots that need to mature before harvesting can be done. Generally, 20 to 25% of the poles in a bamboo forest or plantation can be harvested without diminishing the amount of poles per hectare. Bamboo can also be planted in areas where farming is no longer feasible such as degraded land areas or eroded slopes (van der Lugt, 2017). The World Resource Institute, in collaboration with the University of South Dakota and other partners, have identified forest areas worldwide where opportunities for wide scale, mosaic and remote restoration could be done, including planting of bamboo forests. In the Bonn Challenge, membering countries of INBAR have agreed to restore 5 million hectare of forest land with bamboo by 2020. Figure 4.2 shows where these forest and landscape opportunities are located. This map overlaps largely with the map of the natural growth of bamboo. In India, for example, bamboo has been a considerably important means in landscape restoration, with over 85.000 hectares of degraded land brought back into productivity where mining for brickmaking had eroded the soil. INBAR has investigated the effects of these plantations and has found that it now provides an average 10% of the annual income of farmers, helped raise the water table from 40m below (1996) to 15-18m, helped drop the pH of the soil from 10-11pH to 6-7pH, helped to restore local biodiversity and many more beneficial effects (INBAR, 2014). Care has to be taken however that monoculture is avoided in doing so for this could lead to an increased susceptibility towards diseases, pests and loss of biodiversity (Laestadius et al., 2015).

Even though there is little to no scientific research being done on the topic, it appears that bamboo also offers considerable potential against desertification. Deserts that are advancing into natural or human areas can possibly be halted by bamboo plantations because of its vigorous rooting system. The Permaculture Research Institute posted an article on a project in the Wadi Rum Desert in Jordan where waste water from an industrial agricultural farm nearby was used according to the principals of permaculture to transform a classic inhospitable desert region into a green area (Mackintosh, 2014). Furthermore, bamboo has been identified as successful in the restoration, reclamation and productive utilization of riverbanks, gully heads and riverbeds. In areas that are poor in (agricultural) productivity due to accelerated rainwater runoff, bamboo can aid to retain this water in the soil. This retained water then saturates the soil, after which it reaches and recharges the aquifers. When the soil moisture is conserved, it helps to establish the growth of other plants (Singh et al., 2015).

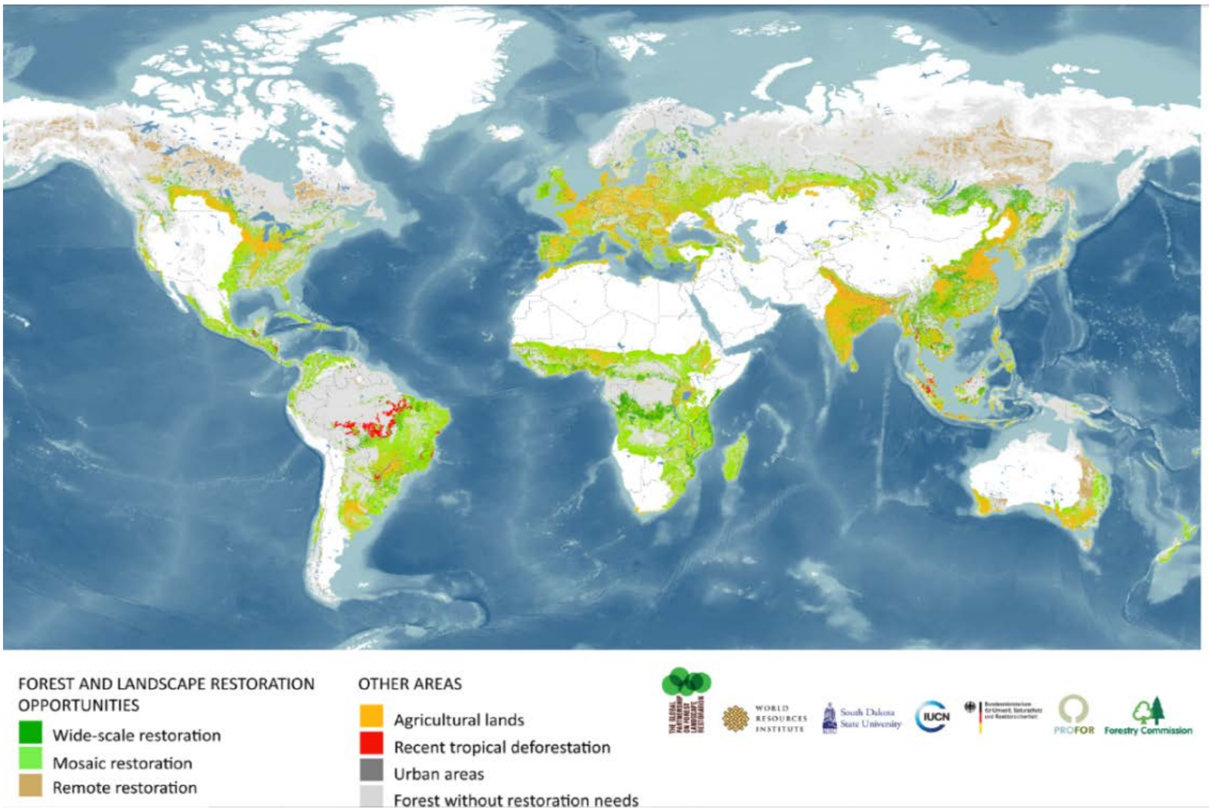

Figure 4.2. Lands with opportunities for restoration of forests and landscapes. Retrieved from Before Bonn and beyond: the history and future of forest landscape restoration (p. 47) by L. Laestadius et al., 2015.

4.1.1.6 Water retention

In accordance with the reforestation qualities, bamboo retains water very well, both moisture and rainfall. The leafy mulch accumulated beneath the bamboo plant conserves moisture and assists the earth to absorb and retain moisture more effectively. Additionally, the level of evaporation is reduced. Bamboo litter has the capacity to absorb moisture up to 2.75 times its dry weight (Janssen, 2000). Other experiments show that bamboo´s total capillary moisture capacity within the depth of 0-60cm in a bamboo forest is measured to be 430.5 mm, and the valid water storage capacity 312.73mm. One hectare of Guadua Angustifolia Kunth can retain over 30.000 liters of water (Minke, 2012). Regarding rainfall, the dense canopy of leaves and the numerous culms intercept a considerable amount of rainfall. The velocity of the raindrops is reduced as they change their direction because of the leaves and culms thereby decreasing direct soil erosion. Research done in China calculated that up to 25% of rainfall is intercepted by the canopy of a bamboo plant, although this varies depending on the quantity of standing culms, the leaf area, the density of the forest, the season and precipitation intensity. Due to its leaves, bamboo forests reduce air temperature through water evaporation (Minke, 2012; Janssen, 2000).

4.1.1.7 Phytoremediation

Bamboo has the capacity to uptake toxins and heavy metals during its growing phase as shown in Table 4.2 (Potters, 2009). This fact increases the environmental benefits when bamboo is sourced from areas that are being cleansed by it. The yield of such plantations might be less when compared to a large full-scale plantation, but the environmental benefits could outweigh the commercial benefit. From a cradle-to-cradle point of view, clearly, the end of life of these bamboos will also need to be considered. When combusted for energy production (bio-mass) metal exhaust should be avoided during combustion. It might be better to use this bamboo as construction material because the sequestered toxins remain inside the stem and form no hazard for the user. When incinerated or decomposed, bamboo will release the toxins that were captured (Joos, 2011). Bamboo has been found to have a higher capacity for the uptake of heavy metals than poplar and willow, both renowned for their benefit in this field. The largest toxin uptake is confined to the top 50-70cm of the bamboo roots whereas poplar and willow can take them up from deeper. Beneficial is that bamboo does not need to grow on prime agriculture land, leaving this available for food crops. Moreover, it can withstand a high number of pollutants that food crops cannot (without becoming inedible). Whilst bamboo can successfully sequester Zinc (Zn) and Lead (Pb), it is less successful in uptaking Cadmium (Cd) (Potters et al., 2009). Although the research by Potters et al (2009) was done in a European context, there is no reason to believe that the outcome would be much different for Latin America. One can only assume that the outcome would be better given the increased rate of growth and larger diameters that are commonly found here. Equal to Europe, Brazil also has many post-industrial areas that have been polluted and are too expensive to sanitize by proven techniques that give result in a short time. Because it is economically not viable, these areas remain untouched and polluted. Often no other function can be given to such terrains due to health hazards. In the research done by Potters et al. (2009), it has been measured that a complete clean-up of a polluted site by a bamboo plantation is a time-consuming process that could take decades.

BAMBOO	*leaves*	*culms*	*rhizomes*
Zn (µg/g)	87-450	141-795	72-1900
Cd (µg/g)	8-27	7-27	5-50
Pb (µg/g)	33-60	33-61	32-260
WILLOW	*leaves*	*stem*	*roots*
Zn (µg/g)	411-695	24-40	ND
Cd (µg/g)	3.07-8.26	0.80-3.29	ND
POPLAR	*leaves*	*stem*	*roots*
Zn (µg/g)	362.5	146.1	243
Cd (µg/g)	4.3	3.6	3.2
Pb (µg/g)	2.9	12.7	17.7

The given range of values for bamboo was obtained in a pot/greenhouse experiment where 5 different *Phyllostachys* species were exposed to different concentrations of Pb, Cd and Zn, comparable to the concentrations of the field experiments with willow (Vervaeke et al. 2003) and poplar (Laureysens et al. 2005). ND : not determined

Table 4.2. Preliminary comparison of heavy metal uptake by different bio-energy crops. Retrieved from Energy crops in Western Europe. Is bamboo an acceptable alternative? (p. 29) by G. Potters et al. 2009.

There exist different forms of phytoremediation; phyto-extraction, phyto-stabilisation, phyto-transformation, rhizofiltration and phyto-volatilisation. The main difference is the way the roots perform and process the uptake of toxins. Bamboo is considered only to be beneficial for phyto-extraction (due to its fast growing cycle) and phyto-stabilisation. Phyto-extraction is the most straightforward form where the plant takes up the toxins through the root system and stores it in the stem, after which these are harvested, removed of its pollutants and re-grown to take up other pollutants. Phytoremediaton signifies that firstly an additive is placed on the soil which binds the metals (Joos, 2011). Regarding the uptake of toxins, one can assume that it is opportune to review the age at which it has taken up most toxins and harvesting should ideally be done, also in consideration with its economic value (e.g. for construction material). A 2-year-old bamboo has a lower strength and higher softness, whilst bamboo with an age of 4 to 6 years gives bamboo with construction quality (high strength and density). When older than 7 years however, bamboo in a bush becomes brittle and reduces in strength (Anokye et al., 2016). Bamboo is considered a hyper accumulator, like other plants that can sequester more than the normal amount of metal, such as Sarepta mustard (Joos, 2011).

4.1.2 Environmental challenges/points of attention

This section addresses the environmental challenges and points of attention in the application of bamboo in construction. Several aspects of bamboo can have a negative impact on the life cycle assessment of bamboo: treatment, transport and possible invasiveness of the bamboo plant itself. After careful consideration it was opted to place the discussion of the different treatment methods for bamboo in this particular section because the chosen treatment has an impact on the amount of energy or chemicals that need to be added which influences the environmental performance. With a proper treatment a higher durability of the bamboo construction is achieved.

4.1.2.1 Treatment methods

Hereafter, possible bamboo treatments and their consequences towards durability, health safety, cost and ecological footprint are given. It helps the user of the evaluation framework to determine the impact of a chosen treatment method. Without treatment, bamboo only has a service life of one to three years when placed outside in contact with soil and up to ten to fifteen years with proper treatment and under good conditions, including positioning bamboo off the ground and in a dry environment (Janssen, 2000). Bamboo degradation can either be caused by biotic or abiotic origin or a combination of both (Minke, 2012). Figure 4.3 presents an overview of the different types of attacks. Biological agents can be subdivided in fungal or insects attack. Both happen as a result of the high amount of starch/sugar content inside a bamboo cane, but differ in the way the bamboo stem degrades. Fungi appear when bamboo´s moisture content is over 20%. Especially in tropical conditions and even more when air is stagnant due to insufficient ventilation, fungi proliferate well. Fungi originate from fine airborne spores in fruit bodies. Whilst surface and stain fungi mainly form an aesthetic problem, decay fungi alters the bamboo beyond structural adequacy for it decomposes the cellulose and hemicellulose (brown rot) or lignin (white rot). Early decay can only be recognized by certain 'dampness' of the bamboo culm. In a later stage, the bamboo will become soft to the touch and turns into a fibrous mass. Even from an early stage however, the structural integrity of the bamboo is compromised (NMBA & TIFAC, 2006; Janssen, 2000; Mertens, 2019).

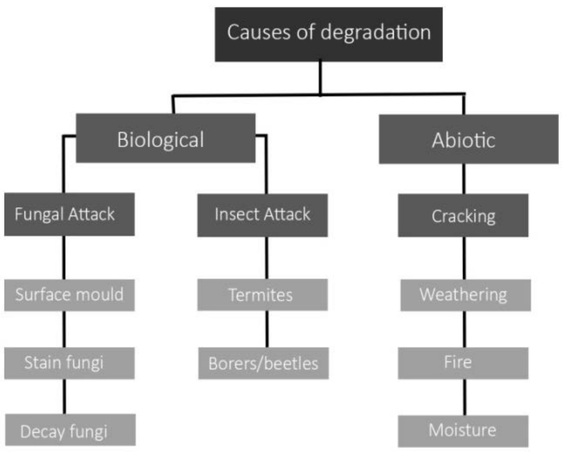

Figure 4.3. Causes of bamboo degradation. Adapted from Preservation of bamboo; a training manual (p.14) by NMBA & TIFAC. 2006. Copyright RSPRINTART.

Insects are the most detrimental biotic agents. Whilst there exists a plethora of insects that can possibly attack bamboo, either to nest or to eat the starch/sugar content, powderpost beetles and termites are the most common ones. Especially, the species Dinoderus and Lyctus are detrimental to bamboo (Kumar et al., 1994). Although they attack under any condition, warm and moist environments proliferate the chance of attack. The powderpost beetle has four stages of life; an egg, larva, pupa and adult. Especially the larvae eat their way through the soft tissue by digesting the tissue in the gut and pushing out a sort of pellet at the rear end (NMBA & TIFAC, 2006; Liese & Kumar, 2003). When coming to adulthood, it eats its way outside laying eggs whilst doing so. When the bamboo is attacked profoundly, only a porous mass with nothing more than a thin outer shell of silica remains. This shell can hold small weights for a short time, but will crack or even collapse eventually. Powderdust below or near the bamboo and exit holes of the adult beetle are the most obvious indicators of such attack (Kumar et al., 1994). Degradation of bamboo can also be caused by abiotic factors such as weathering, moisture or fire. There exists no conclusive treatment method to safeguard bamboo from rotting when in contact with water or sun, therefore good design needs to offer a natural protection from the weather influences, mainly sun radiation and precipitation (Mertens, 2019). Additional protection for fire can be given by applying a fire resistant coating or by a treatment with boron or borax (Kaminski & Trujillo, 2016), as discussed in section 3.6 on fire.

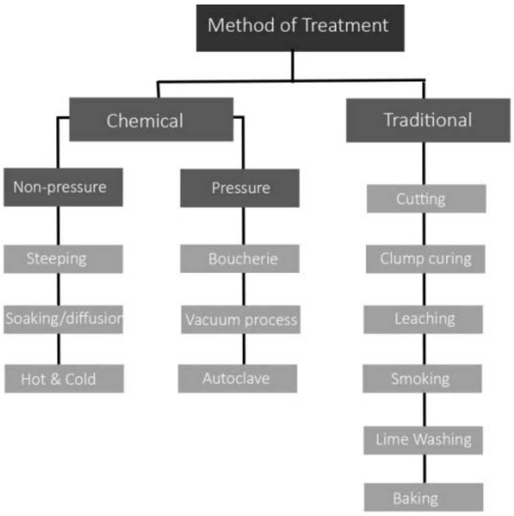

Figure 4.4. Treatment methods. Adapted from Preservation of bamboo; a training manual (p.24) by NMBA & TIFAC. 2006. Copyright RSPRINTART.

Treatment techniques can be divided into two groups: low-tech/vernacular preservation methods and chemical treatment methods. Figure 4.4 provides an overview of the possible treatment methods. Vernacular techniques such as immersion in water, lime washing and earth curing offer a lower efficacy on long term and cannot be depended upon to ensure long durability. It is therefore recommended to employ the chemical treatment methods. However, one needs to consider the main use of its construction and if a construction is temporary or low-cost, also low-tech treatments can be justified. In order to understand how a treatment is applied, it is important to comprehend its internal structure. The outer wall of a bamboo culm (cortex) exists of epidermis cells that are covered with a layer of waxy substance, acting as watertight barrier and protection against physical damage. This epidermal wall contains an inner- and outer layer. The latter is highly lignified. Bamboo is known to have a high amount of silica particles (0,5 to 4%), however predominantly located in the peripheral part of the culm. In the outer wall and in the upper part of the culm, the fiber percentage is higher, which contributes to a considerable slenderness (Liese & Kumar, 2003, Kumar et al, 1994). The pith ring, which is the innermost part of the wall, mainly consists of heavily thickened and lignified parenchyma cells. These type of cells contain in their large volume the nutrients; mainly carbohydrates and starch. Together with the vascular bundles, these axially orientated parenchyma cells form the ground tissue of the culm wall. The vascular bundles are composed of conducting vessels and fibers. The culm wall consists mainly of parenchyma cells (52%), and in its vascular bundles, it holds about 8% conducting vessels and 40% fibers (NMBA & TIFAC, 2006; Janssen, 2000). Clearly, the fibers give bamboo its tensile strength. The embedded vascular bundles in the ground tissue contribute to the elasticity of the culm, like a reinforced matrix. Regarding the treatment, it are the conducting vessels that are of interest as these act as water pipes that transport nutrients as well as water from the roots through the culm up to the leaves. It is in these conducting vessels that the preservative solution, by natural physics or mechanical force, is transported throughout the culm. The starch and other nutrients present in a bamboo culm, can also be made less attractive or unavailable to degrading agents using other preservation techniques, such as applying fire (crystalizing the starch and carbohydrates), adding toxic preservatives to this extent that the available nutrients become lethal. However, such treatment appears to be as successful as treatments that involve transporting vessels. The nodes are composed differently. Cell elements at the top and bottom of a node converge to an axial direction across the nodes. Nonetheless, interconnected conducting vessels still provide transverse movement of nutrients, water and preservative solution (Janssen, 2000; Liese & Kumar 2003). Unlike ray-cells in wood, there do not exist radial pathways in the culm tissues of bamboo. Additionally, bamboo has a mere 8% of conducting tissue, in comparison to 70% in softwood; hence preservation depends on a slow diffusion process. Another complication is that bamboo has a hard to penetrate water barrier in its cortex, making the only entrance possible the top or bottom of the bamboo culm or to puncture each internode. However when a bamboo is cut, a wound reaction starts to block the conducting vessels at the bottom where the cut was made, limiting the access of the preservative. Therefore, bamboo should be treated immediately after harvesting if a treatment method was chosen that makes use of the conducting vessels. When puncturing the inner diaphragms, the bamboo culm can be submerged and the preservative solution can work from the inside out, not using the conducting vessels. If such a treatment is opted, one has to be aware that a classic joint with mortar is no longer possible as the diaphragms will no longer secure the mortar (NMBA & TIFAC, 2006; Janssen, 2000).

Low-tech or traditional treatment methods

<u>Cutting:</u> The season and even the moon phase have an impact on the moisture and starch content of bamboo. Cutting is recommended during the dry season, in the waning phase of the moon and in the early hours before sunrise as the moisture content of the plant is then at its lowest due to its natural photosynthesis process (Minke, 2012: Morán Ubidia, 2002).

<u>Clump curing:</u> Leaving freshly cut bamboo in its vertical position within the bush where it has been cut, reduces its starch content through the photosynthesis process in the leaves, reducing its chance of beetle and fungal attacks. The bamboo has to be left to dry for a minimum of four weeks inside the bush. This method does not diminish the chances of rot nor termite attack (Janssen, 1995; Kumar et al, 1994).

<u>Leaching</u>: For leaching the bamboos are immersed in water, preferentially running water such as a river or a stream, in order for the starch to leech out. The culms should at least be submersed for two to three months. Whilst its success rate is low, it might be a good modus operandi when members will be bend afterwards. However, mechanical properties are affected by the process and applying high construction loads should be avoided (NMBA & TIFAC, 2006; Liese & Kumar, 2003).

<u>Smoking</u>: Fire treatment is a common and traditional way of treating bamboo. It can be done in several ways, although the most common way is to apply smoke of a fire to the bamboo. Mainly in Asia but also Latin-American, Indian tribes store bamboo culms over the hearth of a fireplace. By doing so, the moisture content is reduced and a deposit of smoke is built up which forms a protective layer on the culm. Smoke drying moreover reduces splitting and can even be done on a large scale in so-called 'smoking facilities' where bamboos are stacked vertically or horizontally in an enclosed structure (Janssen, 1995; Janssen, 2000; Kumar et al, 1994).

Lime washing: Slaked lime when painted onto a bamboo culm transforms into calcium carbonate which due to its low PH level acts as fungicide and insecticide. This treatment has mainly an ornamental effect and without any additional treatment, it does not provide an adequate protection for bamboo over time. It appears to have a considerably large eco-cost in comparison to other techniques (Zuraida, & Larasatib, 2015). In order to augment the adhesive capacity of lime, one can first paint the bamboo with an asphaltic emulsion, throw sand over it and wait for the asphalt to dry. In a similar manner, varnish can be considered beneficial, not as a treatment method but as a fungal repellent agent and to offer protection from moisture as both affect durability of bamboo on long term. Care needs to be taken in the kind of varnish that is applied. Varnish that forms a film on the surface can easily peel off and even disappear over time or trap moisture worsening the effect. 'Oil-like' varnish that penetrates the stem offers a better protection (Janssen, 1995).

Chemical treatment methods

Depending on the type, percentage and correct usage, chemical preservation techniques ensure a long-term protection. With a few exceptions chemical preservatives are toxic (NMBA & TIFAC, 2006). It is advisable to use those preservatives that are less toxic. All safe, cost effective, and applicable chemical methods contain boron. Several chemical preservative mixtures are copper-chrome-boron, boron-based fertilizer (Disodium Octoborate Tetrahydrate with sixty-six percent active boron content) and a borax-boric acid (Janssen, 2000). However, even the use of boron implies a negative environmental impact because of its high energy-consumption, water usage and mining process. The commonly used (toxic) chemicals are listed below. Highly toxic chemicals that are prohibited in multiple countries such as Sodium PentaChloroPhenate (NaPCP), Ammoniacal Copper Arsenate (ACA), Copper Chrome Arsenic (CCA) are not listed, despite the fact that these are highly efficient, even for exterior applications, giving a guarantee of 50 years or more. Further research on environmental-friendly preservation methods is needed. Preservation methods applied in the wood or agricultural industry might include good alternatives. Following chemicals can be discerned:

1) *Boron;* has insecticidal (poisonous to insects) and fungicidal properties. It generally has a low mammalian toxicity. Boron usually occurs in compound form, in a mixture of boric acid, borax and water. INBAR recommends a mixture in respectively the following proportion 1:1:54 (Forest Research Institute, 2001). However, also efficient and readymade formulas such as Disodium Octoborate are available worldwide. These boron salts even possess fire-retardant properties in higher concentrations. Moreover, boron is cheap in comparison to CCA, CCB and other modern copper-based wood preservatives (Janssen, 1995). Although precautions must still be taken because in higher concentrations borax acid can irritate the skin and eyes, and if ingested it is moderately toxic. Boron is soluble in water hence exposure to water has to be avoided (Kaminski & Trujillo, 2016; Janssen, 2000). Boron requires an environmental impactful mining process as it is extracted in open-pit mines using petrochemicals and a significant amount of water. The waste product known as tailings is deposited in man-made ponds where water refinement needs to be done before discharged into the local watershed (Scientificamerican.com, 2019).
2) *Zinc Chloride/Copper Sulphate*; both are waterborne single salts and offer limited protection. As they are highly hydroscopic, they repel moisture, yet this fact also complicates the application of varnish or other finishes afterwards. Because of its high acidic character and the fact they cause corrosion to metallic parts e.g. wire rods, hex nuts and washers, its utilization is not advocated.
3) *Copper Chrome Boron (CCB)*; CCB is a waterborne broad-spectrum preservative containing boric acid, copper sulphate and sodium dichromate. It is an alternative to the toxic CCA (prohibited in several countries), however not as efficient
4) *Creosotes*; oil that is a broad-spectrum preservative and cost-effective chemical for exterior applications, also used for treating railway sleepers and wooden poles.
5) *Trichlorophenol (TCP)*; a slightly more eco-friendly variant to Pentachlorophenol. Broad-spectrum preservative that is widely commercially available and often used in combination with (less-eco-friendly) insecticides.

6) *Copper/Zinc soaps (LOSP);* alternative to other organic environmental hazardous preservatives, available ready-to-use and more eco-friendly without foul smell, but economically less interesting (NMBA & TIFAC, 2006; Mertens, 2019).

These chemicals can be applied to the bamboo using various methods. The most common division regarding chemical preservation methods are pressure and non-pressure treatments. Whereas non-pressure treatments work with natural processes such as diffusion or osmosis, pressure treatments force the chemical solution into the bamboo tissue. Pressure treatments allow for a deeper and more even distribution of the chemicals as well as retention of the preservatives in the matter of the culm.

Steeping: This simple treatment method, also called \`butt-end treatment\`, involves placing fresh cut bamboos in a water solution of chemicals, allowing for diffusion by capillary action through the vessels. Depending on the length of the culm and its moisture content, this can be a time-consuming process (7 to 14 days) (Kumar et al, 1994). This is an economically interesting method for small scale treatments (often done in oil drums). The branches and leaves are left in place, serving as a sort of pump through evaporation. When the preservative reaches the leaves, the colour thereof changes and the process is concluded. Recommended preservative solutions for indoor applications are 10-15% Boric Acid or 3-5% CCB in a water-solution. 5-12% CCB allows for exterior use (NMBA & TIFAC, 2006; Janssen, 1995; Forest Research Institute, 2001; Rao, 2001).

Soaking/Diffusion: An effective method, commonly used in Latin American countries, is the complete immersion of the bamboo cane in a liquid that functions both as insecticide and fungicide (Rao, 2001). Preferentially the internal diaphragms are longitudinal punctured by pushing an iron rod through all the nodes. Additionally, a small hole can be drilled in every internode in order for air not to be trapped inside and to facilitate the diffusion process. It is important that the bamboo canes are not too dry because the salt penetrates the bamboo through osmosis. When using two types of salts or augmenting the concentration percentage, the process can be accelerated. However, this process is just like the 'butt-end treatment' considerably slow. Approximately 15-20 days of submersion for round bamboos are needed. It is also a cost-efficient treatment as one only needs to weld a tank of various oil drums or dig a hole in the ground and put a waterproof barrier such as a plastic. This preservation technique has been used for the case study of the community project (section 6.6). Similar solution proportions as suggested for the steeping method can be applied here as well. A variant hereof is the '*double diffusion*' method, where two different salts are used to improve the penetration and the performance of the material in humid conditions. Bamboo is firstly placed in a 20% Copper Sulphate solution for 2 to 3 days, and thereafter placed in a fixing salt such as 20% Sodium Dichromate (NMBA & TIFAC, 2006; Janssen, 1995; Liese & Kumar, 2003; Kumar et al, 1994).

Boucherie method: This technique is most widely known and predominantly used when a certain velocity of treatment is required. It is also known as the 'sap replacement treatment' for that accurately describes it. It is unattainable for small-scale use for it requires a considerable larger investment in equipment necessities, yet the preservation duration time can be brought back to three hours for interior use and six hours for exterior use. For the Boucherie treatment to be successful, the correct moisture content is conditional (Kumar et al, 1994). This technique pushes a preservative solution by means of a pumping system through the bamboo cane. Rubber hoses are fixed to the end of the bamboo where the preservative is pushed in under pressure, at the other end the sap is captured until the preservative solution comes out on the other side. 6-12% CCB is recommended for outdoor use, 3-5% CCB or 4% Boric Borax for indoor use. The solution can afterwards be collected again for re-use when new preservative is added to reach the original concentration (NMBA & TIFAC, 2006; Janssen, 1995; Liese & Kumar, 2003; Rao, 2001).

Hot and Cold treatment: This treatment technique, also known as an open tank process, heats the bamboo canes during 2 to 3 hours to 900°C causing the air from within the cells to expand (partially escaping) (Rao, 2001). When cooled thereafter to normal ambient temperature the contraction creates a vacuum where the preservatives can enter. Preferably Creosote oil is used for this treatment method, but also Boric acid or Borax can be used. In that case it is sufficient to heat to 500° C instead of 900°C. This treatment is also possible for air-dry bamboo (NMBA & TIFAC, 2006).

Vacuum tank/autoclave: Both techniques also require industrial scale investments in equipment. However, as they give a guarantee of 50 years for use in construction, they are clearly highly efficient. These techniques can be applied on dry bamboo as well whereas many of the above mentioned treatments require freshly cut bamboos because they make use of the open transporting canals inside the stem. The process speed and uniform penetration are also beneficial. The preservative is either forced inside the bamboo tissue by evacuating the air from the culm (vacuum tank) or by increased pressure in a pressurized cylinder (autoclave). For these techniques, very often CCA containing arsenic is used. Although according to the producers in safe proportions for exterior use, it is recommended to check the presence of this toxic chemical. It can be dangerous for the bamboo builders when they build without protection and also to the final user of the building. It usually contains 5-8% of CCA, however also solutions of 2-4% Boric Borax are used for indoor constructions. Thick walled bamboo such as Dendrocalamus can also be treated under pressure with creosote fuel oil (1:1) under a hydraulic pressure of 14kg/cm² (Kumar et al, 1994). The high temperatures during the curing process and the use of tank pressure/ fuel and high energy consumption raises questions towards the environmental impact (Zuraida & Larasatib 2015).

4.1.2.2 Invasiveness

When considering bamboo for a construction, one must analyze its origin. Just as bamboo´s capacity for cleaning polluting areas can be beneficial to its environmental performance (section 4.1.1.6), bamboo sourced from areas where it has invaded intact biosystems and becoming the main species generates a negative impact. When considering the main causes of biodiversity loss, invasive species are mentioned alongside habitat change, climate change, over-exploitation and pollution. Bamboo, whether for economic purposes, erosion control, ornamental landscaping or other reasons, has been introduced into non-native areas, which caused in some cases local biodiversity loss through monoculture, especially when it was introduced without proper care or insight. Running types of bamboo are found to be more aggressive than clumping types and the thick canopy of bamboo does not allow for much undergrowth (Pagad, 2016; Moraes et al. 2012). At the Convention on Biological Diversity (2016) invasive species are defined as "*An alien species which has become established in a natural or semi-natural ecosystem or habitat, is an agent of change, and threatens native biological diversity*" (Pagad, 2016, p.9). On the other hand, when clumpers become interplanted with other crops at sufficient distance from each other, it can provide soil protection and fresh nutrients (through leaves that fall) facilitating other vegetation to grow (Moraes et al., 2012). Managed plantations maintain the equilibrium. Local entrepreneurship in small communities, domestication on smaller farms and near residences can be beneficial as long as this means that no harm to local biodiversity is done (Kigomo, 2007). Bamboo plantations can be beneficial to economic return on more than the constructional material level, with value added activities such as food production, handicrafts or other side-products. In harsh climates, these (clumping) bushes also provide adequate shading to the homestead, livestock or shade tolerant crops nearby and retain a healthy water level (Banik, 2001). Assessing the risks in advance and preventing the introduction of potentially invasive bamboo species is the first line of defense. Early detection of invasions, eradication, containment and management of established infestations follow when prevention has failed. Manual, physical and chemical options are available for control (Pagad, 2016). As the demand for certification augmented, the FSC certification system included bamboo since 2008 (van der Lugt, 2017).

4.1.2.3 Transport

In chapter 7, a life cycle analysis is made in which the effect of transport on the environmental impact of a bamboo column is calculated. In this LCA, factors such as harvesting, treatment, processing and jointing methods are also calculated. Unlike what was the author initially expected, (sea) transport has not the highest negative impact in relation to the other factors. In case the bamboo plantation and building site are proximate and local transport (truck) suffices, the impact of transport is even negligible. When a bamboo stem is applied in the country of harvesting, the carbon footprint is only 0,19 kg CO_2 eq/kg stem, making it the most sustainable building material possible. Although outside the scope of this dissertation, it is interesting to mention that van der Lugt researched the eco burden of sea transport to Europe by calculating besides the carbon footprint also the low weight/volume ratio. The carbon footprint including sea transport to the Netherlands resulted in a carbon footprint for production (cradle-to-gate) of 1,45kg CO_2 eq/kg stem (van der Lugt, 2017). The hollowness of the bamboo stem makes the volume very high in comparison to the weight. In this regard, processed bamboo obtains better results. Engineered bamboo is more compact and the higher amount of bamboo that can be transported diminishes the ratio per piece (van der Lugt, 2006). However, it would be very unlikely for a ship to only transport bamboo containers and as sea transport is in the first place limited by its weight and only than by its volume, a bamboo container with relatively little weight could be placed supplementary to an existing freight. In case bamboo is compared to wood, timber utilized in West-Europe is seldom harvested locally and one needs to review where the timber is attained and what transport was required.

4.1.3 Circular Economy - Opportunities of bamboo

Already for many years, the environmental impact of a construction as well as the materials being used, have been a consideration to architects, designers and researchers. Although environmental concerns have augmented considerably in the last decade, these concerns were already present in modernistic architecture such as in the work of Patrick Geddes, Le Corbusier and CIAM, Frank Lloyd Wright, Jean Prouvé and Buckminster Fuller. Whereas the modernist movement tried to resolve both social and ecological concerns with form and mass, nowadays (ecological) architects regards these issues more on material level (Khan & Allacker, 2015). There exist damage-based models and benefit-related models. Damage-based models measure the environmental impact of a material by means of a life cycle assessment (LCA) while benefit-related models such as Circular Economy aim to develop or improve sustainable products redefining the current make-take-waste economy into one where the scarce raw base materials are re-used repeatedly remaining in the cycle. The principles behind circular building is gaining attention because it holds a positive answer to the climatological problems of pollution, resource depletion, material scarcity, over-use of energy and the emission of airborne carbon and other gases (van der Lugt, 2006). The principles of circular economy as well as the role of bamboo are outlined in this section and in chapter 7 the LCA of two different bamboo columns is calculated. According to the Dutch architect and priest Van der Laan, the housing process has four interrelated elements it consists of: nature, home, man and material. Materials can be obtained from nature, houses are built with these materials and men live in these houses. When applying natural materials in their original form the interrelation is the most obvious and 'pure', opposed to complex, processed materials such as concrete or steel, as currently used in the conventional construction industry (González-Diaz & Garcia-Navarro, 2015).

Circularity seen as a 'closed economy' where resources and output remain as long as possible a part of the economy, was already discussed as soon as 1966 by Kenneth Boulding. Although Boulding did not actually use the term circular economy, he discussed a cyclical system that recycles finite resources and simultaneously tries to attain zero waste. He had the insight that it was unsustainable to continue to consume in a linear way (Boulding K.E, 1996). The 'Limits to Growth' report by the Club of Rome in 1972 shared the same notion, as they warned that resource depletion could eventually bring down the global economy (Pauli, 2010). The cradle-to-cradle movement started by McDonough and Braungart claim the original ideas behind 'circular building' (McDonough & Braungart, 2002), but also the Blue Economy movement initiated by Professor Pauli took 'circular building' as a concept a step forward, signifying an important source of inspiration to the current movement. The Blue Economy takes another approach on circularity by viewing the process as a loop with many branches and interconnections rather than a closed circle running from one point to another (Pauli, 2010). The Ellen MacArthur foundation also attributed new ideas to circularity. They state that the use of finite materials should be the responsibility of the manufacturer rather than the end-consumer who leases the products instead of buying. They also view a circular economy in two types of cycles as illustrated in Figure 4.5.

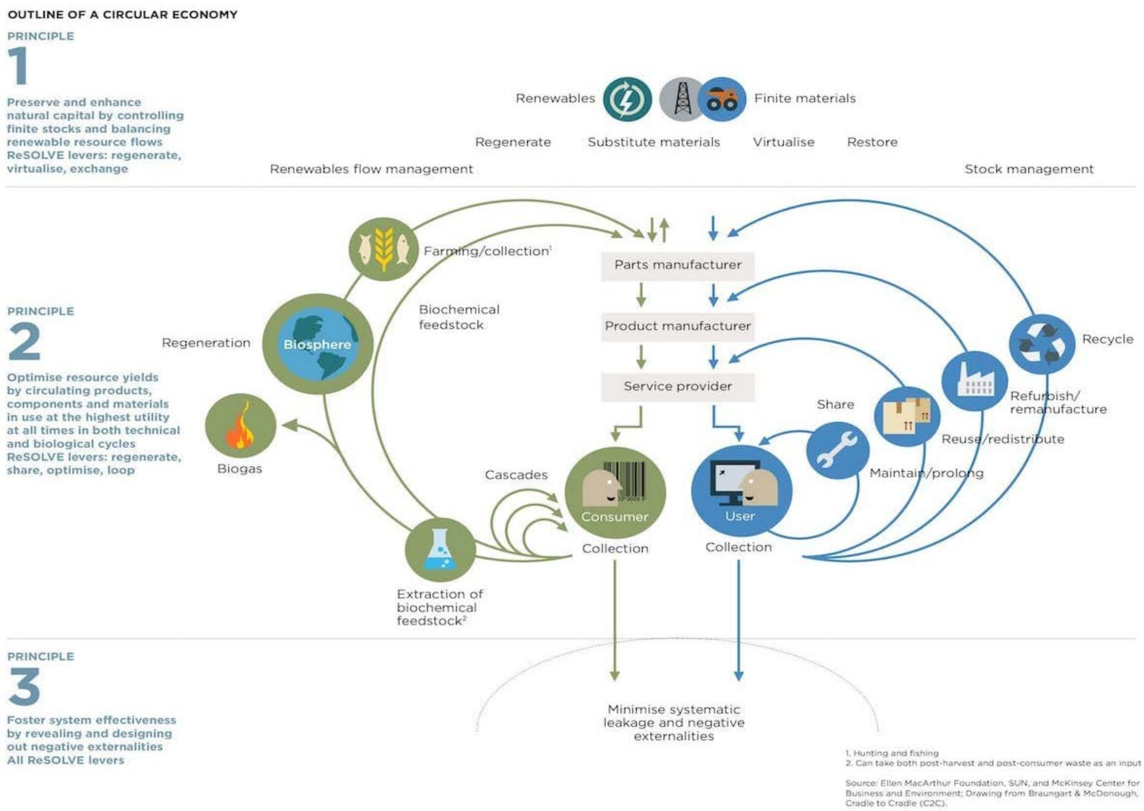

Figure 4.5. Outline of a Circular Economy. Retrieved from the Ellen MacArthur Foundation website on 02 April 2019. http://www.ellenmacarthurfoundation.org/circular-economy/concept/infograpic.

The techno-cycle departs from finite materials such as metals, plastics and minerals. Because these input materials are finite, a long-life cycle is recommended by re-using, repairing, refurbishing, remanufacturing and recycling as opposed to a linear process that has a large (new) resource input whilst creating waste, pollution and emissions at the end and beginning. In the bio-cycle, bio-based materials are used as input that after use return to the ecosystem as biological nutrients, that regrow into new bio-based materials. Whereas in the techno-cycle a long life cycle is required to be sustainable, in the bio-cycle also short-cycle applications are sustainable because of the renewable character of the input materials. Bamboo is a bio-based material that is grown and extracted from nature and after use, it can be biologically decomposed and re-grown, it is naturally part of the biological circle. In this regard, it is essential not to 'pollute' the bamboo culm along the line, for example by adding ecologically undesirable nutrients during its growth, treating it with polluting/toxic chemicals, jointing it with inseparable non-biological elements such as concrete or laminating it with toxic glue. Only then, bamboo is able to return into the biological cycle as compost or biomass. On the other hand, bamboo can also be considered being part of the technical cycle where it is important to ensure an as long as possible life-span by doing maintenance, repair, reuse, recycle, etc. (Ellenmacarthurfoundation.org, 2019; van der Lugt, 2017). Disadvantageous is that the bio-cycle does not take into account material scarcity and assumes an abundancy in renewable materials. Nevertheless, the annual yield of bio-based products is limited to a certain degree. When demand is becoming higher than can be reproduced naturally, this also leads to depletion. This is already the case for hardwood. There exists a high demand for hardwood because of its good technical performances, yet hardwood is susceptible to deforestation because of the slow growth and long rotation cycle. Despite the fact that for softwood from more temperate regions this is not the case as the net area of forests in the Northern hemisphere is slowly increasing, it illustrates that even regrowable resources have their limitations. Factors such as overexploitation and competition with other land uses play an important role. Fully switching to bio-based materials is not yet an option (van der Lugt, 2017).

As bamboo meets many of the circular requisites, it may appear that every bamboo building fits the principles of circularity. This is however not the case if the design does not permit for maintenance, repair or adaptability. In the evaluation framework, these issues will be weighed in order to advice the user regarding the level of accordance to the principles of circularity. What kind of jointing material (steel, wood, rope or bamboo) or jointing techniques (e.g. with concrete inside the node) is used, the possibility of separating added materials afterwards, the possibility of adapting to another configuration, the possibility to do maintenance, etc. When constructive elements are intrinsically interwoven, it is difficult to take out one bamboo member for repair or replacement. All these factors determine whether a certain design aligns better or worse to the principles of circular building. Rope lashings and a simple screw-unscrew system with hex nuts and washers (or a click-system like LEGO-blocks) are preferred over fixed connections with glue or concrete (Vandenbroucke, 2016). Despite the fact that bamboo is a bio-degradable and non-polluting material, these other aspects play a considerable role in the sustainability as well.

In order for ‘circular’ techniques to be integrated in the conventional building industry, it has to be price competitive. There is only a certain percentage of cost-increase a customer will consider when opting for a sustainable material. Currently, bamboo architecture requires specialized craftsmen as well as a considerable longer construction time compared to conventional building techniques. Only when prefabricated with dismountable, easy-to-connect and adaptable connector pieces, the cost and construction time can be reduced, converting bamboo into a viable option. When bamboo columns and beams, with or without the joint already attached, could be provided in standard measurements in a standardized quality, the market-potential could be considerably high. Even a complete wall-system including insulation and a finishing layer, could be developed in a similar plug-and-play setup. This way an entire house can be built in a contemporary way utilizing bamboo. Moreover, when prefabrication is done in a controlled environment specifically designed to manufacture and assemble the individual prefabrication components, it allows for more quality control (VIA Technik, 2019).

Circularity also considers the phase after production or construction in order to close the loop. Hence, maintenance, repair and end-of life of bamboo are equally important aspects. Given the fact that nearly every type of bio-based material in a construction requires maintenance, this factor should be calculated in advance. It can even become a business opportunity to the manufacturer or contractor when maintenance is regarded as a part of a remunerated contract or even offered as a ‘service’ where the bamboo construction is ‘rented out’ and therefore well-maintained for it would be in best interest of the ‘owner’ to provide a construction with an as long as possible lifespan. Similar to how lighting, water or a car is now offered as a service, where no longer the product or installation is bought but rented. Maintenance can become a part of the building contract and even the design itself. For example, in the Mosque of Djenné rodier palm sticks were permanently provided in order to facilitate yearly repairs (Figure 4.6). Integrating maintenance could offer a business opportunity within circular building (Harper, 2019). Another advantage in the concept of offering a bamboo construction as a service to a client, is the fact that it takes away the insecurity of the material because the client is no longer responsible for possible construction defects, repairs or maintenance. He pays only his monthly fee with no financial excesses.

Figure 4.6. Mosque of Djenné. Radical Architecture Climate Change. Retrieved on 11 June 2019 from an online article by P. Harper. http:dezeen.com/2019/06/11/radical_architecture_climate_change-opinion-phineas-harper.

There exist various end-of-life possibilities for bamboo such as reuse or recycling into fiber or particle boards, laminate d or other processed materials, bamboo paper, bamboo textile or as concrete reinforcement. For these applications, bamboo is broken down to its fiber-level (van der Lugt, 2017). The actual reuse of the whole bamboo culms in another construction is not the most desirable option because the structural integrity of the bamboo culms has often been modified (e.g. drilling holes, cracks, deterioration…). Nevertheless, for reutilization in the exact same structural form, such as for example in a temporary, demountable construction, this does not pose a problem. Another viable end-of-life application is its incineration in order to generate energy (biomass). This reduces the need for other (carbon-intensive) resources for example fossil fuels to produce energy and therefore has a positive effect on the carbon footprint.

4.1.4 Conclusion

It can be concluded that the environmental benefits of bamboo outweighs its environmental vulnerabilities. Bamboo´s potential for reforestation combined with its fast growth and associated high amount of carbon uptake and high yields have a positive impact on the environmental performance. Bamboo can be employed to bring degraded land back into production because of its extended rhizome system and water retention qualities. Its fast growth rate results in high productivity of the land, which is important due to land scarcity. The fibers are highly versatile and suitable for use in various industries. The carbon storage and sequestration rate is high, yet carbon is only secured in the stem after harvesting. In applications where bamboo can substitute carbon-intensive materials such as concrete and in particular PVC, steel and aluminum, this would result in a large CO_2 reduction through substitution. Environmental aspects that require attention are the treatment method used, nature of transport utilized and the invasiveness of the plant. Bamboo is a vulnerable natural material and without consideration of insect attacks and rot fungi, it can deteriorate rapidly. Treatment prolongs the service life of bamboo considerably, however it has to be weighed versus the environmental impact. Whereas traditional techniques demonstrate a low environmental impact, these techniques mainly offer short-term protection. When highly toxic chemicals are used, a guarantee of 50 years can be given. To conclude, boron should be regarded as the treatment chemical of choice due to its efficacy, low-cost, low mammalian toxicity and ease of use (Kaminski et al. 2016).

For the evaluation framework, it is concluded that both the treatment method and the influence of the design on the protection of bamboo need to be integrated in the evaluation framework (chapter 8). Boron for example is high soluble in water and can easily be washed out. Therefore it must be protected from rain by keeping it indoors, covered and elevated from the ground (Kaminski et al, 2016). When highly toxic chemicals are required to withstand outdoor conditions, this negative impact on the environment must be included in the evaluation framework. From this section, it also becomes clear that the following aspects need to be included in the evaluation framework: transport distance and means, invasiveness of bamboo and sustainability of the management of the bamboo plantation.

4.2 **Economic Performance**

4.2.1 Economic benefits of bamboo

4.2.1.1 Market growth

The economic value of bamboo is already significantly high, especially China that is leader in the production as well as the export of bamboo products. According to van der Lugt (2017), the global trade in bamboo and rattan is worth 68 billion USD, consisting mostly of domestic sales in the producing countries such as China, Brazil and India. Unfortunately, exact and reliable statistics do not exist because of the multi-functionality of the material, the different nation-customs codes on the basis of which this trade is measured and the fact that many of the economic activities related to bamboo products are not officially registered. In comparison to timber, these numbers are relatively moderate. The wood industry registers a global export value of 226 billion USD. With a forecasted increase of the worldwide population from 6,1 billion in 2005 to 8,9 billion in 2050, the need for housing and inherently construction materials will rise proportionally and as the production of wood is associated with forest depletion, the market is advocating for more sustainable materials. Bamboo is considered as a viable alternative to timber and therefore a growth rate of 5% is estimated resulting in a global market value of 75.5 billion USD by 2020. In a study, already performed in 1981 by Janssen, the similarities/differences between bamboo and other construction materials for strength and stiffness are pointed out. Because of the lightweight of bamboo, the ratio strength by weight in volume is the highest (Table 4.3). Although bamboo and wood are both heterogeneous and anisotropic, bamboo is regarded upon as a more unstable option than wood and even more when compared to the 'industrialized' materials such as steel or concrete (Manandhar et al, 2019). Despite bamboo´s reputation as a poor man´s timber, a shift is slowly occurring through new and higher added value applications, which can become crucial to rural and poor communities where bamboo is abundantly available. Bamboo can help to generate regional economic development and even meet local demands for housing and energy (Lobovikov et al, 2007; van Belzen, 2019; Vos, 2015).

Comparing the efficiency of materials for strength and stiffness

Material	Strength (Nmm^{-2})	Weight by volume	Ratio*	Stiffness (Nmm^{-2})	Weight by volume	Ratio*
Concrete	8	2400	0.003	25000	24000	10
Steel	160	7800	0.02	210000	7800	27
Wood	7.5	600	0.013	11000	600	18
Bamboo	10	600	0.017	20000	600	33

*Ratio = strength or stiffness / weight by volume, Janssen (1981)

Table 4.3. Comparing the efficiency of materials for strength and stiffness. Retrieved from Bamboo properties and suitability as a replacement for wood by R. Anokye et al, 2016. p.73.

4.2.1.2 Versatility of bamboo

The application possibilities of bamboo are numerous, diverse and new products continue to be developed, mainly engineered ones. These versatile possibilities directly affect bamboo´s economic performance. Even more within a holistic framework where every part of the bamboo culm is used for a particular purpose. Figure 4.7 illustrates how a full bamboo culm can be utilized. In China, bamboo plantations sell half fabricates to various bamboo product manufacturers often active in different sectors ranging from paper, food, chopsticks to biomass, charcoal or clothing. By doing so they can utilize 85% of the entire bamboo (van der Lugt, 2017). Hereafter, the most known and important applications are summed up with a focus on Brazil. It is however not the scope of this research to give a limitless overview.

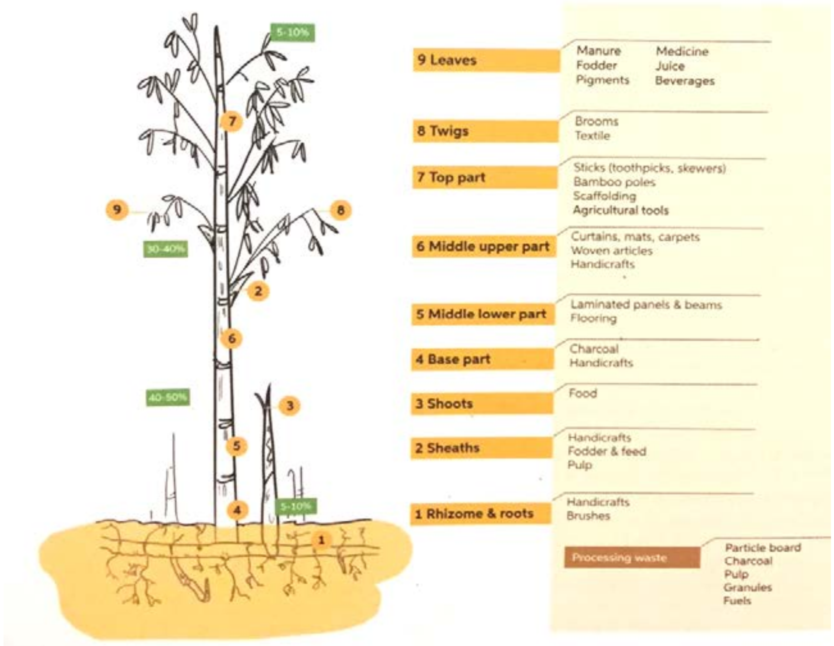

Figure 4.7. Utilization of the full bamboo culm. Retrieved from Booming Bamboo (p.52) by van der Lugt. 2017. Materia Exhibitions.

Biomass: bamboo biomass energy has much potential to become an alternative to fossil fuels. It can be processed in various ways: either by small-scale energy production where through gasification a clean gas is created with charcoal as a by-product or a large-scale power generation with a conventional combustion process, producing both electricity and heat. Currently, the scale of bamboo biomass production is small and lacking a general methodology. Nevertheless, the interest in biomass from bamboo is growing. Amongst others because biomass from wood is under discussion as it encourages deforestation, land degradation and diversity loss. Biomass production is currently researched by different Brazilian companies because bamboo possesses good fuel characteristics. However, bamboo biomass can never fulfill the demand for energy on its own and has to be regarded upon as a complementary solution (An Ha Truong & Thi My Anh, 2014).

Scaffolding: in Asia, especially in China, bamboo scaffolding is well known and economically relevant. The majority of the skyscrapers built in Hong Kong and much of Asia uses bamboo scaffolding. The bending resistance against wind forces is superior to steel scaffolding, the lightweight is beneficial for it facilitates the work and it is very low-cost. Bamboo is strapped together with plastic ties and crews are able to construct up to 93m² of bamboo scaffolding in one day. To protect the structure, nylon gauze is sometimes draped along the outside. Nowadays the safety regulations have been tightened and bamboo scaffolding is used less (Wang & Guo, 2000).

Charcoal: bamboo charcoal can substitute wood or mineral coal as its calorific value is better than that of wooden charcoal. Moreover bamboo grows faster and consequently has a shorter rotation process, it is cheaper and easier to produce. Bamboo charcoal is attained by pyrolysis just like regular coal, but its replacement thereof is of great value in regions (or continents) that suffer deforestation. In Brazil, it is being produced as a pilot project in the state of Alagoas (Moraes et al., 2012). The filtering capacities of active charcoal have been tested in a sewage treatment plant because the absorption capacity of bamboo charcoal is six times higher than wood charcoal. Besides cleaning the environment, activated charcoal can also be used as a deodorant, purifier, desinfectant, medicine, agricultural chemical and an absorbent of pollution or excessive moisture. The culm, the branches and the roof of the bamboo serve to make charcoal (van der Lugt, 2017; Lobovikov et al, 2007; Moraes et al., 2012).

Paper, pulp and clothing: the first paper made from bamboo was produced in China as early as the ninth century and the industrialization hereof was developed around 1910 in India. Both paper and cloth require pulp as base material. In order to become pulp, bamboo sheaths, branches or thin stems, mainly the Bambusa Vulgaris and Phyllostachys Pubescens species, need to undergo a process of shredding, washing, depithing and chemically digesting. The production process involves the use of chemicals thereby diminishing the environmental performance. Less toxic solvents need to be developed. Whilst in the construction industry, only the first 20m of a bamboo stem is applied, the top part could be applied to make pulp. The quality of bamboo paper is practically similar to that of wood. Bamboo fibers yield paper with a high tear index, yet the tensile stiffness is less qualitative. The quality of paper and cloth can be improved by refining the pulp. Whereas the paper industry uses cellulose pulp, cloth requires viscose/rayon pulp. Although bamboo cloth has many beneficial properties such as softness, low wrinkle, good thermal properties, etc., there is not much difference to other cellulose viscose. Bamboo cloth is often mixed with other materials such as cotton to get a better end result. In Bahia state, a large company produces bamboo fibers for pulp and paper. Brazil is not yet known on the international market for the production of long to medium long fibers, however they could play a more significant role in this market because of the availability of many of the suitable species (such as Araucararia Angustifolia) (Moraes et al, 2012; Anokye et al., 2016; Lobovikov et al., 2007; van der Lugt, 2017).

Bamboo panels: there exist various different types of bamboo panels; veneers, strip boards, fiberboards, particle boards, medium density boards and combinations hereof with wood/other materials. The most common species used is the fast-growing Phyllostachys Pubescens, also known as Moso. The main difference between the types of panels is the size of the strips, the positioning and direction of each layer and the density and thickness of the panel. When bamboo is laminated, dry bamboo strips are glued and then hot-pressed into a one-layer panel. Separate one-layer panels can thereafter be pressed into a multi-layer panel or a beam. For strand woven bamboo, rough fiber bundles are crushed and submerged in a resin after which they are cold-pressed under high compression in a mold. Its density is much higher than laminated bamboo and comparable to tropical hardwood. Bamboo boards have several advantages over wooden boards. Due to the rigidity of the bamboo fibers, the hardness and density of bamboo panels is similar or even better than hardwood products and in some cases suitable for heavy-duty applications. The high density of the material inherently provides panels a good fire resistance classification, up to class B. By being multiple layered and cross-pressed the shrinkage and swelling of bamboo panels is less than most solid wood species resulting in more stability. Moreover, the intrinsic elasticity of the material combined with the lamination technique enables curved forms such as for example used in the roof of the Madrid airport. Formaldehyde emissions generated by producing bamboo panels is much lower than other wood products, arriving at the E1 or E0 class, another reason why bamboo panels recently are becoming more popular. Finally, bamboo´s natural gloss gives it a smooth and bright appearance.

Bamboo panels can serve in many different applications such as walls, flooring, concrete molding, window or doors frames, tabletops, partitions, etc. Bamboo panels are produced on large scale in Asia (more specifically China), often manufactured locally as the process is relatively easy to engineer thereby avoiding transport and creating jobs in rural areas. The market has become worldwide, mainly for bamboo flooring and in a lesser amount for wall panels and structural beams (columns and girders). Several distribution centers in Europe (such as MOSO) have secured an important market position for the entire continent. Latin America is slowly following suit. Several Brazilian companies already import bamboo panels for walls and floors. Here, a great potential lies in the production nationally as all resources and knowledge is readily available once the market finds it demand (van der Lugt, 2017; Lobovikov et al, 2007; Hirshberg, 2012).

Bamboo composites: most engineered bamboo products are either laminated or strand woven. However, bamboo can also serve as a cheaper substitution for timber in composites (Siti Suhaily et al., 2013). Whereas the laminated and strand woven boards belong to conventional bio composites, there also exist advanced polymer bio composites that exist of thermoplastic or elastomer-based biomaterials and inorganic bio composites based on inorganic binders such as gypsum, cement, etc. (Mananhar et al., 2019; Siti Suhaily et al., 2013). The base material of such advanced or inorganic bio composites is zephyr. Through a mechanical or chemical separation process called brooming, long fiber bundles are isolated from their parenchyma cells and vessels. Zephyrs form an anisotropic linear block, which in a mat or mesh can be used to form a composite. Because of its excellent mechanical properties, light weight and form freedom, it is mainly applied in the automotive, aerospace, construction, and boat and sport equipment industry. As bamboo composites are a relatively new material, more research is required to improve its technical and economic performance (van der Lugt, 2017).

Bamboo beams and columns: one of the most interesting (recent) applications for bamboo is compressed or laminated beams and columns. Similar to bamboo panels and composites, this is a high-quality engineering material with high strength and stiffness, even more so than the original stem. It is stable in both dry and moist conditions and the strength to weight ratio exceeds that of steel, aluminum, cast iron, timber or concrete (Anokye et al., 2016). Its disadvantage is the high-energy consumption during compression, the transport and the toxicity of the glues used. The recent evolution to reduce the toxicity of the glues can signify a boost for the development of new competitive construction materials, especially because it has the same orthogonal qualities as other load-bearing building materials with a higher density and strength. In China Glubam, a trademark developed by national and internal universities, is already employed in a pedestrian bridge, a roadway bridge and a two-story house (Xiao et al., 2014).

Food: the nutritive properties of bamboo shoots are remarkable. It is rich in vegetable protein, fibers, calcium, amino acids, B1, B2 and C vitamins. Over 200 species provide edible shoots, nevertheless mainly the Phyllostachys and Dendrocalamus genders. Again mainly China sells bamboo shoots for food. Cooked and stored, it can be shipped globally In the São Paulo region they sprout around September-November and January-March. (van der Lugt, 2017).

Others: since nearly all that is made in steel or wood can be replaced by bamboo, there also arise unexpected uses, such as the example of the Edotco telecom tower in Myanmar shows. The Axiata group, in collaboration with the Yangon Technological University, placed a bamboo tower with telecommunication satellites atop a skyscraper in Thanlyin Township as a test case, and calculated that when replacing all of their towers into bamboo towers, they could reduce their dependency on steel by 80 percent, thereby decreasing their carbon footprint by 70 percent. The research showed that the tower could handle windstorms up to 195km/h and the total cost of the structure is 70 times less than their other towers made in steel, with a useful life expectancy of 10 years (due to its exposure to the weather-elements) (Waring, 2019).

Regarding the lack of orthogonality of bamboo, a Colombian technique can also be mentioned. By placing a triangular adjustable metal frame over the shoot of a Guadua bamboo, no higher than 1m, it was found that the bamboo grew in that triangular shape, augmenting the surface area for laminating strips afterwards. Similar tests have been done with rectangular molds in order for the stems to grow accordingly, however the results in this case come nowhere near the straight forms of cut wood (Vos, 2015).

4.2.1.3 Local income generation

Bamboo plantations are mainly located in (sub) tropical countries; hence an increase in the production of bamboo products directly generates more income for the people in these regions. Unlike wood, bamboo has the advantage that it lends itself to continue harvesting since bamboo harvest is selective (Janssen, 2000). However, in order to create a durable market, sustainability and value addition could appear to be essential aspects. Sustainability not only because of the resource depletion but also to avoid or at least diminish harmful emissions that go along with the production of non-renewable materials, leading to diseases that are expensive to treat and therefore block a healthy economic context (Manandhar, 2019). Regarding added value, the case of Japan illustrates this well. In most Asian countries, bamboo is a cheap construction material because the wages of the people harvesting and treating it are extremely low. In Japan however, one of the few exceptions in this region, salaries are too high to compete with its neighboring countries. Nevertheless, Japan has the largest amount of patents on processed bamboo worldwide. By adding value, it allows the harvesting cost to be sustainable (Xiao et al, 2014). This could creae a durable market where the wages would rise in the entire region. It should be studied what exactly the added value for bamboo stems in construction could be. One clear solution would be to prefabricate bamboo modules on demand in the country of origin. This not only increases the return on bamboo for the local community, it also decreases the cost for the industrialized countries where they will be applied. Whilst mass-production and prefabrication result in benefits for the construction industry in terms of speed, cost-reduction, predictability and efficiency, it provides jobs and generates income in the South. Even though the cost of the raw material is low, local communities can benefit from adding labor for treating, processing and prefabrication. On a social level, they can apply their bamboo knowledge to erect community buildings (Golden, 2018). This can also be translated to Brazil. For example, plantations located in rural areas where salaries are lower can benefit from a similar process by prefabricating elements or processing for the construction industry in urban areas with higher salaries. The application of bamboo in its raw form is not the most relevant bamboo product. Engineered products such as composites, laminated or strand woven bamboo panels are presumably more important products that can help to modify the above-mentioned paradigm (Siti Suhaily et al, 2013). The integration of product development, possibly even involving western designers, could be crucial to the success-rate (van der Lugt & Lobovikov, 2008).

Another addition to the value chain could be laboratory testing and codification. As discussed in section 3.3, there exists a lack of a globally accepted codification norm for bamboo in construction. Only in countries with a proper codified system such as Colombia, Ecuador, etc. can be built officially with bamboo without any requirements for extra testing. However, in most western countries and even in Brazil this is not the case and every individual bamboo project needs to undergo a series of tests, raising the construction cost considerably. Because testing also tends to be more cost-intensive in industrialized countries than in lower wages countries, a (controllable and labeled) laboratory facility could be added to the local producing value chain. The bamboo culms could be transported already codified and ready to be used, preferably with connector pieces already pre-assembled thereby augmenting the price per bamboo-element (= local profit). If a worldwide recognized certification system such as FSC or PEFC for timber, would exist for bamboo, the safe use and inherently its popularity would be guaranteed (van der Lugt & Lobovikov, 2008). Not only local revenue would be generated, also certified and safely produced products would be brought onto the (local) market.

According to prof. Hebel from the Swiss Federal Institute of Technology Zurich, bamboo has the potential to completely shift international economic relations as bamboo predominantly occurs in the developing world: '*no pre-existing industrial infrastructure exists to skew things towards the rich world. The past century has seen an unprecedented transfer of products and predefined solutions instead of capacity building programs from the rich countries to poor under the rubric of development aid. The economic incentives for the former are obvious. When developed nations introduce, for example, their reinforced concrete technology to developing nations, those countries must also acquire the proper machinery, the technical expertise to maintain them, and the building materials suitable for those machines, and they must buy all of those things from the developed countries.*' (Hebel, 2014, web article).

Whilst this statement obviously divides the world in producers and consumers, there exists a possibility for materials such as bamboo to break this paradigm. Resource materials that are only available in developing countries can enter the market without the need of machinery from developed countries. In this regard it is essential (and beneficial to both) that the value chain should be concentrated as much as possible in the producing countries; from harvesting, treating, processing, prefabricating to certification. The least interesting way of valorizing bamboo is to simply export it as a raw material, without any further value addition, for this again would turn the advantage in the other direction. Hebel (2014) points out that steel illustrates perfectly the above mentioned statement on the consumer-producer relationship worldwide. While due to their growing population and development rate, developing countries nowadays are using up to 90% of the world´s cement and 80% of its steel, few of them actually produce it. Out of fifty-four African countries, only two produce steel for construction. Bamboo, as the 'vegetal steel', could modify the way this dependency works. From this economic perspective, developing countries (a classification Brazil is slowly escaping from) would benefit greatly from investments made in the research and implementation of this new industry (Hebel, 2014). Nevertheless, some hurdles still have to be taken as engineered bamboo products from developing countries (besides China and Japan) currently suffer from low quality and often with aesthetics that do not fit the western market. Moreover, high amounts of toxic chemicals for the preservatives as well as the glues and resins are still being used. Further professionalization of the market can offer resolution (Koren, 2010).

4.2.1.4 Cost reduction through prefabrication

Mertens (2019) interviewed Elora Hardy from Ibuku on her view on bamboo as a poor man´s timber. Mrs Hardy points out that even though bamboo is less expensive than other construction materials, they have to charge it as a luxury product because of the complex procedure involving many independent parties; harvesting, treatment, design, engineering, construction, furniture and follow-up. According to Mrs. Hardy, they charge prices similar to other luxurious villas (Mertens, 2019). This illustrates the fact that it remains a challenge to build cheaper with bamboo than with the conventional technologies and materials. The high degree of craftsmanship, artisanal connections and detailing prevents mass production that could significantly reduce the building cost. A solution to this inconsistency could be to prefabricate modular elements as such already exist in the timber industry. Prefab housing is characterized by construction quickness, functional flexibility and energy efficiency (Leoncini et al., 2017).

Van den Dobbelsteen et al. (2005) researched a bamboo bridge built in the Netherlands and compared the building cost to that of other materials such as timber, concrete and steel. It was found that bamboo was the least expensive building material, even with transport cost included. However, when considering the long life span of steel compared to the shorter life span of bamboo, steel turned out to be the cheapest (van den Dobbelsteen et al, 2005). It has to be noted that this bridge was built without any physical protection, which is the worst condition bamboo could be brought in, thereby reducing its life span considerably. Harper (2019) advocates to review maintenance as an architectural paradigm-shift, including it as part of the design and cost-calculation of a building. When maintenance would be integrated in the design, bio-based materials could regain their position in architecture and engineering they have lost in the last 150 years (Harper, 2019). The research by Van den Dobbelsteen et al. however does not take into consideration the embodied energy required to produce steel. When the embodied energy required in the construction process would be calculated in economic terms, the eagerness of designers to apply bio-based materials such as bamboo would also increase significantly. The highest cost of the bamboo bridge appeared to be the high labor cost of assembly (van den Dobbelsteen et al, 2005). In order for bamboo to have a future within the construction industry, more research is needed on how the construction process can be simplified and accelerated, most likely by ruling out artisanship (Vos, 2014). Besides the higher cost in assembly, also the avant-garde status of bamboo architecture requires the need for expert consultancy, extra calculations by engineers and extra (codification) testing. These costs can be identified as learning costs with an incidental character. According to the study of Van Den Dobbelsteen et al. (2005) these extra costs are caused by three main factors; the round, hollow and tapering shape of the material, the irregularity thereof and finally the lack of building codes or standardization. In an optimal process, these costs should be avoidable, especially when the provider of bamboo adds value to its chain by certifying and prefabricating the material before transport.

Governments could reward carbon-low building techniques in tenders as well, augmenting the chance for a bamboo building economy to emerge (van Belzen, 2019). Whilst in countries such as Brazil this is currently not a political topic, it is so in many ‘western’ countries. The Netherland has recently (2019) paralyzed the entire building industry. Many new building sites were halted for not meeting the standards laid out by the government on CO_2- and other harmful emissions. In such a context, real-estate developers might start seeing the need for the implementation of more sustainable techniques for this would ease the permission process, saving both time and finances (VPRO Houtbouwers, 2019). Even in a development context where labor-cost is less relevant, simplifying and accelerating the construction process remains relevant because the expertise needed for artisanal connections is not always present and therefore costly, or inaccessible to poor communities that aren’t knowledgeable or taught in these artisanal techniques (as opposed to easy-to-understand IKEA-like prefabricated jointing techniques).

An economic benefit of prefabrication is the seriality and industrialization process that minimizes the cost of production and installation and minimal work on-site. It is ecological because energy efficient criteria can be met using low impact materials and material waste created during the construction process can be reduced (Leoncini et al., 2017). The University of Melbourne calculated that by the optimization of sizes, material loss by cut-offs could be reduced up to 52%. Hence, the mere fact that production is being done in a quality controlled factory environment makes for a safer, easier, faster and cheaper product. The question rises what type of prefabricated elements should be best provided, ranging from structural members, multilayered panels with a framed bearing structure up to entirely prefabricated volumes. A module’s shape and size can vary to suit a desired architectural plan, where the dimensions may only be limited according to the transportation arrangements (Gunawardena et al., 2014). The choice between these options will likely depend on the specific context. However, care has to be taken that there remains a high degree of design liberty, both architecturally as well as structurally. Prefabrication of the structural members offers architects the widest range of possibilities and great adaptability. When the members are provided with a universal jointing system, it allows for connections in multiple directions and situations within any building context. Key Performance Indicators (KPI) should be identified in advance, after which these indicators are assessed to come to an optimal solution (Gunawardena et al., 2014). A point of attention is the structural engineering of a pre-assembled module. Besides the structural design for static and dynamic (lifting) loads, structural cross bracing needs to be provided adequately in relation to the total weight and size for transportation (Ham & Luther, 2014). Going to smaller constructional prefabricated members, the problem of de-contextualization is diminished. The user can adapt the frame to their own (cultural) context, desiderata, design or budget (Leoncini et al., 2017). In this context, the Concert Hall in Nuremberg is worth mentioning as it is designed as a modular building. Standardized elements were used with enough flexibility to form the different parts of the building, whilst repeating the same cubic proportions (Figure 4.8). The result is completely laminated timber buildings that can be modularly adapted afterwards when needs are changing.

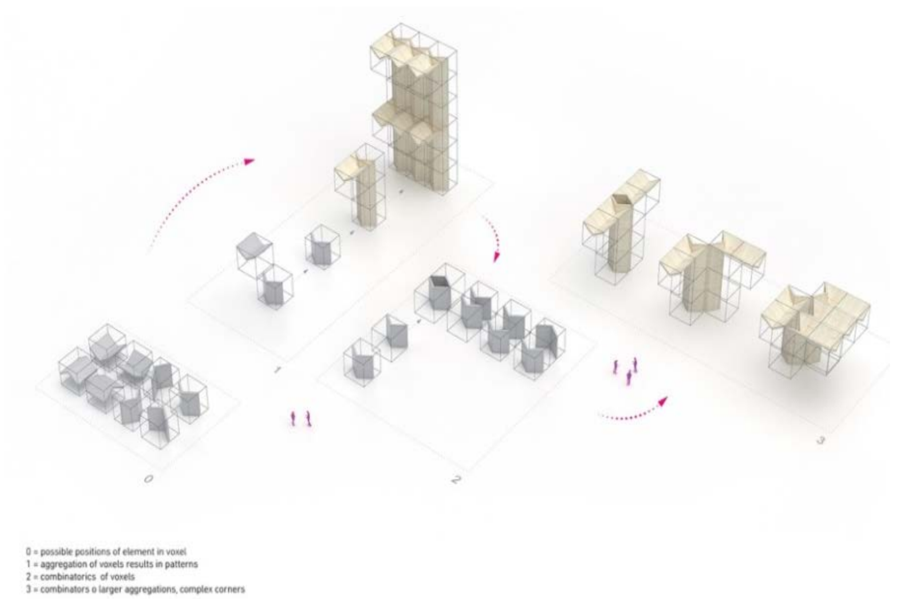

Figure 4.8. Concept drawing for the Nuremberg Concert Hall by Gilles Retsin Architecture. 2018. Retrieved on 21 June 2019 from https://www.retsin.org/Nuremberg-Concert-hall.

Another important issue is the market that needs to be targeted because this enfolds a profound difference e.g. the local market versus the Western market or the humanitarian sector? Especially the latter has already much experience in working with modular, easy to deploy and prefabricated systems as they seek to (re)build many houses at a high speed. However, there already exists a plethora of different organizations and prefab systems ranging from tents to more elaborate refugee shelters or small houses. Even Ikea already deployed ´Flat Pack Shelters’ for Syrian refugees (Cameron, 2013). Not only large companies or organizations commit themselves, also architects as well. Shigeru Ban has set up the ´Voluntary Architects Network` which has designed various displacement-related shelter projects in countries such as Rwanda, Italy, and Nepal, using unconventional building materials like cardboard and paper tubes (Lynch, 2017). For a project in India in 2001 (Figure 4.9) Shigeru Ban designed a paper log house where he combined cardboard tubes with bamboo. For the roof, split bamboo was applied to the rib vaults and whole bamboo to the ridge beams (Archdaily, 2020). Moreover, Ibuku has recently undertaken a series of modular bamboo homes for the garbage collectors in Denpasar, the capital of Bali and the main gateway to the island. Bamboo is employed for the floors and walls while recycled bottles and tetra pack packaging was used for the roofing and insulation (Figure 4.10) (Grozdanic, 2017).

Figure 4.9. Paper Log Houses in India designed by Shigeru Ban. 2001. Retrieved on 26 February 2021 from www.archdaily.com/489255/the-humanitarian-works-of-shigeru-ban. Copyright Kartikeya Shodhan.

Figure 4.10. Bamboo homes for garbage collectors in Denpasar, Bali designed by Ibuku. 2017. Retrieved on 26 February 2021 from https://inhabitat.com/ibuku-unveils-modular-bamboo-homes-for-garbage-collectors-in-bali/

4.2.2 Economic challenges of bamboo

4.2.2.1 Economic dependency of a natural, incontrollable material.

An important challenge to an economy based on bamboo is the fact that bamboo has a remarkable peculiarity namely its flowering. Bamboo blossoms with intervals as long as 60 to 120 years. However, when a specific species starts to flower, it flowers simultaneously, whereafter the bamboo produces fruit (called ´bamboo rice` in China and India) and shortly thereafter dies. Since a bamboo forest usually grows from a single bamboo, the death occurs in a large area and is therefore called mass flowering. This flowering can be devastating to entire economies that depend on this species, as cases in India have already shown. In 2018, there was a mass flowering of the economically important species Moso (Phyllo. Pubescens), followed by a large flowering of another important specie for basket weaving, locally named Suzutake. Until today, scientists do not understand how this flowering happens globally at the same time and why the species afterwards massively dies (Anokye et al., 2016). Nevertheless, it emphasizes the necessity in diversification between the species. In the construction industry, mainly the species Guadua (Angustifolia and others), Dendrocalamus (Asper, Giganteus and others) and Phyllostachys (Pubescens, Aurea and others) are used and it would be wise to be able to switch between those in case of such (unpredictable) event occurs.

Another weakness of bamboo is that it is very susceptible to biotic and abiotic attacks. (A)biotic attacks by insects, fungi or decay by weathering are discussed in section 4.1.2. Despite the fact that a proper treatment and good construction design can aid to maintain bamboo culms in a good condition, bamboo can deteriorate in a short period of time whenever one of multiple of these conditions are not fulfilled. In the worst case, bamboo is attacked as such that it even comprises the entire construction. The cost for treatment or replacement of the attacked bamboos can be considerable depending on the specificity of the construction and is therefore considered as an economic threat.

4.2.2.2 Health and environmental issues

Besides the chemicals used as preservatives (discussed in section 4.1.2.), also the application of toxic additives in engineered bamboo products can lead to health and environmental implications. Much of the shape-forming capacities depend on the glue that is used to make these shapes permanent. As the current consumer become more aware of health and environmental issues, a manufacturer should pay attention for it can economically ruin a business as was the case in a recent scandal (December 2019) concerning reusable bamboo drinking mugs. Whilst bamboo, given its ecologic image, was used as a sales argument, insufficient attention was given to the toxicity of the melamine resin used to shape the cups. The German Federal Institute for Risk Assessment warranted an alert that these cups could not be used for hot beverages, because they leach melamine and formaldehyde. Melamine resin is a polymer and in itself not toxic, but its components; 1,3,5-triazine-2,4,6-triamine and formaldehyde that are released when heated are toxic and carcinogenic when used on daily basis (Krämer, 2019).

For lamination, commonly two processing methods are used; bleaching (chemical treatment) and caramelization (hydrothermal treatment). Although these processes replace the need for a preservation treatment since during both processing methods the sugar and starch content in the bamboo is removed, other (non)toxic products such as formaldehyde, melamine, cyan uric acid, iso cyanates and aluminum oxide are commonly added. Not just in bamboo but also in laminated timber products. These strong adhesives have to be used to keep the fibers together while resist to heat and moisture. Hence, natural laminated flooring does not exist because nature does not produce this kind of glues and the industry has not invented a non-toxic adhesive yet. The same can be said for bamboo fiber composites where the fibers need to extracted either chemically (alkali or acid retting or degumming), mechanically (steam, crushing or roll milling) or a combination of both. When the fibers are extracted from the bamboo, they need to press together under high pression while adding polymers or epoxy (Md Shah et al., 2016; Sharma et al., 2018). According to the tendencies towards sustainability and better consumer awareness, care has to be taken to sell processed bamboo products using toxic adhesives while promoting them as highly ecological. Moreover, the use of preservatives and the handling of treated products need to be assessed carefully for it poses potential risks to humans, animals and the environment (Nurdiah, 2016).

4.2.2.3 Raw material depletion

Due to newly developed bamboo products (bamboo flooring, composites, etc.) in industrialized countries, the relatively high cost of timber and the current tendency towards sustainability, the demand for bamboo is growing thereby increasing the cost of the material. A higher demand for bamboo can lead to serious depletion of bamboo and even deforestation (Manandhar et al, 2019). A study conducted in the northeastern Yunnan province of China showed that one of the major reasons for the decline of bamboo forest was caused by extensive logging of mature bamboos and ravaging of shoots (Wenyuan et al. 2006). Care has to be taken that the success of this bamboo economy, does not lead to over-harvesting or premature harvesting (Manandhar et al, 2019).

4.2.3 Conclusion

There are no exact data on the size of the worldwide bamboo economy available due to its informal character, the different national custom codes and the wide extent of possible bamboo products (e.g. paper, particle boards, panels, composites, biomass, scaffolding, etc.). This can mainly be attributed to the low cost and the versatility of the material and because of the current tendency by the affluent population towards more sustainability. These factors widen the possibilities for gaining a local means of income for people working in the bamboo industry whether it is in in nursery, harvesting, treatment, the construction of houses or in the production of processed bamboo products. Jobs range from low skilled agricultural jobs to higher skilled jobs that are required for the production of value-added products. Especially by adding a value to the bamboo, a higher income can be generated. The main constraint is the lack of sustainable and adequate raw material (Janssen, 2000). When the demand exceeds the supply, this can lead to over-harvesting which on its turn can lead to degeneration of the bamboo forest and/or an increase in the cost of the raw material because enterprises are forced to seek bamboo from far away with high transport costs (Manandhar et al, 2019). Producers have to ensure that the production chain can continue to deliver in case of a higher demand but also when a mass flowering should occur.

Based on the economic aspects, it can be concluded that diversification in species and proper management of the plantation are imperative criteria to be incorporated in the evaluation framework (chapter 8). Moreover, strict regulations on the use of chemicals and dissemination of information on the correct usage, disposal and precautions during usage and disposal are needed to minimize hazards (Manandhar et al, 2019).

4.3 **Social Performance**

Social performance reflects the improvement of social structures by education, expression of culture, standard of living and equalization of rights and prospects. The three pillars, people, planet and profit, are interconnected since one has an impact on the other. For example, when individuals or communities experience better economic circumstances, their social benefits also improve and environmental improvements on healthier living conditions also benefit the social performance. Because some considerations on social performance were already addressed in the previous sections, these will not be repeated. Below, the social benefits and considerations discussed are how cooperative working can augment social cohesion (reviving traditional craftsmanship), bamboo´s resilience to disaster and the benefits it can bring to small scale-businesses for individual families (growing it around the house) or to local communities (Manandhar et al, 2019).

4.3.1 Social cohesion through cooperative economy and traditional craft

Bamboo can strengthen the self-reliance of local communities. Traditional construction techniques were generally handed down from generation to generation becoming part of the socio-cultural structure (Manandhar et al., 2019). As discussed in section 2.2., Brazil lacks such a bamboo tradition, despite the fact that vernacular architecture with bamboo can be found in original Indian tribes and in the traditional 'pau-a-pique' or wattle and daub houses. Reviving such technology, further developing the technology and transferring it to those already familiar with the use of bamboo can strengthen the society (Manandhar et al, 2019). The author perceived, during the execution of the community project in Camburi Brazil, that social cohesion could be enhanced when the newly introduced techniques relied on the traditional skills and the pride in craft already present in the community. Manandhar et al. (2019) point out that since only basic carpentry, masonry tools and skills are necessary for the construction of bamboo houses, it can be easily taught to people with basic or no skills in the community. Another advantage is that because only simple carpentry tools are required to erect a bamboo construction, little capital/input of the community is required to set up a cooperative.

A good example of cooperative community construction from the (distant) past is found in New Gourna, near Luxor, in Egypt. This community project from 1948 is still exemplary because of its relevance and commendable achievements. This village was mainly built by its own habitants, who joined themselves in cooperatives, completely based on vernacular building technologies (mud and brick) (Fathy, 2000; Valverde, 2004). The mere economic fact of participating in cooperative building enterprises augments the economic resilience of poor communities (Manandhar et al, 2019). Revenues can be found within the community, but also outside when the skills of the cooperative members are sufficiently high. Multiple bamboo cooperative members from the community project Bamboostic have worked on bamboo and earth constructions outside the village for a decent wage. The cylindrical bamboo canopy for a hotel (Almada), a guesthouse (Picinguaba), the art gallery (Catuçaba), a bamboo canopy (Guaporé) and recently (2019) a luxurious private residence (Itamambuca) are examples of constructions built outside the community. Some of these were designed by the author while others are from third parties in search for skilled labor.

Any bamboo design or project could benefit from an educational frame, especially public buildings that have an obligation to social progress. When the production, treatment, developing, construction and assembly (or even design) is sourced locally, it is best developed as an educative project in which techniques, plantation but also other aspects such as regulation can be taught (Vos, 2015). With regard to community training of bamboo building techniques, the initiatives of INBAR need to be mentioned as well. INBAR stands for the International Network for Bamboo and Rattan and was initially established in 1997 by the governments of Bangladesh, Canada, China, Indonesia, Myanmar, Nepal, Peru, the Philippines and Tanzania. Currently more than 41 countries have already joined, amongst which also Brazil in 2019 (Golden, 2018; INBAR, 2007). This intergovernmental organization based in Beijing, China advocates for the application of bamboo and rattan by distributing bamboo research and developing social and technical programs worldwide.

In India, for example, the ARS program in the Tamenglong district, Manipur in India, led to the enhancement of local knowledge on building low-cost bamboo housing because the rural community could participate directly in the production of low-cost, quality housing. All parts of the building; walls with integrated doors and windows were prefabricated by the local community in a production hall. The community was trained in plantation management, treatment techniques, building techniques and all other related processes. As a consequence of the physically intensive nature of construction, mainly young men, artisans and carpenters were targeted for the participation of the project, but also women benefited indirectly through the establishment of smaller cooperatives that produced side-products such as bamboo handicrafts and charcoal (INBAR, 2007). In this training program, the process of scaling up and scaling out was applied. Whilst the success of the program attracted the interest of local governments and individuals to provide extra funding, the project was able to scale up the production capacity of bamboo-based dwellings. Due to the large local need for affordable housing (in the North of India approximately 460,000 units were needed at the time of the project start-up of which 90% located in rural areas). Production costs can be kept low because of the production capacity, with a typical 35m² house costing around US$ 2.000. Economic success was attained because the large demand provided ample return. This on its turn encouraged other rural communities to participate in similar programs, creating a regional snowball effect hence 'scaling-out'. The reach of the program could have even been extended more when government housing programs and micro-financing schemes were to be optimized (INBAR, 2007). In order to make successful start-ups possible, INBAR also advocates for the implementation of micro-credits, a system that has proven its worth on various locations around the world, with as most well-known example the Indian Grameen Bank set up by Muhammed Yunus (Yunus, 2003). Local cooperatives are assisted when their capital needs are met during growing phase, whilst pro-poor rural housing loans with achievable credit schemes enable community members to acquire a proper house (INBAR, 2007).

Another example of cooperative working in the prefab bamboo housing industry is Hogar de Cristo in Quayuaquil, Ecuador. This Jesuit Non-Governmental Organization started in 1971 under supervision of SELAVIP (Servicio Latinoamerico y Asiático de Vivienda Popular) in answer to the growing population living in shanty towns on marginal areas (INBAR, 2002). The urban immigration towards Guayaquil represented a population growth of 2,7% which created an entire 'poverty belt' around the city, urging the need for decent and cheap housing. Hogar de Cristo was a pioneer for it combines production with self-aid. The costs for the producer of the houses are kept low because the future owners themselves have to build the houses in situ (whilst receiving a basic training in advance), the materials are sourced locally and modular prefabrication is applied so that production velocity is augmented. The prefabrication process is open and light. Light because it produces bamboo panels that can be easily transported and processed with simple tools. Open technology because the system offers a great flexibility allowing the use of elements (INBAR, 2002). Because of this modular set up, the owner can, in a later stage, upgrade its house when other (familial) necessities arise or dispose over more financial means. In addition, the construction can be applied with other systems in terms of vertical or horizontal extensions. Families are stimulated to improve their housing in time. The bamboo house is just the first step in acquiring a solid, long-lasting, decent house (Inbar, 2002). Lending at beneficial tariffs and repayment conditions (micro credits) furthermore facilitates the acquisition of a house (Hogardecristo.org, 2020).

INBAR also develops ´Technology Transfer Models` called TOTEMS which are practical information resources to aid local representatives in teaching certain skills at community level, thereby assisting in their (economic and social) development. This very same Viviendas del Hogar de Cristo model was analyzed and turned into such a learning model for other communities to copy (INBAR, 2002). It was the (Jesuit) organization itself that provided the TOTEM. Both the production technology as the experience in how to make the houses available to Ecuadorian's poorest (selection and sales systems for purchasers) were described. Such TOTEMS can be a very useful tool in countries that have considerable amounts of bamboo and where a large part of the population lives in plastic or cardboard dwellings or is even homeless. Viviendas del Hogar de Cristo is considered as an artisanal manufacturing system which complies with technical conditions, assembly-line production and high levels of production reflected in the number of houses produced each day (50 houses per day) and the low production cost per house (450$ per house) (INBAR, 2002; Vos, 2015). Education plays an important role in the setup of the TOTEM´s. Aim is to produce locally meanwhile creating local knowledge for producers, users and regulations in how to deal with bamboo. Often such programs are directed to the creation of a private residence for the user. Another possible strategy is to focus on the construction of public buildings while at the same time passing on the technical knowledge to the unskilled workers whom can learn how to build their proper house in bamboo.

4.3.2 Vernacular architecture

Vernacular architecture can be defined as an architecture made without architects, informally and by empirical builders (Widyowijatnoko, 2012). Rapaport points out that it does not have any aesthetic or theoretic presumption and is in accordance with the local microclimate and traditions. Very often it is 'architecture without architects' (Valverde, 2004). Traditional bamboo buildings are part of vernacular architecture. Vernacular architecture is based on construction techniques that have been handed down over generations and that is influenced by the traditions of the respective culture and moreover based on trial-and-error of ingenious local builders in order to get to the most adapted housing for a particular climate (Zhai & Previtali, 2010). An important document to understand vernacular architecture is the 'Encyclopedia of Vernacular Architecture', which is a 4.000 pages research composed by 750 authors by the Oxford University (Zhai & Previtali, 2010).

Bamboo building techniques might be as old as civilization itself. In China, in the middle valley of the Yangtsze River, evidence of the earliest use of bamboo in construction was found. The Neolithic Daxi tribes (5000-3300 BC) constructed a large number of bamboo-mud plaster houses, and possibly even long before that, nonetheless no proof thereof could be found (Golden, 2018). Going back even further, bamboo might even have been one of the first forms of globalism. Although it probably only proliferated during the Pleistocene in Southeast Asia (3 million to 12.000 years ago), scientists have reason to believe that bamboo was propagated from continent to continent in the form of rafters, as proof was found from Bambusa Vulgaris-rafts from the earliest seafarers. In this Southeast Asian region, the raised platform house historically was, and still is, the most predominant housing typology. For example, the Bahay Kubo is a type of stilt house made from bamboo and nipa palm leaves (Golden, 2018). It is built some meters from the ground to provide protection from soil moisture and animals as well as to create natural ventilation. Also Latin America has an important tradition in building with Guadua, especially in the Colombian, Ecuadorian and Peruvian region, long before these were 'colonized' by European countries. In Ecuador, during the Valdivia civilization, one of the first examples of bamboo in construction in reinforced earthen walls was discovered dating back as far as 5000 to 3500 BC. Bamboo is also commonly used in the bahareque technique where a bamboo post and beam structure is filled with a lath covered with a mud plaster. By throwing mud simultaneously from both sides, the earth clings better to each other (Achila et al., 2012). In Brazil, this technique is called pau-a-pique, as described in section 2.2. In Colombia, mainly Manizales, there still exist two and three stories bahareque houses that originate from the 1920's (Golden, 2018). Even though vernacular architecture has fallen into oblivion, mainly after the world war when new and fast building construction materials such as concrete and steel were developed or modernized, it remains relevant to study for much can be learned therefrom. In vernacular bamboo constructions the characteristics that are specific to bamboo are optimized. These constructions even poses connections that Widyowijatnoko (2012) defines as 'original bamboo connections', for they cannot be applied to other materials. Nevertheless, designers should be careful not to merely copy/paste vernacular ideas for this could easily lead to a 'pastiche' that might even work counterproductive. Moreover, modern inventions that genuinely improve the functioning of a building should not be neglected. The cultural difficulty lies exactly on the dichotomy between globalization and vernacular, where the first is characterized by efficiency, mass production and prefabrication, and the vernacular by local climate, geography and cultural traditions. A correct balance between globalization and local culture has to be found (Valverde, 2004). Often the need for competitiveness, cost-reduction and efficiency drives out cultural construction phenomena. Designers should be careful that the prefabrication-process of bamboo constructions does not fall in the same trap and leaves ample of flexibility to add or subtract culturally determined elements.

When considering vernacular architecture, the building envelope can often be subdivided into two categories; massive and lightweight. Bamboo can be the basis of both forms depending whether it is protected or covered for example with mud such as in bahareque or pau-a-pique. Often massive walls are combined with lightweight roof structures such as thatch. The hotter and more humid a climate is, the more lightweight its building envelope. In vernacular architecture, air exchange and natural ventilation (e.g. rising of hot air, thermal mass, etc.) determine the building technology. In hot, humid temperatures, such as in the tropic zones, very often the buoyancy stack-effect is used to cool and ventilate dwellings. By raising the dwelling, the shaded area beneath it brings cool air up from under the dwelling. A good example thereof are the Toraja dwellings in Sulawesi as they are lifted high above the ground and are provided with large eaves that extend outward which gives a large shaded area all day long. The roof is foreseen with a thick insulating mass of layer upon layer of bamboo or reed, which traps cool air in one single chamber, whilst the height of the roof stratifies the heat through the buoyancy stack effect (Zhai & Previtali, 2010).

In this context, also worth mentioning is 'critical regionalism'. Kenneth Frampton regards building from a regional point of view as opposed to some modernists that are of opinion that modern buildings can be built in any region without taking into account the characteristics thereof. In critical regionalism, cultural aspects and languages of the architectural program are emphasized without literally copying architectural examples from the past (Valverde, 2004). Regionalism can only be successful once architects identify the interstices in modernity where the regional consciousness can flourish (Jameson, 1997). Another way to review regionalism is found in 'abstract regionalism' as is defined by Suba Özkan. He advocates for the examination of abstract qualities of a building or architecture within a specific culture in order to determine appropriate languages to be used, e.g. proportions, solids and voids, mass, volumes of light, structural principles, sense of space, privacy (going from public to private, use of courtyards, etc. and reinterpret these abstract ideas. Another important aspect of both the critical and abstract regionalism is the material choice as they believe that the natural environment close to the culturally determined building provides the material which is to be used, not (only) from an ecological but from a cultural point of view (Valverde, 2004).

4.3.3 Resilience to disaster

Bamboo as a building material has a positive social impact on the people affected by disasters as it can be used for fast construction of houses, either permanent or temporary, in disaster stricken areas and can aid to support livelihoods to recover from those disasters (Manandhar et al, 2019). Disasters are mainly caused by natural phenomena such as earthquakes, landslides or flooding's. Nevertheless also human destruction such as deforestation can provoke a disaster and/or trigger communities to undertake urban migration. Manandhar et al. (2019) emphasize that a natural disaster can cause psychosocial depression to the affected people or communities, often forcing them to leave behind their agricultural activities and move to urban centers where they do not stand a chance of competing in the local economy because of their lower education level.

Disasters are mainly discussed in relation to poor communities as they are the most affected due to their minor economic resilience. However disasters can also affect middle or high end residences such as for example in earthquakes. Because earthquake forces are a result of mass and the imparted acceleration thereon, the lightweight nature (high strength-to-weight ratio) and the ability to absorb energy at connections, especially if used nails, makes for resilient buildings. Bamboo has a better resilience than timber which has a higher density (Janssen, 2000; Kaminski et al, 2019). These characteristics of bamboo are also beneficial to middle-class or high-end buildings made from bamboo as these tend to be larger and often multistory, increasing its mass and thus making it even more vulnerable to seismic activity (Manandhar et al., 2019). Earthquakes in Ecuador and Colombia have demonstrated that structural bamboo members did not immediately lose their structural integrity and instantaneous repair of the affected bamboos was possible by placing fortifications, ropes or tension bands, thereby enabling these people to continue inhabiting their proper home (Van Drunen et al., 2016). Kaminski et al. (2016) however point out that even though bamboo have performed well in earthquakes, this is closely related to the fact that those dwellings were built with vernacular techniques such as bahareque that are lightweight and use nailed connections. Bamboo possesses several brittle failure modes which could affect its seismic performance and therefore it is not a characteristic which can be easily translated to modern bamboo constructions which tend to be heavier and have smaller movement tolerances. Another observation in the use of bamboo for earthquake-prone areas concerns the occurrence of fire caused by earthquakes. A Colombian research demonstrated that the popularity of bamboo as an earthquake-resistant material was diminished after the devastation caused by fire originated by the earthquake. Bamboo´s susceptibility to fire can be remediated by covering the bamboo structure with plaster or cement. Gutierrez (2004) developed a highly seismic resistant modern 'bahareque' building' using a structural bamboo frame where the walls are made of bamboo lath panels finished off with a cement-sand plaster. This specific criteria was afterwards added to the Colombian Code of Earthquake-Resistant Constructions (ICONTEC, 2006; Manandhar et al., 2019). Minke points out that the architecture of seismically resistant bamboo houses has many similarities to the requirements for houses constructed in other materials. The structure must be well-anchored to the foundation and the roof well-anchored to the walls. The roof must not be too heavy in relation to the rest of the structure. The floor plan must not be very elongated and structures of more than one volume must behave independently from one another (Minke, 2012).

Bamboo can also help against erosion because of its extended root system for example in areas that have been affected by flooding or other water-related disasters such as tsunamis. Erosion control can be done by planting bamboo in the pluvial deposits which are the result of the sedimentation of a flooding and that form adequate subsoil for bamboo to grow in (Manandhar et al., 2019). Although rather abstract, bamboo also contributes to the occurrence of climate related disasters such as hurricanes, drought and flooding by sequestering carbon and other gases that causes these.

For emergency sheltering, the low-cost and speed at which a bamboo shelter can be erected, also signifies a great benefit to affected communities. Regarding the use of bio-based materials in the production of emergency shelters, the work of Yasmeen Lari in Pakistan should be mentioned as well. This architect, that used to work with conventional materials such as concrete and steel, changed to local building techniques with vernacular materials after the earthquake and flooding's of 2010 in the Sindha Valley and the Balochistan earthquake of 2013 in the Awaran district of Pakistan. Lari, in contrast to mass-produced and prefabricated housing by humanitarian organizations or governments, uses local labor, vernacular knowledge and materials such as earth and bamboo to maximize the amount of decent dwellings. In an interview with Al-Jazeera in 2014, she advocates to not treat disaster-affected households as destitute, needing handouts, but with dignity (Archdaily.com, 2014).

Recent disasters in Brazil where bamboo could play a positive role in the restoration process are the extended Amazon fires in August-September 2020 and two dam collapses caused by mining in Minas Gerais in 2015 and 2019. Scientists attribute the fires to the warming in the tropical North Atlantic Ocean pulling moisture away from South America. The fires have not only burned deforested areas and farmland, but also virgin forest. This is a worrying trend that suggests the rainforest is becoming drier and more prone to fire. The continuous deforestation makes Brazilian Indian tribes migrate or simply succumb at an alarming rate. Indigenous people are among the most vulnerable to deforestation and fires, as they rely entirely on the forest to meet their needs for food, medicine and shelter. Forest destruction can also push them from their territories into forced contact with outsiders. This means exposure to diseases for which they have little to no immunity (Kimbrough, 2020). As discussed in section 4.1.1 on the environmental benefits, bamboo has the potential to relieve pressure from deforestation by offering an alternative to tropical hardwood and by replacing vegetation and biomass at a faster rate than trees are able to do. The two dam collapses in an iron mine caused in both cases a toxic mudflow to spread out which devastated most on its way. Humans, cattle and other animals died in the mudflow. The failure of the dam released mine tailings into the river thereby polluting it. Hundreds were displaced and cities along the river suffered from water shortages when their water supplies were polluted. After the disaster, many agricultural areas could no longer be used (Wikipedia, 2020). Planting bamboo could alleviate the toxic residue of this mudflow by the process of phytoremediation and bamboo could deliver cheap and fast building material to counter the housing deficit caused by this man-made disaster. Even though it cannot strictly be considered a disaster, the housing deficit in Brazil has been calculated to be 7.9 million residential units. This problem could also become partially alleviated by bamboo buildings (Sá Ribeiro, 2014).

4.3.4 Other considerations on social performance

An interesting angle on poverty is provided by Shafir (2014) who analyzed the psychology of scarcity. People's behavior is fundamentally different with perceived scarcity, whatever that scarcity may be: time, financial, friendship, calories, etc. Although considerably adapted to handling short term-problems, this ability often impairs the capacity to think long-term. This scarcity makes the one perceiving it, focus on the direct lack of the scarce item thereby pushing the long-term perspective to the background, making decisions seem illogical when viewed long-term. The immediate need for food, money, shelter etc. takes up what Shafir calls 'bandwidth', leaving fewer bandwidth for long-term decisions. He tested the effect of income scarcity in the Viluppuram and Tiruvannamalai district in India, for at a given time of the year they are relatively 'rich' due to the harvest of sugar beet as they receive 60% of their year income at once. The other part of the year, they are poor. Shafir tested their cognitive abilities during both periods of the year and found that an average of 13 points on the IQ-scale were lost. The same person remained, yet with a modified bandwidth (Shah et al., 2014; Bregman, 2013). This perceived scarcity also has an effect on building with bamboo and on the acceptance thereof as a building material. When a dwelling is financially hard to attain, the decision concerning the choice of material also gets clouded, which was also the case during the community project in Camburi. Even when all of the benefits were shown, preference was still given to the more expensive conventional materials such as bricks and concrete. The short-term problem of ´lack of housing` makes the perception of superiority of brick and concrete buildings (nearly) impossible to perceive the health, financial and structural benefits of bamboo building. To save money, less concrete is used in the construction which enlarges the danger of collapse. Another example from this preferred western style in architecture and materials over natural (cultural) building materials was noted in the case of the Chinese rural village of Zhengjia. In this case, bamboo was a traditional building material for millennia which had become a touristic attraction of the traditional villages. Nevertheless, in the 'Area X project', it was perceived that villagers (by aspiration for modernity) preferred steel and concrete to provide for new touristic infrastructure. Even when the researchers calculated and presented the difference in environmental impact between steel and bamboo, still the first was chosen. Whilst attracting tourism by offering a copy of traditional architecture is rightfully objected, a contemporary variant could arguably attract more revenue of tourism than the same style of buildings that can be found in the city architecture where the travelers to rural China originate, following certain Critical Regionalist architecture (Statamatis & Gangyi, 2019). A possible explanation given for this particular example is that the Chinese contemporary bamboo building examples, in contrast to the Colombian and Indonesian examples, rarely take into account the protection by design and therefore easily deteriorate which generates a negative attitude of rural Chinese dwellers towards this kind of architecture. This again emphasizes the need to provide adequate examples of bamboo architecture, preferably structurally sound concepts above design liberty (Statamatis & Gangyi, 2019).

4.3.5 Conclusion

The pillar of social performance is arguably the most difficult one to be quantitatively assessed for it affects people, education, traditions and culture. To determine the level of social performance, one needs to establish social performance indicators to measure that performance. Attempts for standardisation are still under development and are hence not yet as established and internationally established than environmental or economic indicators. This is mainly due to the coarse nature of the social performance indicators. Developing a bamboo-based construction industry cannot only preserve traditional skills but also create new income opportunities and ensure a much stronger social cohesion (Manandhar et al., 2019). Bamboo can be implemented to reduce deforestation which is a key cause of poverty and urban migration. By developing housing based on locally available building materials, the skills of local people can be increased, which in turn can support them in income generation and prevent them migrating elsewhere, thus improving the social fabric.

Based on this section, it can be concluded that indicators to be included in the evaluation framework of this dissertation (chapter 8) are the fact whether or not a bamboo project utilizes local labor and if training for the unskilled workers is included. Furthermore it should include the evaluation if social entrepreneurship is promoted and if a strategy of scaling out or scaling up is possible and how this will be done. In addition, it should also assess if the bamboo design considers traditional building techniques (vernacular architecture) and if it is set up according to bio-climatic principles? Finally, it is found that disaster-proof and flexibility of the building is important and hence should be included in the framework.

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CHAPTER 5 Component 3: Aesthetic Quality (Venustas)

5.1 Introduction

This research includes the parameter aesthetic quality. It has been noted that the general perception of bamboo as a construction material is one of the criteria that precludes bamboo from a greater market access. Even though bamboo is gaining more interest as a building material, it has not reached its full potential as a competitive alternative to conventional construction materials. During the decades of academic research, the physical and mechanical properties of bamboo, adequate treatment methods and building techniques have been extensively researched and described. Its environmental, economic and social benefits have been reported on. Nevertheless, its existent application in the construction industry remains relatively insignificant. The author attributes this to four main factors. Firstly, bamboo is still considered as a 'poor man's material' with a perceived short life span. Secondly, there exists a higher construction cost because it is more labor intensive. Thirdly, architects/contractors are still unfamiliar with bamboo design and its construction techniques. Finally, there are lacking well-designed and replicable examples.

In the first place, bamboo´s low-cost perception is generated by its fast growing-rate. People are convinced that since bamboo is abundant and cheap, it is of poor quality. In tropical countries when one does not dispose over enough financial possibilities to build with bricks or concrete, he will most likely apply bamboo because it can be cut for free locally and put together with simple lashes. Secondly, the low-cost perception is enhanced by poorly executed examples. Destitute people will often not built according good design principles nor give bamboo culms the proper treatment for this would cost too much time and money, amplified by the fact that they lack information about proper treatment and do not have access to chemical preservatives. Such low-cost, often vernacular, examples contribute to the negative perception of bamboo. Mertens researched the opinion of Balinese people on bamboo housing and concluded that principally in local communities, bamboo has this negative connotation as a ´poor man´s material, ephemeral and of poor quality (Mertens, 2019). In Western countries, bamboo is mainly viewed as a poor man´s material in the sense that it is believed that bamboo should be applied in ´poorer` tropical countries and not in the richer western countries. Moreover, there exists no tradition in building with bamboo in Europe. Mertens explains how, in contradiction to the above mentioned perception, some interviewees regard upon bamboo as a luxurious and expensive material because they reference to the luxurious bamboo villas, hotels or restaurants (Mertens, 2019). It frequently astonishes clients when the real building cost for a bamboo construction is presented. Jointing bamboo culms is complex and therefore more work intensive than jointing an orthogonal material such as wood or steel. Organic structures are even more expensive because bending bamboo is a time-intensive process and costs considerable amounts of energy, all adding-up to the building cost. The higher building cost is also underlined by Elora Hardy from Ibuku Studio in an interview with Mertens (Mertens, 2019). Prefabrication could offer a solution to keep the labour cost low. Finally, because contractors as well as designers lack practical bamboo architecture knowledge, there often exist unrealistic expectations of what is possible with bamboo and consequently poorly designed or executed examples appear, also in the media. At first the construction will appear beautiful and deterioration will only starts shortly after, predominantly due to an over-exposure to sun radiation and precipitation encouraged by a perceived liberty of design such as one has with concrete or steel. This can become problematic when design flaws lead to structural problems that will be (incorrectly) associated to the material. On the other hand, lack of knowledge can also lead to a lack of confidence where contractors and/or designers are afraid to apply bamboo and prefer to rely on conventional materials. Besides the above-mentioned factors, Mertens noticed that some of the interviewees also had concerns regarding fire safety and flammability of bamboo in a building. Paradoxically, they tend to trust bamboo more in case of an earthquake (Mertens, 2019). Plausible even other factors and personal preferences play a role in dismissing bamboo as a construction material. Nevertheless, it can be assumed that bamboo is facing a perception problem, which could possibly be remedied by aesthetics: acceptance through design. With qualitative and copyable examples, others can become inspired. In addition, a balance in cost-efficiency must be found. Qualitative bamboo architecture should become affordable for a broader public. Therefore, the aspect Venustas (appearance) is included as an evaluation parameter in the framework. This chapter studies the following; what is beauty and is it conceived similar to all people or not? How can beauty be attained in bamboo architecture? What exactly does quality of appearance consists of and can there be drawn general 'rules-of-thumb'?

5.2 **Philosophical framework**

According to Webster´s online dictionary aesthetics is "*a branch of philosophy that explores the nature of art, beauty, and taste, with the creation and appreciation of beauty*" (Merriam-Webster.com, 2020). Aesthetic quality is the extent to which a building is perceived as beautiful, stimulation or original; the way it is experienced. In its widest sense it means the integration of functional, formal, technical and economic issues (Van der Voordt & Van Wegen, 2005). When examining an unmeasurable and multi-interpretable aspect such as aesthetics, care has to be taken to review it as objectively as possible. Immanuel Kant (1724-1804) points out that there cannot be made a scientific judgment on beauty itself, only a critical review on past theories and writings on specifically defined aspects for it is not considered scientific to have an opinion on beauty, although it can be considered a scientific approach to gather knowledge and statements made about beauty. Without stating whether a building is indeed aesthetically pleasing or not, one should investigate which rules and techniques were applied to make it so in the past (Cohen, 2014).

Kant's work was ground-breaking and still influential and relevant today, even if much of what Kant writes about aesthetics might seem outdated, his Critique on Judgement is one of the first works in the field of aesthetics and one of the most important treatises on the subject (Burnham, 2000; Cohen, 2014). To Kant, there were four 'degrees' to aesthetics; the agreeable (a purely sensory judgment based on inclination), the good (an ethical judgment-conforming moral law), the beautiful and the sublime. Kant believed that ideas on 'the beautiful' and 'the good' are supposed to be universal however objective for 'good' and subjective for 'beautiful'. Therefore, we retrieve in history the definitions that were given to both. As 'the good', according to Kant, is a perceived quality based on ethical values of a society, one can research what ethical values in modern society determine this aspect of aesthetical appreciation or quality (Burnham, 2000; Cohen, 2014). Kant´s opinion that aesthetics is subjective was shared by many other such as for example Rousseau who regarded upon taste as a microscope of judgement meaning that one could be ecstatic on a beautiful picture or artwork that someone else does not even notices (Eco, 2004). On the other hand, the ideas of Kant were also criticised, amongst others by Schopenhauer, whom believed that Kant was too concerned with analysing abstract concepts, rather than with real objects (Burnham, 2000). How true this may be, objectively reviewing what can be considered aesthetical, rather than talking about aesthetics or subjective feelings itself, assists to give an objective overview of what could arguably play a role in determining a building's aesthetics (Eco, 2004).

In Greek times, the concept of beauty was closely interlinked with ethical values such as moderation, harmony and symmetry (as balance). An interesting point of view is given by the philosopher De Botton who noted that it has become an unanswerable question to know what defines a beautiful building because how can anyone claim to know what is beautiful? Aesthetical assumptions used to be codified and popularised in pattern books for 'ordinary builders´. Originality was far less of an impulse of the architect or client. Following the ´rules` of beauty was the norm (De Botton, 2008). In this sense, the 'originality' of the architect was seen as counterproductive. John Ruskin already noted in 1849 that there is a loss of visual harmony in city centres because architects were called upon to be original and to invent new styles (Ruskin, 1989). De Botton explains that architects have turned against the very idea of these ´rules` declaring them as naive and absurd. The concept of beauty has been deemed elusive and therefore quietly sidestepped. Yet, even without knowing the sum of what contributes to the beauty of a building, architects should search to venture theories on this subject in the hope of triggering others into complementary ideas. Instead of aesthetics, one should speak about the values a building represents (De Botton, 2008).

A multitude of studies have focused on creativity, a major element in design quality. Demirkan and Afacan (2012) found that three main factors demonstrate creativity; the novelty of the designshape, the characteristics associated with the geometry and figure/ground relations, and the compositional factors including rhythm, repetition, harmony, unity and order. De Botton notes that the developed world has become rule-bound, punctilious and routinely which provokes a longing for the natural, unfussy, rough and authentic (De Botton, 2008). De Botton's idea of describing beauty in a building by analogising it with ethics holds one more advantage over the 'absoluteness' of using a proportional system for 'good' architecture, it helps to discern that it is unlikely ever to be a single source of beauty in a building. De Botton proposes several 'keystones' to do so. Clearly, these 'keystones' are limited and incomplete. There are as many ethical values imaginable as there are currents in contemporary architecture or society for that matter. Limited as they may be, they do gain insight in what ethical values could mean for the evaluation of designs and buildings, in this particular case for bamboo buildings (De Botton, 2008).

As a first ethical keystone to aesthetic quality, De Botton outlines ´**Order`.** One of the reasons order might be an essential quality is that it represents a victory over nature and we rely on order to suppress nature that is able to destroy our buildings, roads, etc. There exists a tendency to believe that important architectural works should be complicated, yet many aesthetically appealing buildings are often surprisingly simple. Society might benefit from those who lay aside their ego to be a genius architect and devote themselves in creating buildings that fit inside the existing framework (De Botton, 2008). Clearly, many contemporary architects will disagree on this fact but it is something to consider. Many examples exist where disorder issues ugliness as a result of this ego. For example, Figure 5.1 illustrates two divergent designs located next to each other, a situation where client and architect used their design liberty thereby creating disorder. On the other hand, there exist many ancient cities in Mediterranean countries such as Greece with similar architecture and characteristics (order) that are considered to be beautiful (Figure 5.2).

Figure 5.1. Ugly houses in Belgium. Retrieved from https://uglybelgianhouses.tumblr.com/page/22 (22/09/2018). Copyright Ugly Houses Belgium.

Figure 5.2. Oia Village in Santorini. Retrieved from https://www.greeka.com/cyclades/santorini/villages/oia/ (22/09/2018). Copyright Greeka.com.

The following keystone ‘**Balance**’ is represented in a building where the architect has mediated well between numerous oppositions (old vs. new, natural vs. technical, luxurious vs. modest, masculine vs. feminine...). According to De Botton, a well-balanced building possesses a quality containing a distinctive human kind of goodness and maturity (De Botton, 2008).

‘Elegance’ refers to the apparent ease in which a structural problem is resolved, for example in a delicate yet concrete bridge. We admire the seemingly effortless way a construction accomplishes its task thereby realizing that it is not effortless at all. Elegance is present if an architectural work succeeds to combine grace as well as strength (De Botton, 2008). We are inclined to determinate the aesthetical value to the amount of forces needed to resolve and with what kind of ease it does this. In this context, the virtue of constraint should be mentioned, avoiding overdimensioning, which is especially important in bamboo design as it is very common to use rather more than less bamboo.

‘Grace’ is an ethical keystone that can be interpreted belonging to elegance, however it is slightly different (De Botton, 2008). As a reaction to the grand theory of mathematics and order in the Renaissance where the freedom of architects was restrained by rules and lines, many artists and architects were drawn to different art forms such as Rococo, Mannerism, Eclecticism and other architectural influences where the idea of artistic freedom prevailed. This often led to very poetic and grand architecture with a certain grace in its decorative lines (Eco, 2004). These reactionary movements also searched for ‘the sublime’ as Kant had called it but in their opinion, the sublime could not be contained in rules and therefore depended on the genius of the architect (Kant, 2007).

´**Lightness**` is often mistaken for elegance, but it refers to how well the light is brought in. Many modernist thinkers refer to it as Le Corbusier. He phrased architecture as the practice of forms assembled in the light (Corbusier, 2004). Eco interprets it as ‘luminosity’ (Eco, 2004) and according to Aquinas beauty consisted of three things; proportion, integrity and claritas (De Botton, 2008).

De Botton explains ‘**Coherence**’ according the fact that nothing in architecture is ugly in itself; it is merely in the wrong place or of the wrong size. Coherence also refers to location and climate. Just as typical Dutch houses copied in China or Dubai would seem awkward, so are tropical bamboo houses in a cold climate. According to De Botton, buildings need to cohere with their setting, communicate the significant values and characteristics of their location and era (De Botton, 2008). Whilst vernacular building might be the most appropriate solution to a specific location, exactly copying it would not be the correct answer. However, a subtle analogy, relying on proportions and relations instead of appearance, might be a way to augment a buildings’ coherence to its place and era.

When a building reflects a simplistic vision of the user rather than the complex reality a user really is, the architecture will lack **´Self-knowledge’**. De Botton illustrates this based on the ´Plan Voisin` that Le Corbusier proposed for Paris, where he would tear down at least half of Paris to build better houses. Although it seems understandable, given the scale of the crisis of the at that time cholera-plagued Paris, that he felt the need to shield himself from any sentimental side effects in order to attain a new plan, it would have been disastrous if his plan would have been executed. Solutions, certainly at a larger scale, can never be too uniform or simplistic (De Botton, 2008).

The final ethical value **‘Criticism’** is to review buildings in another light and to put questions to what one considers the truth (De Botton, 2008). In this chapter, much attention is given to proportional systems, yet it is important to be critical to one´s proper assumptions. Therefore, the critique on these systems is also discussed.

5.3 **Proportional systems**

When analysing the literature on 'beauty', the emphasis of the text often directs to the connotation with proportional systems. From Plato to Le Corbusier, many authors have linked beauty to harmony and harmony to proportion. Since proportions are determined in mathematical terms, an objective description can be given to the techniques hereof. Therefore, proportionality is singled out in this dissertation as a key element in this chapter and will be used as an objective instrument. Proportionality contains more than merely the aesthetical benefit. Just as Le Corbusier and other modernists noted, it has the capacity to facilitate modularity, which is of great help when upscaling housing by reducing cost. Probably for these reasons the use of proportional systems surged again in post-war modernism where there was a significant lack of housing and a need for fast construction methods. The combined aspect of applicability on large scale and inherently aesthetical qualities was not only applied by Le Corbusier, but also by many other (Mattei, 2014).

It can be noted that in most literature, mainly two large strands of proportional systems can be found; the musical proportion and the human or 'golden' mean proportion. Although both systems are closely interlinked, golden' proportions can be found everywhere in 'musical' schemes, they will be discussed separately in section 5.3.1. and 5.3.2. A reason to describe these proportional systems in different section is that they were also discussed separately in the main works by the classic authors. Another reason is that the 'golden' mean, unlike the musical proportional system, has received much more attention in the 20th century with fierce adepts, but also vehement adversaries and critics. These critics are discussed in section 5.3.3. Section 5.4. addresses how the proportional system was used in the art gallery (case study discussed in section 6.8.).

5.3.1 The musical proportional system

One of the first known sources that compared beauty to proportion and the proportional system to music was **Pythagoras** (572-500 BC). He found interrelations between the sounds produced while striking an anvil and shortening a string at set distances to produce the chords we still use today. Shortening the string in half produced an octave. Two strings set at a difference of a 2:3 ratio is what we call today a fifth and a ratio of 3:4 is called a fourth. When we assume the note 'Do' as the basis of the scale, the first note that creates a melodious tone is 'Fa', in a (length) proportion of 4:3, and the next one is 'Sol' in a proportion of 3:2 (Seraj, 2017). Two notes an octave apart (ratio 1:2) will blend and sound appropriate together. Nowadays we can measure frequencies and amplitudes between harmonic chords that could not have been known to the Pythagoreans. Nonetheless this validates Pythagoras´ idea that they are harmonic because they can be pasted onto each other showing the same frequency, or 'resonate' with each other without discrepancies, which is not be the case in a discord (Concordia.com, 2020). When these ratios are put together one comes up with 1:2:3:4, and these ratios were considered mystical and therefore important to the Greek. Perfect geometrical figures were equated with perfect whole numbers - 1, 2, 3, 4- and subsequently with the perfect harmonic sounds they produced. These are also called 'the perfect octave, the perfect fifth (3:2); the perfect fourth' (4:3) and so on (Jencks, 2013). To the Greek, (the) God(s) created all things to be in harmony with itself, so anything that bespoke of harmony had implications beyond music, especially in architecture. Pythagoras and others compared musical harmonies to the rhythms of a well-proportioned building, forming a code of musical architecture. Jencks points out how the Greek temples were created based on musical performance. The perfect form of the stones reflected the sounds of dancing and singing while the intercolumniations created a steady beat of solids and voids. These rhythms were conventionalised and the architect would refer to them instead of to exact dimensions. Pycnostyle was the fastest beat of intercolumniation, Systyle and Eustyle middle speeds, Diastyle and Araeostyle the slowest and most stately rhythms (Jencks, 2013). Nevertheless, many authors have put this theory under discussion referencing to a musical play which is a linear process with a beginning and an end whereas the viewpoint of architecture is that the user can vary at any moment, possibly changing the experience of the rhythm and order. Because bamboo architecture revolves for a great part around the correct positioning of the load-bearing columns, the Greek idea of using their placement in a musical order might be interesting as an experiment to examine whether this idea would still stand and would be perceivable by an unaware user.

Vitruvius (80-15 BC) later on proposed using music theory in practical architecture design, including the construction of columns using architectural order analogous to the Greek Aristoxenian, whom stated that architects can discover the secrets to form by listening and decomposing music (Walden, 2014). The link to the human or 'golden' proportion and the musical proportion was very explicit in Vitruvius' time, even if it was not called 'golden' at the time. Vitruvius recommended tuning the chords of a catapult in order for it to throw with more precision (Walden, 2014). Unlike the human proportion, the way these musical schemes needed to be applied in practice was not specified in Vitruvius' book Libri Decem (Vitruvius, 1999). Most likely, they were used as a module in the design process, described as related to the column shaft diameter, height and distance between columns. A (musical) proportion of for example 2:3 or a perfect fifth, would result in a column of three parts high with two parts in between the columns (usually expressed in cubits, brachia, palm, etc.). This was an early form of modularisation which depended on prefabrication. The majority of the column shafts that were made in quarries came in prefabricated standard heights corresponding to pre-existing shaft diameters (Bosman, 2015). Architects at that time did not need to be aware of the mathematics behind these musical proportions, the modular schemes already led to a correct and aesthetic proportional application. A critic was that without the consensus on the aesthetical value of certain widths and heights, the intrinsic quality of such a proportional system would depend on the inherent value of musical schemes in architecture (Walden, 2014).

After the Roman era, the idea of musical proportion in architecture (at least in writings) disappeared in the background until it came back during the 'Renaissance' from 1400 on, the era of re-birth of ancient Greek and Roman ideals. Many Greek texts were lost in the early Christian era and 'the dark ages', but some had been preserved by Jewish and Islamic scholars such as the Aristotelian Averroes and were reintroduced to Europe at this time. However, even without these texts, Greek traditions must also have been passed on (via the guild?) for in cathedrals such as the Notre Dame the musical proportions such as stacking columns three to four levels high (Arcade, Triforium, Gallery and Clerestory as shown in Figure 5.3) were still applied and even refined (Jencks, 2013). Each of these subdivisions had a set width-to-height proportion (a perfect fifth was one of the most preferred) that providing the architect sufficient freedom to arrange these proportions as would be the case in an actual musical piece, never sounding or looking equal. The fact that these four subdivisions can be found in mostly all Christian religious buildings, even today, is a clear sign of the copyable modularity of this proportional system, with arguably inherent aesthetical qualities. However, proof hereof can be reduced from the literal durability of these constructions, referring to many Christian churches and cathedrals (+ 800 years) and even to Roman and Greek buildings (+ 2000 years).

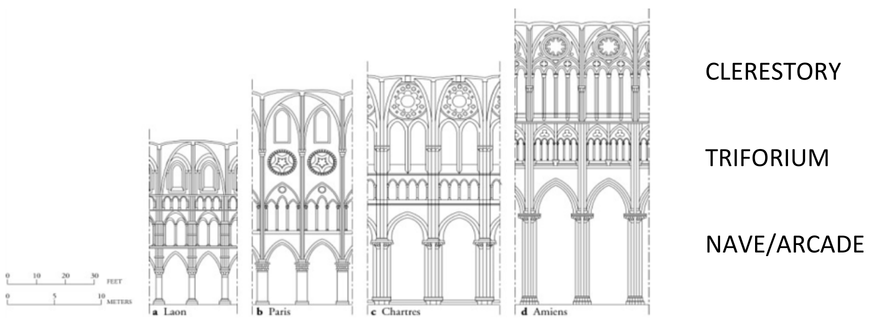


Figure 5.3. Evolution of the High Gothic. 2013. Retrieved from architectural-review.com/essays/architecture-becomes-music/8647050.article (p.7). 15/05/2018. Copyright Charles Jencks.

The knowledge that musical proportions were used to build cathedrals was a popularly known fact. In this context, there is often referred to Goethe´s popularly used quote: *“Music is liquid architecture, Architecture is frozen music*”. Originally Goethe wrote it to his friend Eckermann less poetically; "*I have found a paper of mine among some others in which I call architecture 'petrified music.' Really there is something in this; the tone of mind produced by architecture approaches the effect of music*." (Goethe, 1850, p. 146).

Alberti (1407-1472) devoted in his book ‘Re Aedificatoria’ an entire chapter (chap. V) to beauty and what it consists of. He concluded that beauty of edifices principally arose from three things namely the Number, the Figure and the Collocation of the Members. Again here, a rather mathematical approach to aesthetic quality is exhibited. Beauty does not arrive from the ‘uniqueness’ of the architect but rather by a scientific arrangement of elements. Alberti also continues on the idea that art is a science and that just like the other ‘arts’, for example navigation, it is based on rules that have evolved over thousands of years (Alberti, 1988). This might seem stringent today as it completely contradicts the contemporary idea of total design liberty by the architect. When describing these guidelines, Alberti refers to the musical proportional system rather than to absolute dimensions. He lends concords from musicians, such as the diapente or fifth, diatessaron or fourth, diapason or eight, etc., and explains that they are the lengths on a string that form a harmony and when played together harmonious tones are produced. Architects can use these ‘numbers’ (as he calls the proportions) for planning squares, open areas, public halls or council chambers (Alberti, 1988). As he specifically gives only examples of buildings and urban areas where some kind of status was to be considered, it might be concluded that these proportions were not to be used in every type of constructions (Cohen, 2014). Figure 5.5 gives an overview on how Alberti’s proportions could be transformed into geometrical figures (Essley, 2015). The proportional system was obtained by adding a rectangle to a square that is half as wide as that particular square. The new shape is then rectangular in the ratio of 2:3. When half of that rectangle is added to the rectangle of 2:3, the newly formed rectangle will have a ratio of 4:9. When fourths are used instead of fifths, a rectangle is obtained in the proportion of 9:16. In a similar way, a third set of three shapes can be added in the proportions of 1:3, 3:8 and 1:4. In this way, musical proportions can be translated into geometrical figures for architecture (Boyd-Bent, 1997).

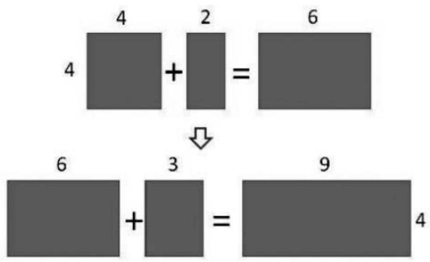
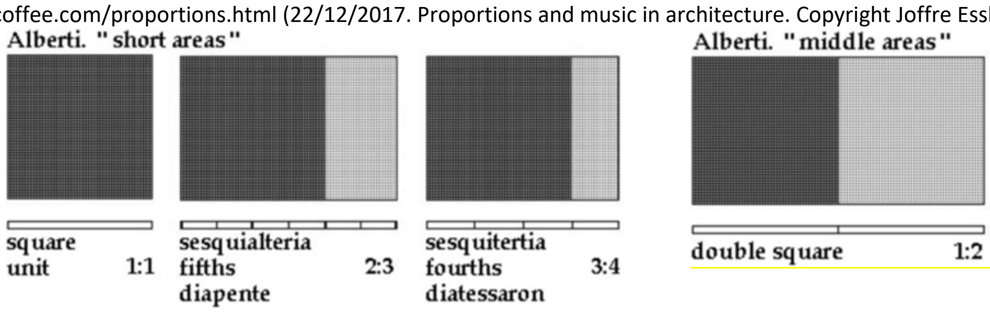


Figure 5.4. Geometrical system behind Alberti´s proportions. 2015. Retrieved from https://www.house-design-coffee.com/proportions.html (22/12/2017. Proportions and music in architecture. Copyright Joffre Essley.



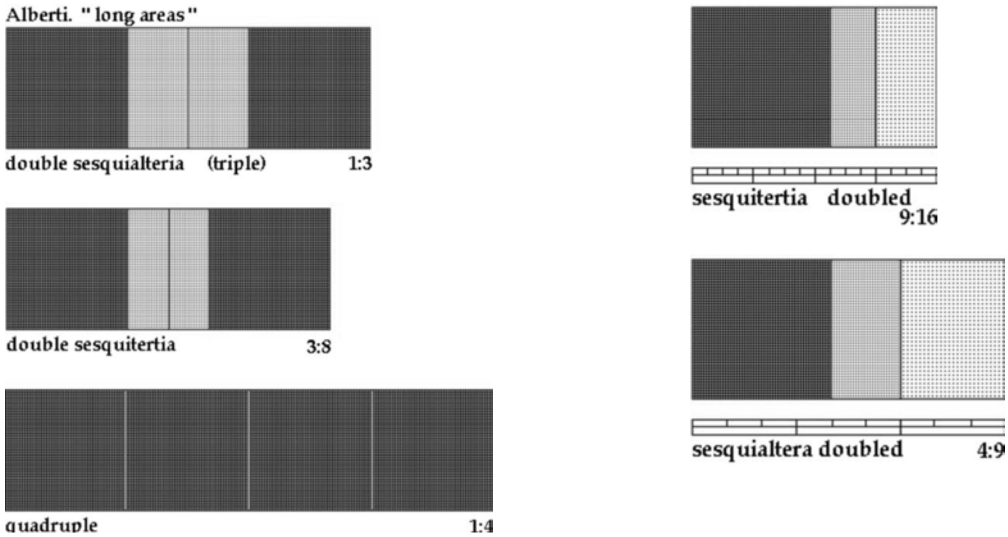


Figure 5.5. Alberti´s proportions represented in geometrical figures. 1997. Retrieved from http://www.aboutscotland.com/harmony/prop2.html (22/12/2017). Copyright J. Boyd-Brent.

In the century after Alberti, **Palladio** (1508-1580) elaborated further on (musical) proportions in architecture. Similar to Alberti, he also uses the square (1:1), a square plus a third (3:4), a square plus a half (2:3); a square plus two-thirds (3:5) and a double square (1:2) as seen above. However, he adds the diagonal of the square 1:1.414 which relates to the square root of 2, demonstrated in Figure 5.6 (Essley, 2015; Palladio, 1997). This square root is an irrational number and cannot be described as a finite number or ratio, just like Pi. It can only be expressed graphically (Figure 5.7). Therefore, the ancients attributed it to the divine properties. It also formed a helpful tool for architects when designing heights and interspaces between columns with the use of a compass. This square root of two is the only proportional system that is applied both in musical proportions as well as in the golden proportions (Boyd-Bent, 1997; Cohen, 2014). Just like Alberti, Palladio applied the natural proportions in which he determined the Arithmetic, Geometric and Harmonic means (section 5.3.2). Up until Palladio, the musical proportional system was principally used for official and clerical buildings, buildings with an 'official' status and splendour. In Palladio's second book, we can however see plans of domestic buildings that also applied these proportions, democratising the modular system for wider application (Cohen, 2014).

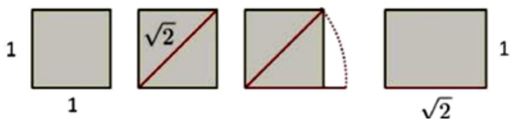


Figure 5.6. Rectangle based on the square root of two. 2015. Retrieved from https://www.house-design-coffee.com/proportions.html (22/12/2017). Copyright Joffre Essley.

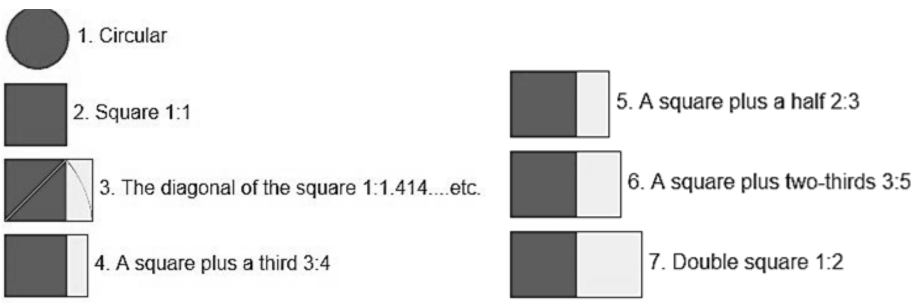


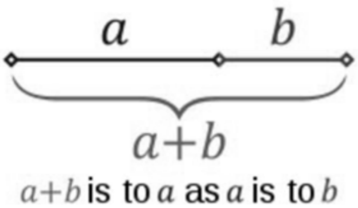
Figure 5.7. Palladio´s proportions. 1997. Retrieved from http://www.aboutscotland.com/harmony/prop3.html (22/12/2017). Copyright J. Boyd-Bent.

Vignola (1507-1573) also discussed the use of modules in architecture. Similar to Alberti and Palladio, he referred to the writings of Vitruvius. However, he believed that the architect, in order to solve his design task, needed to gain control over the overall measurements and therefore started with the height of a building and worked his way down to the module. In this system, the architect would first decide the height of a building and then divide this height into a number of modular parts. Vignola did not make a model book of the well-known five orders of columns, but a useful tool to aid architects in the application of these classical rules. He did not apply any measurements, but made a distribution of the proportions based on simple numbers (Vignola, 1999; Bosman, 2015).

After the heyday of the renaissance, the application of musical schemes continued to be used, however less was written about the proportional system behind it and simply referred to the important works mentioned above for the theory. In the 19th century, the idea of the architect as a free spirit and an artist became more and more popular. The architect did no longer need to restrict him/herself to the rules or guidelines any longer and the proportional systems and the theory behind it fell into oblivion. Contemporary architects apply the notion of musicality merely as an inspirational source in their work. According to Jencks, the architects Libeskind, Gehry and Prix have composed parts of their buildings inspired by Schoenberg and ’60´s pop music, but none of them has specifically written about this (Cohen, 2014; Jencks, 2013).

5.3.2 The human proportional system or golden mean

Most classic authors always discussed both proportional systems together. Yet, in later works such as the works by Le Corbusier and Wittkower, the musical idea of proportionality got less attention in favour of the ‘natural’ number or the golden section as Euclid’s division was called from the 18th century on (Snijders & Gout, 2007; Livio, 2002). Amongst scholars there exists the discussion whether the ‘golden’ proportion was even considered aesthetically pleasing before the ‘cult’ worshipping of this number in the 18th century started when the word ’golden’ was coined to **Euclid**’s Phi-proportion (365-300 BC). Without taking a stand in this discussion, we need to start with a brief summary on Euclid´s work to understand better what this Phi-proportion is about. Geometry (or geodesy) was already used by the Egyptians and possibly even before, birthed in the necessity for measuring land. The difficulty of measuring territories led to the development of a theory, which later became a science (geometry) to serve the measuring (geodesy) (Duvernoy, 2015). In the abstract geometry, one would draw lines, areas or volumes to represent quantities. Mathematical operations can be done by drawing figures; addition lengthens a line, a rectangle is the multiplication of two numbers (multiplying by itself creates a square) and multiplying this again creates a cube (hence square roots cubic numbers, etc.). This way, the existence of irrational numbers could be known by drawing them, proving the scientific value of graphic depiction (Duvernoy, 2015). Euclid divided a line as such that the ratio of the shorter segment to the longer segment is the same as the ratio of the longer segment to the whole line. That is, if ´*a*` represents the length of the shorter segment and ´*b*` represents the length of the longer segment, values for ´*a*` and ´*b*` can be found such that a/b =b/a+b where a + b = 1, or put in other words (a+b) is to a as a is to b as represented visually in Figure 5.8 on the left (Duvernoy, 2015; Euclid, 2006; Wikipedia, 2020).



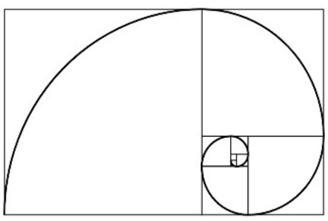


Figure 5.8. The golden section presented on a line and in a rectangle with spiraling diagonals. Retrieved from The golden ratio, the story of PHI, the world´s most astonishing number (p.85) by M. Livio. 2002. Copyright Broadway Books.

The division of a line that answers to this requirement has become known as Phi (Φ, ϕ or φ) named after the Greek sculptor and one of the supposed architects of the Pantheon Phidias. Later it became also known as the 'golden section', which numerically is expressed as (1+ √5)/2 or 1,16180339887….. (Green, 1995). This section was not only applicable on a line, but could also be translated to a 'golden' rectangle, which served as the basis of a regular pentagram. The construction of this pentagram was the main reason Euclid developed or 'discovered' this geometrical section/ratio. The famous example of a spiral inside a golden rectangle shows the possibility of endlessly subdividing the golden rectangle in smaller parts (Figure 5.8 on the right). As for any rectangle, it can be divided into a square and another rectangle where the remainder is also a 'golden rectangle' and can likewise be subdivided into a square of which the remainder again is a golden rectangle and this endlessly. No other ratio or geometrical figure has this capacity. The curve drawn in opposite corners of each square forms an endless spiral, which resembles a snail's shell, hinting at its providence in nature. If one draws diagonals in 'mother-daughter' pairs of rectangles in the series, they will all intersect at the same point, and the series of continuously diminishing rectangles converges to that never-reachable point, making some refer to it as "the eye of God" (Livio, 2002; Wikipedia, 2020). Euclid encompassed this and other mathematical knowledge of his time in one of the most influential mathematical textbooks called 'Elements', which was nearly unaltered in 2000 years (Euclid, 2006). His name is linked to plane geometry that we refer to nowadays as Euclidian geometry (Livio, 2002).

Also Plato attributed 'higher' values to these figures. To him these numbers were fundamental cosmic entities. Plato´s fascination for this ratio was triggered because of its unique algebraic properties which, according to the Greek and later generations, gave the ratio mystical qualities. Besides being an irrational, incommensurable (never-ending) number (1.61803), its square gives 2.618033… and its reciprocal ("one over") gives 0.618033… All with exactly the same digits after the decimal point (Livio, 2002; Snijders & Gout, 2007). The square is produced by simply adding the number 1 and the reciprocal by subtracting the number 1. Also, in mathematical entities known as continued fractions. The one corresponding to the Golden ratio is composed of ones only and therefore converges very slowly making it more difficult to express as a fraction than any other irrational number. It is considered the 'most irrational' among irrationals (Livio, 2002). Euclid himself never referred to it as the golden number or the divine proportion, he used the terms extreme and mean ratio (Snijders & Gout, 2007), but presumably he attributed the same mystical and aesthetical properties to it as was done to the other irrational numbers such as Pi or the square root of two. It was not until the publications of Adolf Zeising in 1844 that the name ´golden ratio` became popularly (Brown, 1963).

Vitruvius (80-15 BC) described the common construction knowledge of his time in his ten books on architecture. In one of his books, he translated the Euclidian proportions into human proportions. Vitruvius calculated 6 feet for the total height for a person, and found that each part of the body has a different ratio. The face for example is around $1/10^{th}$ of the total height, whilst the head itself would be around $1/8^{th}$. He used these ratios to prove that the composition of classical orders mimicked a human body, and thus securing a harmonious aesthetic experience of the user of this architecture (Suppus, 1991; Vitruvius, 1999). The famous drawing of the Vitruvian man was clearly not made in Vitruvius´ time but drawn by Da Vinci made as an illustration to the findings of Luca Paciola on this topic many centuries later. It does however show what the proportions at which Vitruvius hinted were about (Livio, 2002). The theoretical background and mystical origin of this human proportion and its derivation to columns, widths and heights was known to 'academics' like Vitruvius. However, for the common architect this modular proportional system was merely a rule of thumb to determine which type of column(width) was appropriate to their work, especially since the quarries provided prefabricated elements in standard diameters (Snijders & Gout, 2007; Livio, 2002).

It was not until Leonardo Bigolio Pisano**,** also known as **Fibonacci** (1170-1240), that Euclid's division could be determined mathematically (√5 can only be determined by approximation). Fibonacci found (or possibly recuperated from ancient Indian texts) an integer sequence (later called the Fibonacci sequence) that was composed of numbers that were the sum of the previous two numbers in the sequence; 0,1,1, 2, 3, 5, 8, 13, 21, 34, 55, 89, 144,… (Fibonacci, 2002). These numbers have a close interrelation to the golden ratio and to Phi. The latter was discovered by Kepler some centuries later. He found that dividing a number of the Fibonacci sequence by the number before it, gives an ever more precise approximation of Phi (1.618033…). For example, when one divides 8 by 5 the result is 1.6, but when numbers further up in the sequence are divided, for example 987 by 610, the number 1.618032786885246 are obtained (Sigler, 2002). When one reverses the ratio, a close approximation to 0.618… is obtained (instead of the 'other' golden number 1.618…). It has to be noted that these divisions however never exactly reach Phi, for it cannot be expressed as a ratio. They can only come closer to the value of Phi by enlarging the numbers that are divided. According to Von Ettingshausen and Prokorni, this ratio and its approximation to the Fibonacci sequence, is supposedly also present in some natural phenomena such as the growth of plants and that this prevalence in nature might be the reason why the ratio is found to be aesthetically pleasing to man (for it mimics the surrounding nature) (Snijders & Gout, 2007). A striking fact as well is that the position of leaves (such as in a fern) are often found in an angle of 72°, which happens to be the base-values of a triangle formed by this Phi-ratio. In classic, medieval and renaissance buildings, this 72° is often used in rose windows and other decoration elements (Snijders & Gout, 2007).

Another interesting 'golden section' technique that was applied in the Cathedral of Chartres, the Notre Dame in Paris and other renaissance buildings is 'Ad Quadratum' and 'Ad Triangulum'. Ad Triangulum was a technique that was easy to use, based on an equilateral triangle with the numbers 3, 4 and 5, whilst the Ad Quadratum technique was used to design buildings based on a square as illustrated in Figure 5.10. Because there exists very little written sources about it from that time, many academics do not support the idea that this was in fact the case. Nevertheless, striking examples point to such usage. Lund provides apparent evidence that these techniques have been used throughout many centuries. In Figure 5.10, he illustrates how the design of the cross-section of the Notre Dame Cathedral in Paris is based on the system of a pentagram. In the western façade of the Chartre Basilic (king's portal) Aristotle and Euclid are depicted, a clear reference to the 'inventors' of the golden ratio. Moreover, the floorplan of the Milan Cathedral conforms perfectly to an equilateral triangular scheme (Lund, 2003).

Alberti (1407-1470) and **Palladio (**1508-1580) take the theory into more complexity by differentiating besides a harmonic mean, also a geometric and an arrhythmic mean. Figure 5.11 translates this theory visually (Boyd-Bent, 1997). When Alberti discusses the 'invention' of columns, he clearly sees the 'natural' origin of this golden or Euclidian section that Vitruvius had described, even referring to the use of the golden section in the bible for the Ark of Noah. Looking up these biblical proportions, we find indeed in Genesis 6:15 that the ark was meant to be built in 50 cubits by 30 cubits (by 300 cubits long) which ratio following Fibonacci´s number and gives Phi (Alberti, 1988; Voet, 2016). Bouleau underlines that in the early middle ages an architect had less free play. He willingly accepted traditions, customs and consecrated correspondences. The aim of an architect was not to make an original work of art but a beautiful one (Bouleau, 2014). Temple outlines that Alberti was seeking to fuse the irrationals of the 'Ad Triangulum' with the whole number ratios of 'Ad Quadratum' as Alberti had said that there is more to world making than the geometry of a square (Temple, 2006). He was convinced that these proportions were to be foreseen in the third dimension (Voet, 2016).

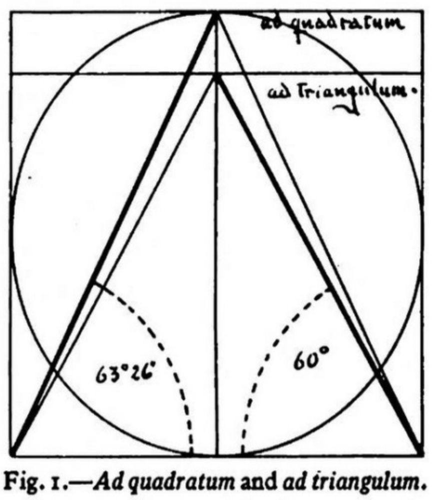


Figure 5.9. Ad Quadratum and Ad Triangulum. Retrieved from Ad Quadratum; study of the geometrical bases of classic & medieval religious architecture (p.24) by F.M. Lund. 2003. Copyright Batsford. Original publication date 1921.

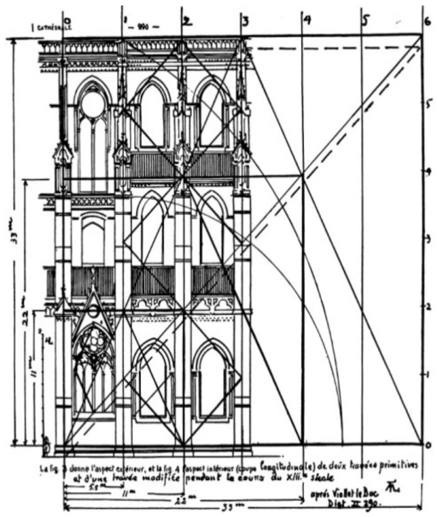


Figure 5.10. Ad Quadratum and Ad Triangulum at side elevation Notre-Dame, Paris. Retrieved from Ad Quadratum; study of the geometrical bases of classic & medieval religious architecture (p.59) by F.M. Lund. 2003. Copyright Batsford.

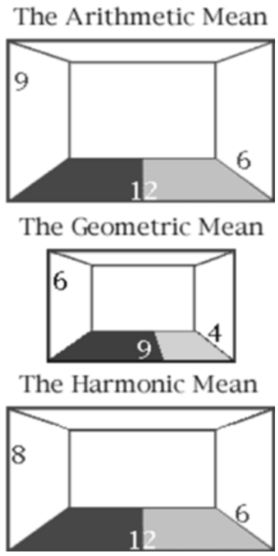


Figure 5.11. Palladio´s proportions. 1997. Retrieved on 22/12/2017 from www.aboutscotland.com/ harmony/prop3.html Copyright J. Boyd-Bent.

Luca Paciola´s (1445-1517) ´Divina Proportione` in 1497 (and a second part on architecture in 1509) is one of the most decisive works on the use, calculation and origin of the by Paciola called divine proportion. Alberti´s writings had clearly been influential to Paciola (Livio, 2002). Because this work contained original drawings by Da Vinci its fame was enhanced even more, which had clear consequences on the application of this proportion in the architecture of that time. Although Paciola, contrary to what has been attributed to him, never advocated the 'divine' or golden proportion as the determining proportion in all works of art, merely as a particularly wonderful ratio that can possibly be applied. When it came to design, he was an advocate for the use of simple, rational proportions such as the ones proposed by Vitruvius (Paciola, 2014; Livio, 2002).

Whilst Paciola democratised and popularised the knowledge behind Euclid's divine proportion, the possibility of large-scale application was brought by **Albrecht Dürer** (1471-1528). Dürer gave clear instructions how the golden proportions could be realized with the use of a compass. This made the mathematical or philosophical knowledge superfluous to make more complex structures beyond the Ad Quadratum or Ad Triangulum rules-of-thumb (Dürer, 2003). Although, it remains a discussion point amongst scholars whether or not these rules-of-thumb were rigorously applied in the centuries after these writings, it seems highly unlikely that no application at all was made. However, it might be the case that theory and practice stood further from each other than desired by the architect due to constructional realities and problems on site.

A few centuries later, a renewed interest was could be noticed, amongst others in the writings of **Wittkower** (1901-1971) and **Le Corbusier** (1887-1965). Whilst **Wittkower** was an academic who methodically researched the writings, plans and actual buildings of Palladio and the theory of Alberti to uncover whether the proportional system had been applied, it was Le Corbusier who popularised it in the heyday of modernism (Wittkower, 1971; Benelli, 2015). The decade of the 1940´s was crucial to the rebirth of the theory on proportion in architecture, entailed by both art historians as well as by practising architects. Especially in Palladio's plans and measurement notations thereon, Wittkower found proof of his theory. In most of Palladio's architectural plans, the numbers of the intended proportion (the length and width of a room) were often written aside as exact numbers (Francalossi, 2015). In his study on the villa Malcontenta (Figure 5.12), he discerned the absolute measurements from Palladio´s plans and unrevealed relationships of the spaces that produced the harmonic sequence 12, 16, 24, 32. Particularly 12 and 32 correspond to the dimensions of the portico, which is the relationship of a diapason to diatessaron (Fracalossi, 2015). Wittkower also made diagrams of Palladio's buildings (Figure 5.13) that would serve as a basis for later re-interpretation in modern buildings (Hays, 2016). As Wittkower was not an architect, some of Palladio's works that did not correspond to his theory, such as villa Rotonda, he determined as fugal. Surpassing the exact measurements of the proportional system in real-life buildings is where most criticism stems from. However, these critics appear to be mainly made by non-architects (often mathematicians) unaware of the consequences of the reality when building (Benelli, 2015).

In 1951, Wittkower was one of the main organizers of the conference 'De Divina Proportione', which was held as part of the 9^{th} Triennial of Milan. This event had as objective to show the transversality of the ideas on proportionality and demonstrated the importance of the idea of proportionality and modularity based on classical knowledge (Benelli, 2015). Besides the contributions of le Corbusier and Wittkower, also other influential persons presented their papers such as Pier Luigi Nervi, Siegfried Giedion, Matila Ghyka and Bruno Zevi. There existed a 'spiritual yearning' for the development of a unified basis for art and science that could reform society and ultimately help to recover from the World War II trauma (Cohen, 2014). During this congress, Wittkower encouraged artists, architects and thinkers to develop new kinds of proportional systems that would better reflect the contemporary condition and materials.

Although Wittkower is discussed in this chapter on the golden proportion, he could also be placed under the previous section on musical proportion as in the fourth part of his study, he focusses on how Palladio applied harmonic musical ratios in his work. To Wittkower, the renaissance aspect of aesthetics was to be found in a mathematical definition of beauty that is precise, of symphonic quality and manifested as logic (Payne, 1994).

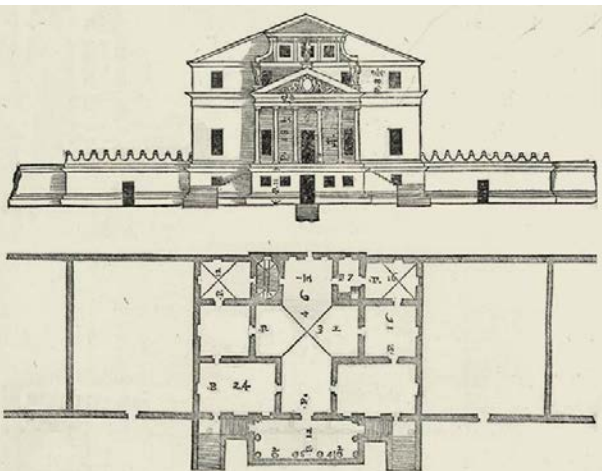


Figure 5.12. Villa Malcontenta by Palladio. Retrieved from: A sistema de proporções Fugal de Palladio/ Rudolf Wittkower (p.5) by I. Francalossi. 2015. Portuguese translation of Rudolf Wittkower Palladio´s fugal system of Proportion. Copyright Rudolf Wittkower.

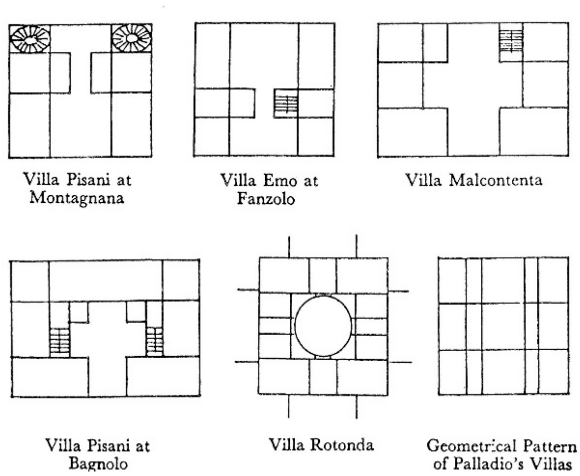
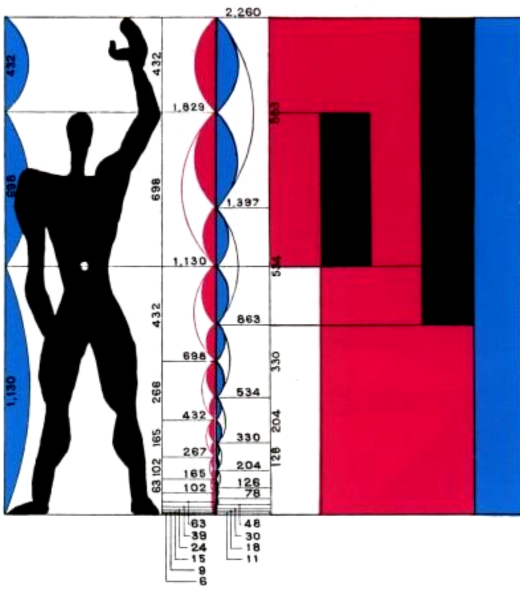


Figure 5.13. Generative diagrams of Palladian villas. Retrieved from Architecture´s appearance and the practices of imagination (p.208) by K.M. Hays. 2016. Copyright Log.

Le Corbusier did with the 'Modulor' just what Wittkower had suggested; provide for a proportional system that suits the needs and materials of his time. Le Corbusier, in his explanation of the Modulor, showed himself also a great adept of the use of mathematics and the golden section (Ostwald, 2001). After the World War II, the general idea amongst architects was that the lack of dimensional standardization as well as the incompatibility of the two main different metric systems blocked the efficiency of the building industry that was so needed because of the housing deficit after the world wars. This, together with Le Corbusier´s fascination of the apparent link between the human body (serving as the most important measurement reference for a building), led him into making his Modulor (Ostwald, 2001; Le Corbusier, 2004). A famous quote Einstein supposed to have said to Le Corbusier when he explained his proportional system to him sums up what the quality of such could be (even today); "*A scale of proportions which makes the bad difficult and the good easy*" (Phaidon.com, 2019). Le Corbusier sought, just like Vitruvius and Alberti, to connect the human proportions to architecture, but in doing so he clearly idealised them. For his Modulor, he did not apply a generic man, but it was based on an English male body with his arm raised. According to Le Corbusier the French were too short to work well and also a female body was rejected as a source of proportional harmony (Le Corbusier, 2004). Ostwald points out another problem of the Modular. The division between the ideal dimensions were too widely spaced to be practical. Ostwald therefore divided the Modulor into two parallel strips of dimensions; the red series in a sequence of 1.130m multiplied by the 'golden' number Phi and the blue series on a sequence of 2.260m. Ostwald´s improvements to the modular can be seen in Figure 5.14 (Ostwald, 2001). Even though it was a brave attempt to modernize the proportional systems of the past, it came with serious limitations such as the impossibility to use it on a large scale and as Le Corbusier recognizes himself as well, the fact that the use alone would not ensure aesthetically sound buildings. Adding this to the fact that no industry was following these measurements, led to the abandonment of the Modulor, even by Le Corbusier himself in his later work (Le Corbusier, 2004; Ostwald, 2001).



série rouge		série bleue	
mètres	Pouces	mètres	pouces
4,79	116"1/2	9,57	233"
2,96	72"	5,92	144"
1,83	44"1/2	3,66	89"
1,13	27"1/2	2,26	55"
0,70	17"	1,40	34"
0,43	10"1/2	0,86	21"
0,26	6"1/2	0,53	13"

série correspondante au corps humain (statique)

série correspondante à l'occupation de l'espace par l'homme (dynamique)

Figure 5.14. The blue and red series of The Modulor in drawings and tables. Retrieved from http://www.fondationlecorbusier.fr (13/04/2018). Copyright Le Corbusier.

Some decades after Le Corbusier, **Dom Hans Van Der Laan** (1904-1991), a Benedictine monk described his ideas on the 'plastic number', an elaboration (or to him an improvement) to the golden number theory. Van Der Laan was of opinion that these proportions could be better adapted to human ability when differentiated in sizes. Instead of the well-known Phi he proposed the plastic number to be 1,324718, a derivative of the proportion 3:4 with x as plastic number in x + 1 = x 3 (Laan, 1983; Proietti, 2015). Voet (2016) points out this his work can be read either as a philosophical principle but also as a practical design tool. This characterizes the separation mentioned already by Alberti and in other classic writings on the topic as well. Whilst the aesthetic connotation or background can be ground for academic suspicion (for being ‘unmeasurable’), the proportional system can also be analysed for its valid way to facilitate modularity and even prefabrication. Being besides a monk also a university professor, he engaged his students in the counting science and grouping of pebbles; from which he tried to derive perceivable differences and proportionalities to form the definitions on the proportional system he proposed. Van der Laan established a sequence which he called the ‘order of size’ that reminds of the sequence of musical scales. Figure 5.15 shows the proportions: 1 4:3 7:4 7:3 3 4 16:3 7 (Voet, 2016; Proietti, 2015).

As not all of these proportions were practical, just like Le Corbusier’s red and blue series from the Modulor, Van der Laan developed a second interwoven series ´the derived order` (Proietti, 2015). Van der Laan also defined a spatial cell (3m x 5m) that could be used as a module for larger spaces. The cell itself was based on the capital/top of the column or height of the module in a 1:5 or 1:7 ratio. The wall(size) played an important part in Van der Laan’s proportional system, he used it as a ‘yardstick’ for measuring spaces. For example, an abbey-wall with a thickness of 0.5m that enclosed a space of 3.5m wide (from axis to axis) formed a 1:7 relation (Voet, 2016). Van der Laan provided his students with several devices to visualize the plastic number, such as the abacus (a set of small figures with different lengths), the triangle of forms and the ‘morphotheek’. The latter is a set of regular geometric volumes that followed the progression of the plastic number as displayed in Figure 5.16 (Proietti, 2015). Similar tools could be devised for building with bamboo, as they can serve both a specialist as a novice in designing with bamboo. Even more than Le Corbusier, whose modulor-dimensions were strange to the industry, Van Der Laan was successful in what Wittkower suggested; to make a proportional scheme that could easily be used. Van der Laan altered the five distinct column intervals and proportions drawn up by Vitruvius into ratios of the order of size by eustylos as he believed it was the most pleasing (Voet, 2016).

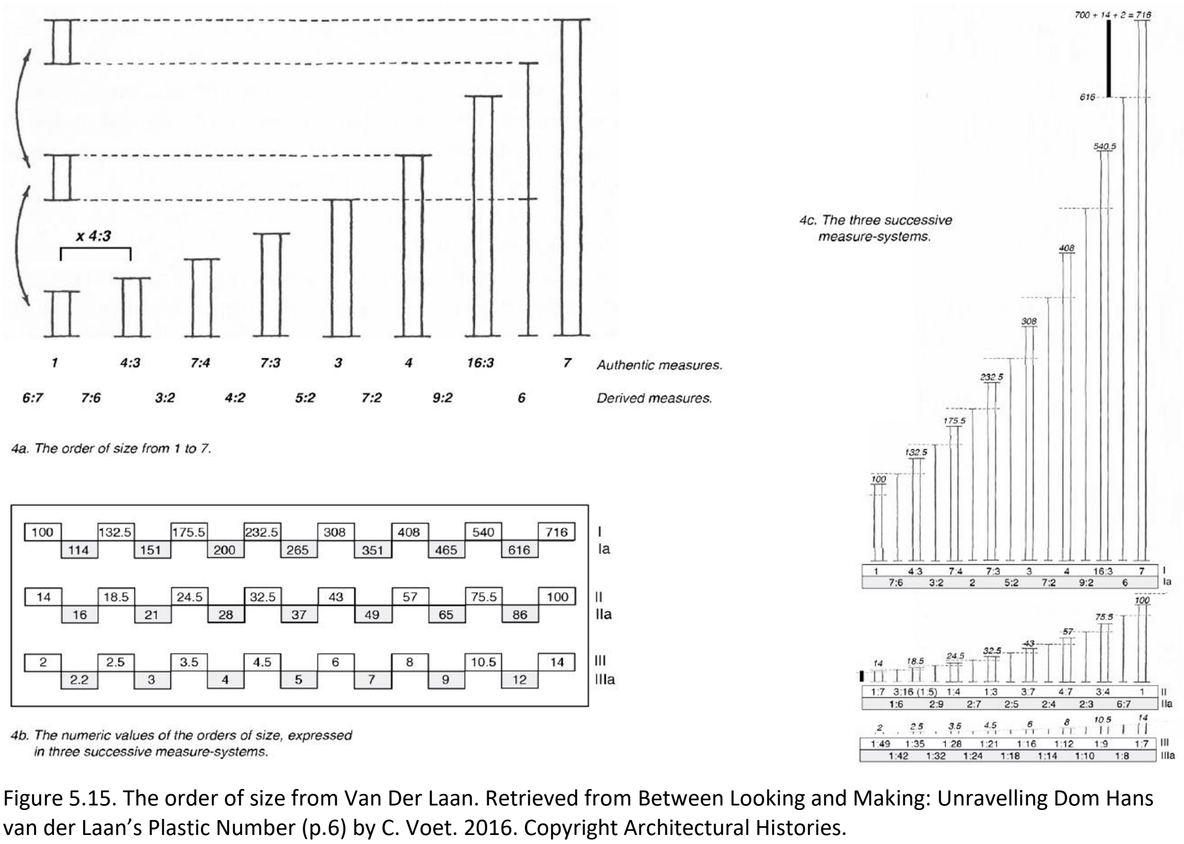


Figure 5.15. The order of size from Van Der Laan. Retrieved from Between Looking and Making: Unravelling Dom Hans van der Laan’s Plastic Number (p.6) by C. Voet. 2016. Copyright Architectural Histories.

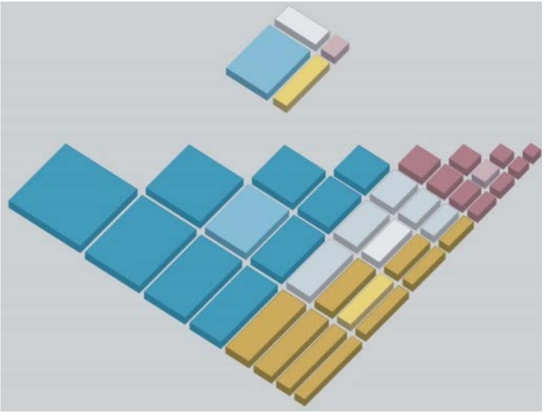


Figure 5.16. Morphotheek from Van Der Laan. Retrieved from http:www.vanderlaanstichting.nl/ hetplastischgetal/voorbeelden/morphotheek (13/04/2018). Copyright Van Der Laan Stichting.

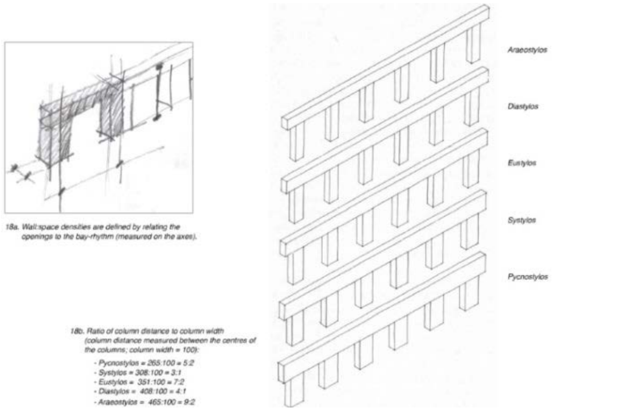


Figure 5.17. Five Column spacing's of Vitruvius according to the plastic number. Sketch by Rik Van Der Laan (a) and figure by Hans Van Der Laan (b). Retrieved from Between Looking and Making: Unravelling Dom Hans van der Laan's Plastic Number (p.18) by C. Voet. 2016. Copyright Architectural Histories.

This ratio of column distance to column width and height by Van Der Laan (Figure 5.16) can easily be translated to bamboo architecture. Bamboo columns can be outlined with a fixed intercolumniation distance, which could even vary depending on the load-case and/or the desired aesthetic effect. As discussed in chapter 6 on the case studies, the author often designs bamboo columns in pairs of four with a varying diameter between 4 to 12cm, similar to the ratio set out by Van Der Laan. As the art gallery was designed according the golden proportion, its principles are discussed in section 5.4.

Wittkower's legacy on the subject is as equally important as the Modulor of Le Corbusier. Reyner Banham stated in 1955 that Wittkower's work had a decisive impact on the New Brutalists whose representatives used the modular system as a starting point for new formal expressions (Benelli, 2015). In North Europe, architects such as Hendrik Petrus Berlage, Rietveld and even Mies Van Der Rohe began to take interest in proportional systems. Pier Luigi Nervi who structurally speaking has a portfolio containing the most interesting work when it comes to the possibility of translating structural 'ideas' to bamboo architecture. Nervi was convinced of the possibilities of proportional systems to produce aesthetically pleasing structures. As a professor at the University of Rome he taught his students to understand the harmony of the physical laws that regulate the equilibrium of forces and the resistance of materials, to honestly interpret the essential factors to each problem and to understand the limitations of the past (Cresciani, 2005).

Wittkower's findings also form the basis of space frames, amongst others encouraged by Buckminster Fuller, Nervi and Waschmann in the course of the 1950´s (Figure 5.18 and Figure 5.19) (Watson, 2017). Space frames are composed of platonic solids with 72° angles similar to the drawings of Da Vinci in Paciola's work (Paciola, 2014). Mattei proclaims that space frames could be seen as an extreme translation of the golden section (Mattei, 2014). Fuller's most known example, the Dynamaxion house, exists of a space frame that, according to Fuller himself, consisted of a 'universal' and not an 'international' form. It could easily be camouflaged between natural a form, which was a critique on the contemporary way of building (Watson, 2017). Regarding aesthetics **Richard Buckminster Fuller** (1895-1983) once said: "*When I am working on a problem, I never think about beauty. I think only of how to solve the problem. But when I have finished, if the solution is not beautiful, I know it is wrong*" (Brainyquote.com, 2020). The geodesic dome is one of his most famous examples which have already been executed in bamboo many times. Fuller specified the lengths required. It is however difficult to provide a geodesic dome in other than a temporary structure as the round shape offers little possibilities for integration in other structures, furniture, providing isolation or waterproof finishing, etc. Space frames however offer more possibilities than a geodesic dome and can be designed in numerous set-ups (Leopold, 2014; Mattei, 2014).

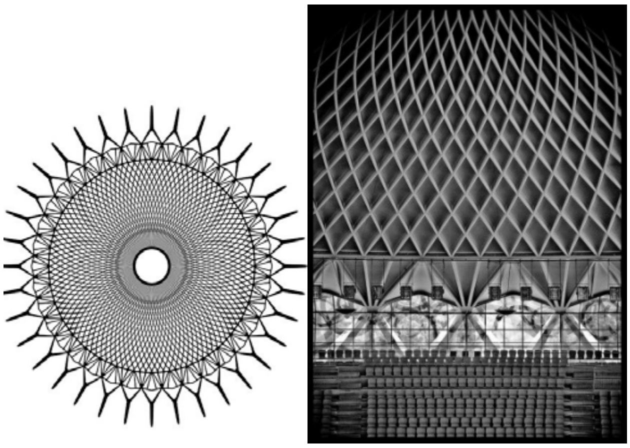


Figure 5.18. Spaceframe in the Palazetti Della Sport, Rome designed by Pier Luis Nervi. Retrieved from https://theforeignarchitect.com/blog/pier-luigi-nervi-in-rome/ (18/04/2018). Copyright Pier Luis Nervi

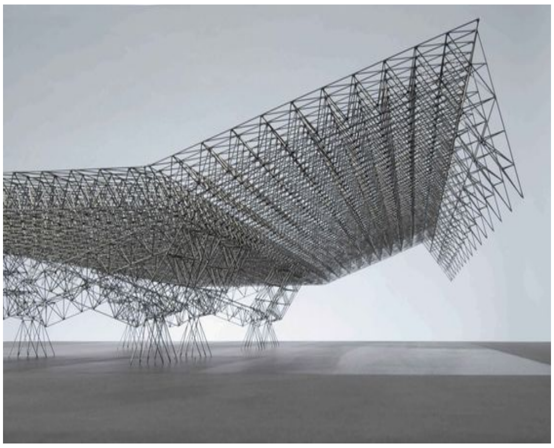


Figure 5.19. Spaceframe for the USAF aircraft hangar designed by Konrad Waschmann. www.atlasofplaces.com/architecture/usaf-aircraft-hangar (18/04/2018). Copyright Konrad Waschmann.

5.3.3 Critics on the proportional systems

In this section, an overview is given of the main critics on the use of proportional systems. Interestingly, no authors were found criticising proportionality based on musical rhythms, merely on the golden mean where mainly the mathematical theory behind it is criticized. Only very few architects attempted to deconstruct the efficacy of the proportionality rules and only disregard these rules when not believed in. Academics who expressed their doubts are psychologists and remarkably often mathematicians. The ferocity in which mathematicians such as Markowsky, Devlin and Livio ‘question’ the use of the golden proportion as an aesthetic factor to art is remarkable (Markowsky, 1992; Devlin, 2017; Livio, 2002). They especially focus on the use in paintings and pre-Vitruvian architecture, nevertheless to a lesser extent on the validity of aesthetical value in art as well. Herein might lay the ‘problem’ of their criticism, they tend to see the ratios as ‘absolutes’, whilst architects realize that a paper design and building reality are not always coherent. It is important to know the theory behind the proportional system, analysing if the intentions of the designer are demonstrated in the design, to conclude afterwards if the architect was capable of implementing it in the building.

One of the most cited ‘debunkers’ at this moment is Dr. Devlin, a mathematician from Stanford University. His lecture series from some years ago is often referred to when making ‘critical’ reviews on the sense or nonsense of proportional rules. Devlin particularly doubts the occurrence of ‘golden proportions’ in the human anatomy because people come in all shapes and sizes. It is indeed a fact that Vitruvius, Da Vinci and Le Corbusier used an idealized figure to determine the origin of the proportions that needed to be followed. Devlin moreover criticizes the complete lack of proof for the assumption that these proportions would lead to ‘beauty’. Even though Devlin acknowledges that there is indeed a golden ratio in natural growth patterns, he believes that there lacks mathematical proof that these qualities signify ‘beauty’. Finally, Devlin denies that there is any relevance or real application of the golden ratio in architecture and arts. He states that the ‘craze’ of the application of the golden ratio only begun when A. Zeising published his book on the topic in 1855 (Devlin, 2017). Whilst it is true that the term ‘golden’ was coined in this era, it is incoherent to state there exists no proof that it was being used in arts. When Da Vinci made the drawings for Luca Paciola’s book, he had to have known the theory behind it (Paciola, 2014). In Figure 5.20 it can be seen how the fingers point right exactly at the vertical and horizontal line of the golden proportion (Meisner, 2016). Bouleau offers ample proof in his book ‘The painter secret geometry’ that there is indeed, certainly from the Renaissance but possibly earlier on, usage of the proportional system of the golden section.

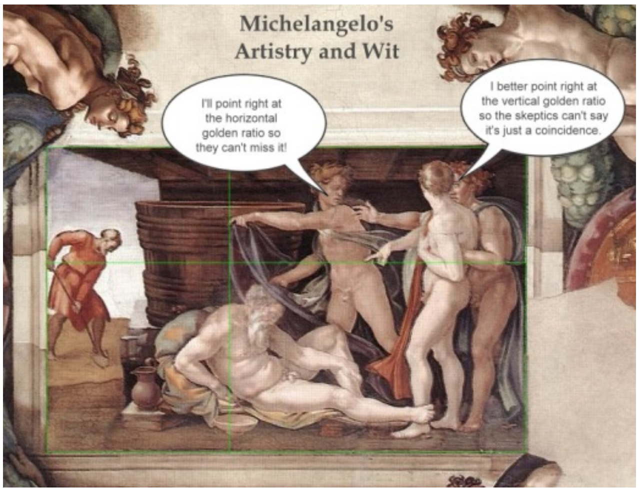


Figure 5.20. Michelangelo´s ceiling painting in the Sistine Chapel. Retrieved from www.goldennumber.net/michelangelo-sistine-chapel-golden-ratio-art-design (18/4/2018). Copyright Meisner. 2016.

Albeit at times in 'easier' applications such as the '*ad quadratum*' or '*ad triangulum*'. It was also presumably taught at academies of fine arts as a basis for a painting set-up (Bouleau, 2014). Bouleau's finding that the golden proportion was already known and used before Paciola's work is particularly doubted by Livio, another expert on the matter. Livio does not find any evidence to support Bouleau's statement as documented history on the golden ratio is inconsistent. Livio states that the assumptions for the usage of proportionality based on mere measurements are unprovable. By reason of a lack of a description hereon by the artists themselves, it will remain an undetermined fact (Livio, 2002).

Notwithstanding Devlin and others critics point out that the efficacy of the golden proportions with beauty as a result cannot be proven, neither can any 'abstract' human sentiment (such as friendship, love, pride,…). The fact that many artworks (renaissance and other) that have applied proportions survived through time and can even objectively be described as 'masterpieces', arguably do point to a beginning of proof. Devlin also expresses his concern regarding the 'exactness' of dimensional properties in order to 'proof' the use of golden proportions because for example Phi cannot even be measured in the real world being a never-ending irrational number (Devlin, 2017). Although this fact being true, it also underlines the difference in exact and humane sciences. The author is convinced that proportions mainly serve as a design tool to aid with the first set up of a building based on schemata or diagrams from whereon the architect started to refine its design. It is particular in these first schemata that the proportional system demonstrates its benefits.

The mathematician Markowsky tackled already in 1992 the same issue; the lack of exact measured dimensions that can demonstrate the use of the golden ratio in frequently cited architectural examples. Markowsky determined a range of 2% in which the closeness to the golden proportion would remain valid. The great pyramid of Giza, as one of the most mentioned examples to hold the 'golden' proportions. Yet, under scrutiny of Markowsky, current measurements that place Giza within 0.09% of Phi are not correct if one considers a text by Herodotus in 425 BC that the original dimensions would have been different and changed over time due to erosion (Markowsky, 1992). As the Giza pyramid was build 2000 years before Herodotus' text, the correctness hereof is also unprovable. As Livio points out correctly, numerical 'juggling' of inaccuracies in dimensions can nearly always provide prove 'close' to the golden ratio (Livio, 2002).

In this context, Markowsky mentions that the Parthenon (447-432 BC), also quoted as an example of the golden ratio, does not possess the golden ratio nor was it intended by the Greek to do so either. Markowsky points out that parts of the Parthenon, such as the edges of the pedestal fall outside the golden rectangle drawn around the Parthenon and that the dimensions differ from source to source, depending on which points are being used for measuring (Markowsky, 1992). Livio on the other hand identifies that most mathematical theories concerning the golden mean have only been formulated after the Parthenon had been constructed. However, it has to be noted that considerable knowledge already existed from Pythagoras on and arguably the architects (Callicrates, Ictinus and Phidias) would have decided to base the design of the Parthenon on prevailing knowledge about aesthetics known prior to Euclid's 'Elements' around 300 BC (Livio, 2002).

Both Markowsky and Livio question the use of the golden section in the work of Da Vinci and Seurat, although both acknowledge that Da Vinci was a close friend to Paciola and that he made the illustrations for ‘Divina Proportione’. They base their assumptions on the fact that Da Vinci mentions nowhere the golden mean in his writings and the fact that some of Da Vinci´s paintings with the attributed proportions were made before Da Vinci met Paciola (Livio, 2002; Markowsky, 1992). This is however as much evidence contra as pro. The fact remains that it is not known to this date if Da Vinci had knowledge of the system before he met Paciola and perhaps Da Vinci did not want to state the obvious as many of the knowledge was ubiquitous after the publication of the ‘Divina Proportione’.

Throughout the last 200 years, multiple psychological tests have been undertaken to research the validity of the aesthetical appeal of the golden section. Strangely enough all of these experiments involved the golden rectangle whereas the original mean ratio developed by Euclid (to be able to construct a pentagram) was a simple position on a line. When Adolf Zeising published his work in 1855 thereby starting a craze in the use of the proportions, it also triggered into one of the first scientific research attempts by the psychologist Fechner to validate these supposedly inherent aesthetical properties (Green, 1995; Fechner, 2011). Ever since that time, the idea has been proven and thereafter dismissed again in subsequent studies by structuralisms, behaviourists, psychiatrists and neuroscientists, often depending on the point the researchers wanted to make (Green, 1995). Fechner, in his first attempt, presented the test persons ten rectangles varying in side length ratios from 1:1 to 1.5:1, and asked which one was aesthetically most pleasing. In this test, 35% of subjects expressed a preference for the golden rectangle, 20.6% preferred the 1.5:1 rectangle and 20% chose the 1.77:1 rectangle. None of the subjects selected the golden rectangle as their least preferred (Green, 1995; Fechner, 2011).

According to Green, who cross-examined all the research done in the last 130 years on the subject dispersed over 34 universities, there was a certain tendency amongst psychology researchers to discount the golden rectangle a priori as a numerical fantasy, whilst others presented the results in such a way that a ‘nearness’ to the correct value was considered as proof. In this respect, ‘apophenia’ should be mentioned. This is the tendency to perceive meaning or connections in random numbers or data where there is none. A returning fallacy in composition in many of these studies is the methodological set-up because the way the rectangles are presented greatly affects the outcome. Green is led to believe that measuring the existence of the golden mean is nearly impossible for it is a fragile aspect and the psychological instruments to measure it are too crude to give indisputable results (Patina, 2016; Green, 1995).

Another interesting and relevant addition to the discussion was made by Dr. Bejan at the Duke University, USA whom reverses the discussion. It is not because of the golden ratio that we are inclined to find certain shapes pleasing. It is because the golden proportion comes very near to the ratio that eases the transfer of information to the brain. Bejan determined that eyes take up information more efficiently when they scan side to side, rather than up and down. Most likely, this stems from an evolutionary origin being able to scan for danger in a horizontal field, moving faster as a result. Shapes that resemble the golden ratio hence facilitate the scanning and transmission from the eyes to the brain and its configuration in dendritic architecture of the nervous system which releases endorphins (pleasure). Because it gives us pleasure, it is referred to as beauty. Bejan notes that this is a natural phenomenon as proportions that approximate Phi occur around us in large numbers in nature (Bejan, 2009). It also explains why measurements, in buildings or other objects that supposed to follow the golden ratio, are always a little off or float around it. The evolutionary predispositions to find rectangular shapes that coincide with the visual field have in other studies also been called the ‘perimetric hypothesis’ (Green, 1995). Proportions similar or close to the golden ratio occur in large numbers, obeying physical laws rather than mathematical laws (Bejan, 2009).

A study at the University of Parma, Italy in 2007 corroborates the theory of Bejan that one perceives neurologic pleasure when viewing objects containing the ‘golden’ proportions. Viewers naïve to art were presented images of masterpieces produced with the golden proportions mixed with artwork with deviating proportions. This study found that there were both objective and subjective factors that intervened in determining the appreciation of an artwork. This could be seen in the different regions that were highlighted in the brain using MRI technique. The tests showed appreciation based on ‘pleasant experiences from the past’ (subjective), but also aesthetical appreciation that was universal for all the participants. It was concluded that despite individual biases, elements that determine aesthetical experience are deeply involved in our biological heritage and not merely an experientially determined concept (Di Dio, Macaluso & Rizzolatti, 2007).

5.4 **Application of the proportional rules-of-thumb to the art gallery**

5.4.1 Introduction

The research on the proportional systems discussed in the previous sections calls for a translation to bamboo construction in specific. In the case of the art gallery, proportionality was used as a starting point in the design. By analyzing these measurements, it can be indicated where the proportions coincide and whether the usage hereof facilitates prefabrication and/or adaptable modular systems. Whereas in the past ‘ideal’ proportions had to be calculated or drawn (e.g. with a pair of compasses), in modern times this can be done with the aid of computerized software. The proportional software PhiMatrix version 1.681 designed by Gary Meisner (2014) is used for the measurements. However, there also exist other software programs such as Atrise version 2.1.0., Composition Pilot and Design Grid. PhiMatrix applies a technically more correct version of the artist’s “Rule of Thirds” as an aid to draw a horizon line or to position a key element on a picture (Meisner, 2014). Meisner is besides the software developer of PhiMatrix also the author of the book “*The Golden Ratio. The Divine Beauty of Mathematics*“. PhiMatrix allows the user to place a ‘golden’ form such as a rectangle, circle, square, etc. that refers to this ‘rule of thirds’ over any computer drawing (AutoCAD or Vectorworks) used to design a building. The chosen geometric figure ‘floats’ above the drawing. It does not require a plug-in. In its most straightforward form, the grid can be used to apply a golden ratio as a guide to align key elements of composition (Figure 5.21). This can either include the position of a horizon on a landscape or general dimensions of a new design. In its more extended form, the grid can be used to create a framework upon which key elements of the design can be placed. When the grid is removed, the underlying proportions remains visible in the proposed project.

Figure 5.21. Control panel of PhiMatrix software. 2014. Copyright Meisner.

5.4.2 Translation of the ´golden` proportions into specific sizes

Before the actual design process of a building can be initiated, the program of demands, organization of spaces, orientation, general concept and other key-design principles have to be set out with consideration to the specific characteristics of the construction site. It is in this phase, arranging the base elements of the design, that the proportional systems can be a viable tool. For the design of the art gallery the software PhiMaxtrix was used to determine the sequence and spacing of the different subparts of the art gallery, such as the courtyard, the bamboo structure, the door openings and the interior spaces. The proportional relations of the main elements were drafted in a rough floor plan (Figure 5.22). It is easier to define sizes and spacing with aesthetical coherence when they are conceived from the onset with the aid of a proportional software tool. Elements that are perhaps too detailed for a first draft, such as the footing of the bamboo columns, can actually become an essential factor to the coherence of the measured interrelations. Although the PhiMatrix software can be used into great numerical detail, it was preferred to restrict it to those numerical values that interrelate to the golden proportion and more specifically the numbers from Fibonacci´s sequence. A general lay-out was made in 2D (Figure 5.23) whereafter it was translated into 3D to define a rhythm and height for the construction, bamboo frame, door openings, etc. The bamboo columns are placed on the grid precisely in the middle of each door opening. The height of each door is 210cm with another 50cm above the door. The columns are put on a stone base of 34cm high... All of these measurements refer to the Fibonacci numbers. A rather straightforward application of the golden numbers was performed. Experimenting with musical proportions such as a perfect fifth (3:2) or a perfect fourth (4:3) might have been even more impactful towards the design composition. This case furthermore demonstrates the disparity between the actual and intented measurements. It is nearly impossible to have both measurements align entirely due to the reality of the construction site, construction techniques, subsoil particularities, etc. However, when the proportional system is set out in the design, it will appear in the final composition as well, even if the execution is not flawless.

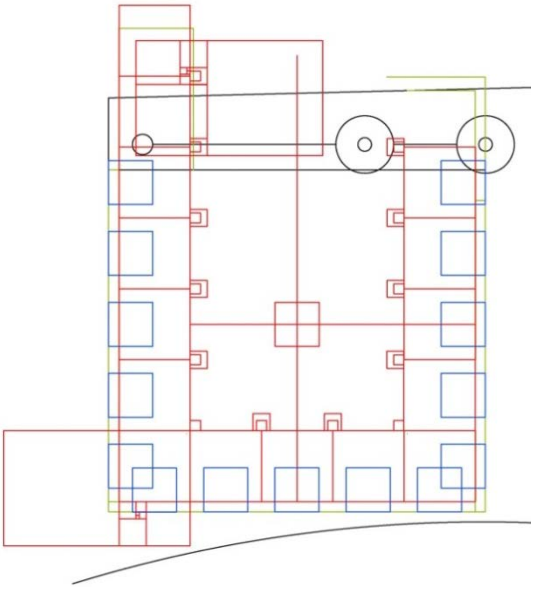


Figure 5.22. Application of the PhiMatrix software to the floor plan of the art gallery during the design phase. 2016.

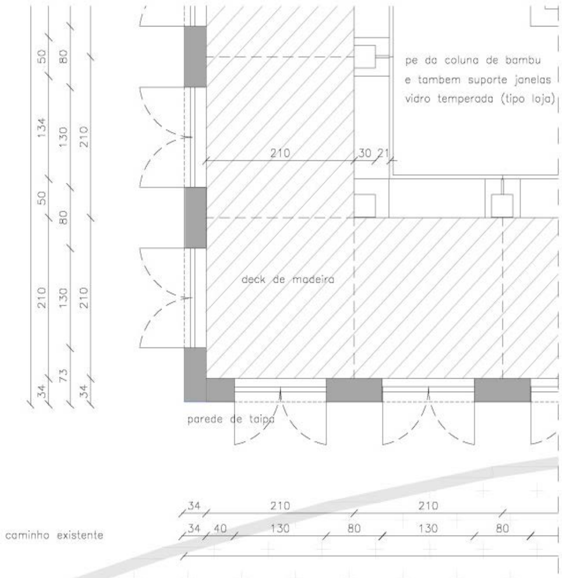


Figure 5.23. Application of the Fibonacci numbers derived from the Euclidian proportional system. 2020.

5.4.3 Proportional systems translated into (bamboo) columns

The application of a proportional system is the most obvious in the measurements of the columns. Vitruvius describes in his book Libri Decem (1999) the relation between the column shaft diameter, the column height and the distance between two columns, expressed in cubits, brachia or palm. The majority of the column shafts were prefabricated in quarries in standard lengths corresponding to shaft diameters (Bosman, 2015). The measurements of these columns could easily be translated to bamboo columns. It was in fact an early form of prefabrication and modularization. There were only several dimensions to choose from, all referring to a certain proportional system, whether it was ‘musical’, ‘Euclidian’ (‘golden’ did not exist as a name in that era) or another (Bosman, 2015). Although, it might appear that the proportional system is not visually noticed, the question can also be reversed. If one had to sell a standardized column and shaft, what dimensions should these have? It would be plausible to reach for sections and dimensions that are generally accepted as agreeable, as is also the case with the standardized paper sizes (A4, A3) that correspond to the ‘golden section’ (Petterson, Strand, 2005).

Figure 5.24 illustrates the design and form of one module. The marked section coincides with the ´golden rectangle`. The rule of thirds was used to subdivide the sections in vertical ‘golden rectangles’, whilst the rhythm of the middle sections was determined on a shifted ‘golden rectangle’ marked in red. The ‘golden spiral’ was used to determine the curvature and starting point of the bamboo arches. As can be seen, the beams coincide (largely) with the first part of this so-called ‘golden spiral’, but not entirely as the idea was to connect them in the middle of the assembled module and not on the Phi section (1.618) as is the case in the ´golden spiral`.

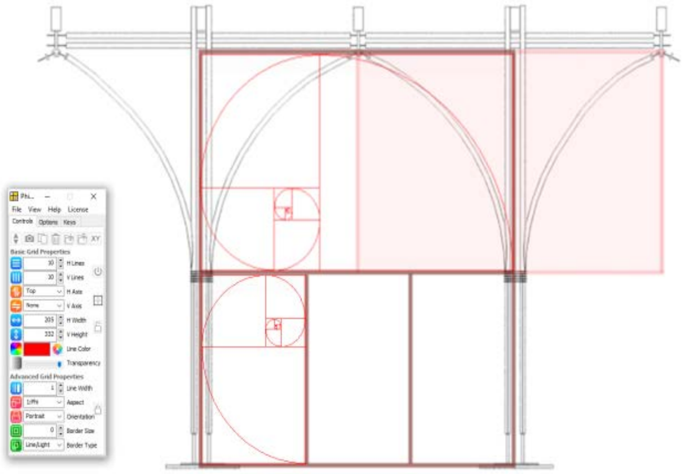


Figure 5.24. Application of golden rectangle to the bamboo colonnade. 2020.

The column design for the art gallery is inspired on classic monastic architecture. In monasteries, covered walkways, the original ‘galleries` to pray and reflect, were composed around a central courtyard separated by a colonnade of columns. Usually, these columns had a standard width and height corresponding with the chosen proportional ideal. For example, the columns at the San Lorenzo nave in Figure 5.25 align with the square root of two, which when using a compass and ruler also contains the golden rectangle. The square root is an irrational number and cannot be described as a finite number or ratio; it can only be expressed graphically. The square root of two is the only proportional system that is applied both in musical as well as in the golden proportions (Boyd-Bent, 1997; Cohen 2014). Different from the San Lorenzo nave where the golden rectangle is used in a vertical position, the art gallery positions the golden rectangle vertically at the base and horizontally in the upper part of the column structure.

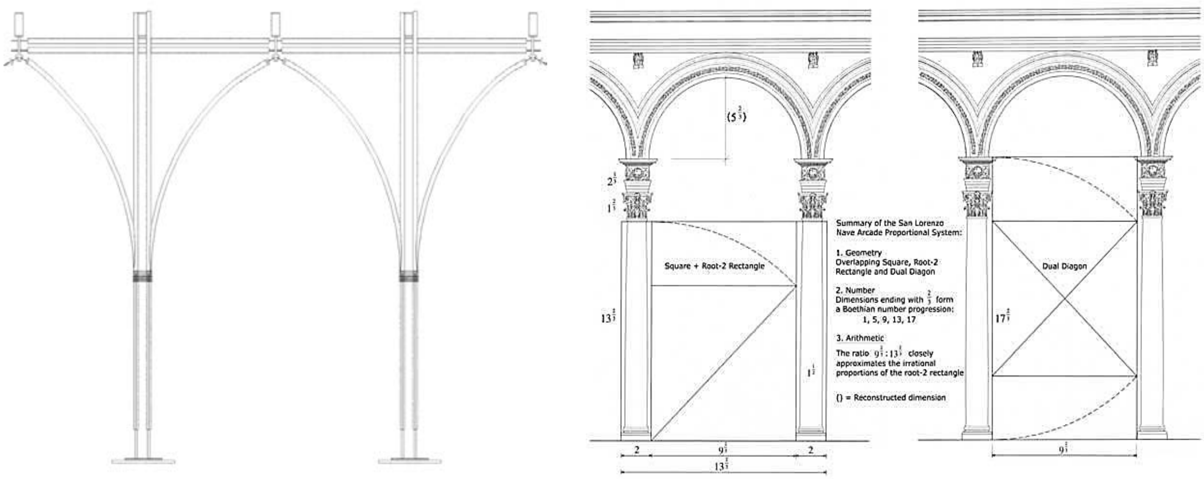


Figure 5.25. Comparison between classic prefabricated shafts and the bamboo columns from case study. 2020.

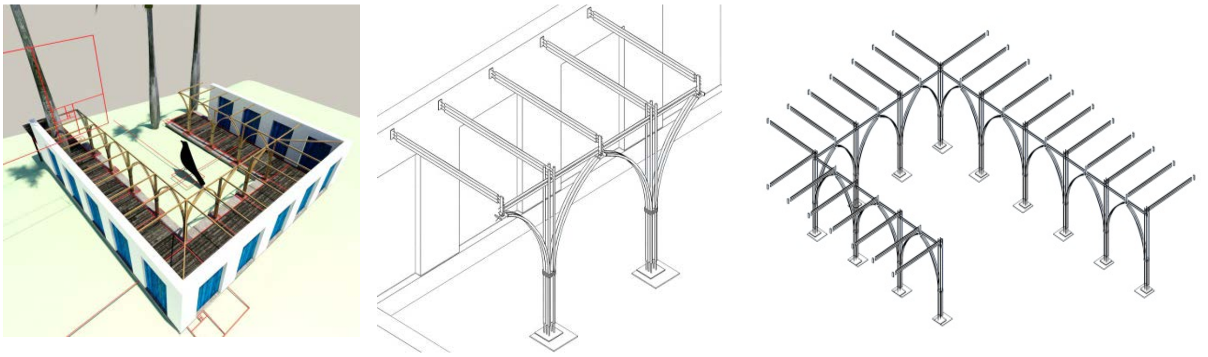


Figure 5.26. The application of proportionality in three dimensions to enable prefabrication and modularization. 2020.

In Figure 5.26 is demonstrated how a module consists of two bamboo columns with an arch connected in the middle and three horizontal beams to support the roof structure. This module is repeated eleven times. In the corners, the horizontal beams have a greater length for it is placed diagonal. The structure itself is quite simple and straightforward.

If a bamboo industry emerges, it could be beneficial to prefabricate elements such as columns, or beams in large quantities with preset heigths and diameters off site. This could either be done at a short distance from the construction site but also in proximity of the plantation. This way value could be added on the 'producing' side. Furthermoree, this would imply a better control over quality of the bamboo, the treatment and additives. Architects that want to build with bamboo no longer need to worry about these technical aspects nor about ideal proportion/dimension. Even though this might seem limiting the freedom of an architect, it might also signify freedom of design as the architect can safely and freely design with the available dimensions. In this context IKEA should be mentioned as well for they democratized interior design and enabled design for the masses which would have been impossible without prefabrication and research into dimensions, foldability, jointing systems, etc. Continuing on the idea of prefabricating components, also complete systems could be developed much like the Abacus by Dom Hans van der Laan where building blocks are set out in carefully chosen dimensions as a sort of rules-of-thumb that supersedes the architect's opinion.

Another project currently in development by CRU! Architects, in collaboration with Studiebureau Mouton, also apply the principles of proportions in the geometry of the +25m high bamboo tower set out over the entrance gates to the Zoo Planckendael in Mechelen (Belgium). Preliminary drawings of this project are illustrated in Figure 5.27.

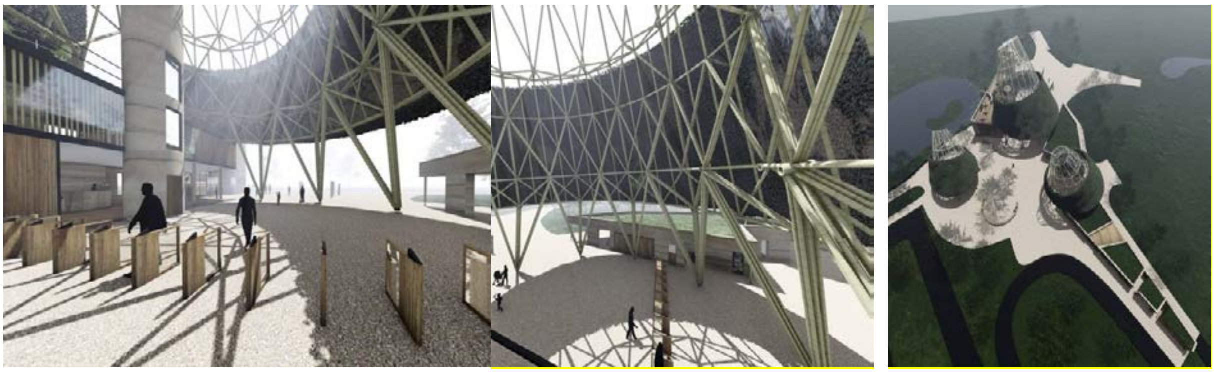


Figure 5.27. Preliminary 3D drawings of the bamboo-rammed earth entrance buildings for the Zoo Planckendael. Copyright CRU! Architecten. 2020

5.5 **Conclusion**

The historical analysis of proportional systems shows that the use of these can be considered proven if two elements are met: the intention of the architect in some kind of written form and dimensions that corroborate the application hereof, regardless the fact of construction reality. Palladio, Alberti, Michelangelo, Le Corbusier, Van der Laan, Nervi, Fuller and others have produced aesthetically pleasing architecture and in parallel wrote about how these proportional schemes were applied in their buildings. Golden proportions have been applied in architecture over 600 years and if the Greek and Roman are to be taken into account more than two millennia. In that time, proportional systems merely meant a rule of thumb to determine which type of column(width) was appropriate, especially since the quarries provided prefabricated elements with standard diameters (Snijders & Gout, 2007; Livio, 2002). As Kant mentioned, one should not need to take a stance on the fact of beauty (or not), but present the history behind the system so the reader can form his/her mind on the sense or nonsense of the system (Kant, 2007). One can argue that the world has become too complex for such a simplistic system. Yet, it might be incorrect to call it simplistic as the connection between mathematics, philosophy and architecture is complex and interdisciplinary. There is a tendency to look at architecture from a more complex angle: the process of architecture is evenly important to make the architecture and is not limited to the use of predefined constructs or modules (such as any 'golden ratios'). Architecture in contemporary architectural movements such as phenomenology and deconstructivism is characterized by discontinuity and heterogeneity (Patina, 2016). Nevertheless, it may be concluded that the use of proportional systems can support the realisation of appealing architecture. No claim is made that the ratios 'prove' or 'produce' beauty, at best they arguably aid to understand, create and refine aesthetics in buildings that are also prevalent in nature. It would also be wrong to assume that these proportions are more important than any other set of numeric systems or formulae needed to produce a well-functioning building. Instead of controlling the entire design, as was the case in multiple historical buildings, proportions could be one of the base principles in the design process. Whenever an architectural project incorporates the golden or musical or any other proportion as base principle, people do not even need to be aware of the principles behind it, to find it aesthetically appealing.

Implementing this to bamboo constructions, differentiating for example bamboo lengths in combination with different bamboo diameters could allow to reach proportionality comparable to the column height and interspace systems of Van Der Laan, Alberti and Palladio. Examples of this idea are presented in the next chapter.

Besides proportionality, other aesthetical values such as grace and coherence should be added by the designer. De Botton (2008) emphasizes that there is certainly place for new kinds of aesthetics and building styles and not much is needed to create a new evolution. Who knows bamboo might be part of a new evolution. Exemplary buildings and books have usually been sufficient to provide viable models for others to follow such as the Renaissance, the rebirth of Classicism and the New Architecture entailed by Le Corbusier (De Botton, 2008). Modern bamboo architecture is at the beginning of its era, and the importance of aesthetic quality bamboo buildings therefore cannot be overestimated. The next chapter discusses the attempts of the author to contribute to this challenge.

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PART II:

CASE STUDIES

CHAPTER 6 Cases of the bamboo constructions in Brazil

This chapter discusses nine cases designed and built by the author between 2004 and 2019. This chapter represents the experimental part of the research. The starting point for these experiments is the community development project in Camburi by the non-profit organization Bamboostic. First background information is given about the context and location of this project. Most of the cases are located in the municipality of Ubatuba, with exception of two; the art gallery and the bamboo canopy. The cases are listed in chronological order and at the end of this chapter; the conclusions and possible criteria for the evaluation framework are summarized. The main part of the community center was built in 2005-2006 (15 years ago) therefore this chapter also includes a durability analysis of its building performance over time. Besides the constructions built in Brazil, the author also built a bamboo house in Ghent, Belgium (2011). This project is however not discussed in this chapter due to its location outside Brazil.

6.1 **6.1. Context of the community development project in Camburi, Ubatuba**

6.1.1 Introduction

The community development project in Camburi (Ubatuba), Brazil is founded in 2004 amongst others by the author and was named 'Bamboostic'. The main objective is to convey different means of revenues for the inhabitants of the remotely located community of Camburi. This community encounters difficulties in earning their own viable financial income by fishing and agriculture, which both have been limited due to environmental restrictions imposed by the national park Serra Do Mar where it is located (Bamboostic.be, 2012). Several young architects and engineers have been working for the Bamboostic project in the past decade, performing a tech-transfer of bamboo construction techniques to the local community by building various (touristic and community) constructions together. These projects have meant a significant step forward in the entrepreneurial development of the village by bringing, in collaboration with the PUC University of Rio and KU Leuven, technical knowledge on bamboo and other non-conventional materials. Simple construction techniques have been used in the building processes to make local execution feasible and to ensure affordability of the constructions (Bamboostic.be, 2012).

6.1.2 History of Camburi

The history of Camburi is briefly discussed to provide the reader more information of this community and to clarify why this project location was chosen for the Bamboostic project. The municipality Ubatuba extends over an area of 723.88km² along the southeast Brazilian coastline and the Atlantic mountain range land inwards. More than 80% of its territory is located inside the Serra do Mar state park. Ubatuba features over almost 100 beaches and Camburi (nr. 92 in Figure 6.1) is the final coastal town (beach) on the north side of Ubatuba, 50km away from the city center and on the border of the municipalities Ubatuba and Paraty which is at the same time the border between São Paulo and Rio de Janeiro state. Camburi is one of many Quilombo villages in Brazil. These are small settlements created around 1800 by run-away or ex-slaves from former coffee or sugar cane plantations. The historical roots of Quilombos in Brazil provide a critical context for understanding the difficulties they face today. Legal slavery was present in Brazil for approximately four centuries, with the earliest known landing of enslaved Africans taking place 52 years after the Portuguese were the first Europeans to set foot in 1500. The demand for enslaved Africans continued until mid through the 18th century. Most slaves worked at sugar cane plantations or in (gold) mines. Around the beginning of the 18th century, more French and Portuguese entrepreneurs arrived to Brazil whom transformed multiple smaller farms into huge coffee plantations that emerged all over the region of São Paulo. Many of these coffee plantations did however not last for very long. Exemplary to this fact is also

Fazenda Cambory in Camburi that started around 1825 and was declared bankrupt in 1855. It is unclear whether the owners abandoned the plantation and the ex-slaves occupied their land or that beforehand the land was divided, sold or even given to the slaves (Lima, 2016; Mattos & Abreu, 2009). While numerous of such small Quilombo villages have existed for hundreds of years, only in recent decades they have intensified their efforts to gain legal titles to their lands. Unfortunately, they have encountered numerous obstacles, many of which stem from disagreements over the definition of a Quilombo as well as from their socially and economically marginalized position within Brazil (Mattos & Abreu, 2009). After years of legal prosecution, Camburi finally received in 2005 its official legal recognition and land title by the Federal Government (Lima, 2016).

Figure 6.1. Map of the beaches and towns within the municipality of Ubatuba. 2020. https://mapasblog.blogspot.com/2012/01/mapas-de-ubatuba-sp.html.

The Quilombo community of Camburi had lived over hundred years isolated from society, until in 1970 a sequence of events entailed important changes. When the missing part of the BR101 highway between the cities Ubatuba and Paraty was finalized, land grabbers, companies and speculators were drawn from across the country. They used various methods to oust the original inhabitants. In the early seventies, 80% of Camburi was appropriated by two landowners, forcing the local inhabitants to move to less accessible areas or to other cities along the coast (Lima, 2016). In order to protect the Atlantic rainforest extending along the Atlantic coast of Brazil against these real estate speculations but also against farming, wood exploitation and city expansion, the Brazilian government created state parks. In the past centuries, over 84% of the original biome of the Atlantic rainforest had been deforested (Prado, Esteves, Ramires & Begossi, 2015). These state parks protected enormous pieces of primary Atlantic rainforest but some of them also included small villages such as Camburi, Fazenda and Picinguaba. The State Park Serra do Mar, founded in 1977, imposed significant restrictions on the activities of its residents. Their traditional way of life was based on agriculture, hunting, gathering and fishing. Fish or vegetable surplus was sold or traded in Ubatuba or Paraty for manufactured goods. Since the formation of the park, there were put severe constraints on fruit collection and logging wood. Plantations where forest needed to be cleared to grow crops became prohibited. Fishermen were no longer allowed to chop down the specific trees to make their canoes. The environmental restrictions but also its secluded geographical location, a rough sea complicating fishing, the illiteracy of the people made income generation very limited and insufficient to ensure proper maintenance of the population living in the village. Today, approximately 50 families, around 230 people, live in Camburi with primitive fishing, manioc growth and tourism as their main activities. Often fishermen work for several weeks on large vessels at open sea (Lima, 2016).

6.1.3 Climatological region

Being essential to the design and the durability of bamboo constructions, a brief climatological review of the region is presented as the climate of Brazil varies from the tropical north to more temperate zones in the south. The climate in Ubatuba, due to its geographical location at the sea surrounded by the mountainous Atlantic rainforest, is warm and humid. According to Köppen and Geiger, Ubatuba´s climate is classified as Af, meaning a tropical rainforest climate, albeit with noticeably cooler and warmer periods of the year. Regions with this climate typically feature tropical rainforests, usually found along the equator. However, several exceptions exist such as Ubatuba which is not only far removed from the equator, but is actually located just outside the tropics as the Tropic of Capricorn passes the city center (Wikipedia, 2019).

A tropical climate is influenced by the low-pressure area of calm zones with little air movement resulting in cloudy and humid conditions throughout the year (Lauber, 2005, p.85). The relative humidity in Ubatuba, continuous between 84-88%, makes the air moist and damp favoring molds and fungi. The average annual temperature remains constantly high with slight variations. Ubatuba´s average is 25,2°C in the warmest month February and 19°C in the coldest month July. The rain season extends several months with high level of levels of precipitation, even in the driest month. In a year, the average rainfall in Ubatuba is 2552mm. The driest month is June, with 84mm of rain whereas the greatest amount of precipitation occurs in January, with an average of 343mm (Figure 6.2). Buildings in this context need to deal with heat, strong solar radiation, high levels of air humidity and torrential rainfall. Architects are challenged to design buildings that offer comfortable spaces without requiring mechanical cooling systems (Climate-data.org, 2019).

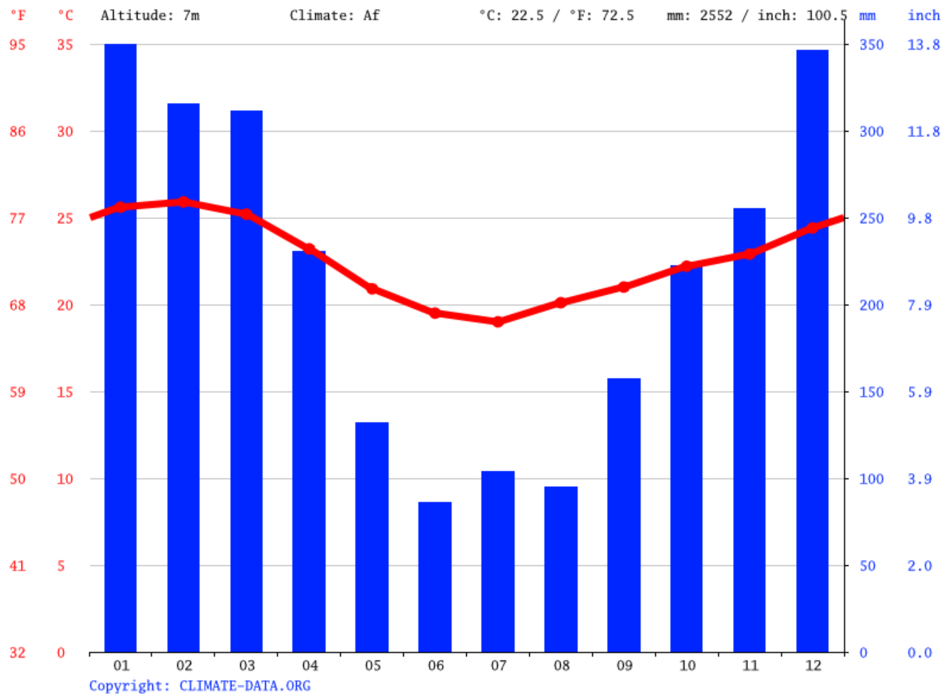

Figure 6.2. Climate graphic Ubatuba. Retrieved from the climate data website. 2019. http://en.climate-data.org.

6.2 **Bridge, Camburi, 2004**

6.2.1 Introduction and Design

The first bamboo construction that was made in the context of the community development project in Camburi was a pedestrian bridge. The community leaders requested Bamboostic to provide for a bridge where at that time a cut-down tree was used to cross an abyss located on a small trail through the jungle, serving as a shortcut from the BR101 highway directly to the town center (Figure 6.3). This tree log became very slippery when it had rained and the situation was prone to accidents. The project posed several severe obstacles such as the difficult access to the worksite requiring descending an inclined slope of 300m. Every day, a power generator (for using power tools), construction materials and work equipment had to be carried up and down this slope. Another difficulty was the impossibility to excavate foundations, without the aid of more heavy machinery, as a result of the rocky ground. Furthermore, only a handful of locals ´helped ` us with the construction, instead of Bamboostic ´helping` them. It was a test case and can even be considered as a metaphorical bridge to the community. If the bamboo bridge proved worthy, the Bamboostic team would be allowed to execute other projects inside the village.

Figure 6.3. Tree-log to pass a large abyss. 2004.

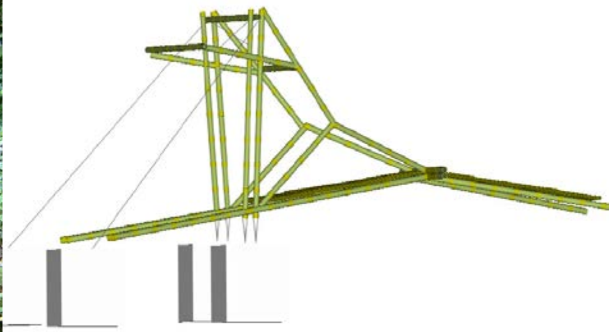

Figure 6.4. 3D design of the bamboo bridge. 2004.

6.2.2 Construction

The construction of the bridge initiated in October 2004. It took the team five months to build it due to the difficult accessibility, the rocky surface, the lack of skilled labour and the relative complex design (Figure 6.4). In Figure 6.5 the pouring of the left foundation is shown. On the right, a prominent rock formation complicated the making of the foundation. As the rock could not simply be cut away on this remote location, an experienced stonecutter was called upon to manually drill holes into the rock to attach armed steel and serve as a part of the counterweight. Subsequently, temporary scaffolding was provided enabling the team to work on the bridge while at the same time the structural bamboo poles were kept in place until the interconnections were made and the tensile cables were attached. The scaffolding was made from Bambusa Vulgaris cut in the jungle nearby (Figure 6.6.). This is a species that is easily attacked by insects due to its high starch content contrary to the Dendrocalamus species used for the final structure of the bridge. The latter were cut from a bamboo bush in the village of Camburi and put into a dry-installation for one month while making the foundations. Thereafter, small holes were drilled into every node whereafter a 30ml solution of borax (25%) and water (75%) was injected, see Figure 6.7). The structural bamboo elements were prefabricated in the town centre during several workshops trying to get more locals involved. For the perpendicular bamboo connections, a common fish mouth connection was used. A wire rod (M14) was bent into a hook and placed inside the bamboo that connects to the 'mouth'. The end piece needs to be carved out perfectly in order to avoid splitting. In case it unequally distributes arriving forces, it can cause the bamboo to crack. The hook is snagged behind a transversally put wire rod in the connecting bamboo whereafter both are tightened together with hex nuts. The so-called fish mouth connection is named as such because the connecting bamboo resembles a fish mouth. To secure this connection, the internode where the connection occurs, needs to be filled with mortar. A hole of 3cm in diameter is made in the upper part of this internode by means of a hole saw. After the filling, this opening is sealed off again with the conserved drilled circle (Minke, 2012). Bamboo sawdust mixed with wood-glue is used to close off the cavities to avoid insects or water entering inside the culm. For a different connection, a galvanized steel plate was placed on the outside of the bamboo to offer an extra reinforcement (Figure 6.8). It is essential to use galvanised steel due to the high humidity. Normal steel is affected very quickly by corrosion weakening the structure.

Figure 6.5. Concrete foundation for the bridge. 2004.

Figure 6.6. Scaffolding in Bambusa Vulgaris. 2004.

Figure 6.7. Borax preservation treatment. 2004.

Figure 6.8. Bamboo connection with an outer steel plate. 2004.

Figure 6.9. Making of bamboo walkway. 2004.

Figure 6.10. Completed bamboo bridge. 2005

After the bamboo structure was finished and the steel cables were fastened to help maintain the structure in place, the scaffolding was carefully taken away. Yet, the right concrete foundation, which was partially drilled into the rock, proved to be insufficient and the bridge began to sink slowly to the left. Immediately the scaffolding was reset and a few meters away from the rock, an entirely new foundation was dug. Luckily, the bamboo structure had suffered no damage because the scaffolding was taken away slowly and consequently the failure occurred gradually. Finally, after redoing the right foundation, the scaffolding was removed again and this time the structure remained into place as intended. For the walkway of the bridge small bamboos were secured onto the bamboo structure beneath (Figure 6.9). Figure 6.10 illustrates the completed bamboo bridge in February 2005.

6.2.3 Analysis

Many aspects could have been improved regarding the design and execution of this project. Firstly, it is incorrect to expose bamboo directly to the weathering conditions. Notwithstanding that in this case a roof covering would not have made a significant difference due to the high humidity level in the dense rainforest. Figure 6.11 proves that where there is little ventilation and a high air humidity, mold and decay can flourish. The mold was not encountered everywhere on the bamboos, merely where water or moist remained longer or where the sun radiation had more exposure. No other bio-based material (i.e. wood) would have withstood similar humid conditions significantly better. Even the wire rods, hex nuts and steel cables suffered from corrosion, despite the fact that it was galvanised material. Secondly, the design of the bridge was too complex for the low skilled workers to truly comprehend thereby making it impossible for them to copy the construction techniques or even repair the bridge when necessary. Thirdly, immediate action should have been undertaken when it was perceived that the rocky surface was impossible to drill into deep enough without the aid of heavy machinery. Fourthly, the bamboo walkway was drilled straight onto the structural and load-carrying bamboo culms of the bridge thereby unnecessarily weakening the bamboo structure. In addition, the small bamboos serving as walkway perished their good condition within less than two months' time and needed to be replaced by hardwood timber panels (Figure 6.12). Finally, applying varnish in such a continuously humid environment appeared to be far from ideal. The varnish could never dry enough to offer a good protective effect. On the contrary, moisture remained trapped in between. In terms of the project itself, other issues needed to be revised as well. No salaries were paid to the workers, all work and involvement in building the bridge was done voluntarily. Yet, it was incorrect to not remunerate the workers for their invested time in the project. As head of the family, these men were responsible for earning a living and could not justify to their families to work without a pay. On the other hand, a compensation should not be as high as a normal wage for it remains a community development project where it has to be surpassed that people come to work only for the money, an investment from their part is required as well. Furthermore, we had to adapt our attitude to a more Brazilian way of thinking. For example, when there are days with tropical rains, it is impossible to work on the construction for the machinery is drenched in no time and the earthen trail turned into mud (or a river). It was only natural that under such circumstances no one turned up to work. It was our typical Belgian way of thinking that we had to continue each day. It is however much better to accept the situation and employ such rainy days for administration, preparational work or the acquisition of construction materials. Finally, it was mistaken to expect immediate results. It takes a certain amount of time to gain confidence and to realize a project in this context (bureaucracy, tropical weather conditions, distance to the city centre,...).

It can be concluded that despite several missteps, the first bamboo project had the desired effect. It prove to the community that the Bamboostic organization kept its promises and had perseverance. The bridge remained in place for six years, even with several degraded and weaker points. It even surpassed a steel/concrete tensile bridge that was built around the same time by the government over another river, yet in the same town. The bamboo bridge was dismantled in 2011 because it became unreliable to cross the bridge and was replaced by a concrete and steel bridge.

Figure 6.11. Mold where there is little ventilation due to high humidity level. 2005.

Figure 6.12. Bamboo bridge with hard wooden timber walkway. 2005.

6.3 **Handicraft Shop, Camburi, 2005**

6.3.1 Introduction and Design

After the completion of the bridge, the local inhabitants manifested more appreciation for the Bamboostic project and more interest in bamboo as a construction material. Meanwhile constructing the bridge, the community leaders had already decided upon a subsequent project, namely a community centre. In the meantime that the author was designing and setting up this project and waited for the permits, other smaller experiments were built. Important to underline is the fact that the Bamboostic project members were always humble and never interfered in the discussion of what type of buildings should be built. It is essential to depart from the community´s demands and needs and not from your proper ideas. Every project was discussed and decided by the community leaders thereby making a clear distinction between our input (tech-transfer & funding) and local decision-making. The first experiment that was built after the bridge was a handicraft shop in the town centre serving for the artisans selling their artwork to tourists. The artisans requested a small yet open structure to expose their handicrafts and making it easily accessible for tourists. Because of the high humidity and for safety reasons, the storage of the handicrafts was not foreseen in the shop itself, but in the private residence of one of the artisans living close by. Rather than a traditional structure, a 'modern' look was designed with a roof slope draining to one side (Figure 6.13).

Figure 6.13. 3D design of the handicraft shop. 2005

6.3.2 Construction

To diminish the environmental impact of the construction and avoid problems with the state park, hard wooden beams were preferred over concrete for the foundation. These beams were partially excavated into the ground (Figure 6.13). The hardwood (Jatobà) proved to be a good alternative to concrete in terms of the counterweight of the structure as well as the stability issue. To prolong its life span, the wood was varnished with a resin. The bamboo species is Dendrocalamus Giganteus of which a small amount was left after the construction of the bridge. The bamboo was cut and treated equally as described in section 6.2.2. The small quantity of bamboo culms defined to a large account the design. The connection between the hardwood and the bamboo culms was resolved by providing a conical aluminium funnel supporting the culms. Two holes of 20cm deep were drilled on each outer end of the triangulation whereafter wire rods were inserted protruding for another 80cm. The funnel and the bamboo culm were placed on top of the wire rod. The funnel and bottom part of the bamboo culm was filled with mortar in order to secure this wire rod inside the culm and maintain the correct direction of each culm. The connections at the top were made with the same fish mouth connection as described in chapter 6.2.2. Smaller bamboos were placed at 30cm distance from each other to support the thatch roof (Figure 6.15). As the roof did only have one slope, the degree of inclination to disperse water was limited. To compensate this, the bamboo columns were put outward-looking. As such, the roof covering extended beyond the construction beneath thereby protecting the base against sun radiation and precipitation. The reed used for the thatched roof was cut by hand on a remote location in the village and carried in bundles for about 15min before reaching the closest road (Figure 6.16). The reed species called by locals is ´Sapé Caipim', however the scientific name is probably '*Imperata Brasilienses*'. Reed has good waterproof capacities, under the condition that it is placed under a sufficiently high inclination.

Figure 6.14. Hard wooden foundation.2005.

Figure 6.15. Bamboo structure. 2005.

Figure 6.16. Reed bundles for the thatch roof. 2005.

Figure 6.17. Completed handicraft shop. 2005.

6.3.3 Analysis

The completion of the handicraft shop (Figure 6.17) took the team three months. When building these experiments, the detrimental consequences of a poor bamboo design were not yet known by the author. This only became clear after a certain time, when the bridge as well as the handicraft shop began to suffer from weathering. From the start, the concern existed that the inclination for the thatched roof would appear to be insufficient. This fear was confirmed when after six month the thatch roof started to show signs of rot as a consequence of stagnating water. Molds and fungi were registered scattered at the underside of the roof. As it was impossible to increase the inclination of the roof, the thatch was removed and replaced by green recycled corrugated sheets. A misfortune because the thatch had a pleasant cooling effect due to its thermal mass and was also preferred for aesthetical reasons. It can be noted that bio-based materials do not allow the same artistic liberty as concrete or steel. For the consecutive projects, a more straightforward design-strategy was applied to guarantee a proper protection of the bio-based materials.

The hardwood foundation resisted the direct contact with the soil (sand) very well, presumably because sand does not retain water well. The hardwood foundation was excavated during the demolition and although some parts were rotten, it was still strong. Nevertheless, questions can be posed to the application (and justifiable cost) of hardwood in a foundation.

The bamboo culms themselves withstood time and weather conditions well, although the lower sun radiation made the culms slowly weather. Varnish was reapplied in the first years after the construction. Yet eventually this was no longer done thereby facilitating weathering. Insects never attacked these bamboo culms hence the borax treatment appears to have been sufficient. Nine years after being built, the handicraft shop had to dismantled because of its poor condition. Similar to the bridge, the design did not permit easy replacement of the bamboo members making it impossible to repair. Each bamboo design strategy should allow for disassembly of a weathered bamboo member for replacement. In general, it can be concluded that when a design protects the bamboo culms well against the weather conditions and regular maintenance is performed, the life span of a bamboo construction is prolonged significantly.

6.4 **Information booth, Camburi, 2005**

6.4.1 Introduction and Design

Another experiment was the construction of an information booth at the exit of the BR101 highway and the entrance to the village. The 3D design in Figure 6.18. shows that the information booth consists of an enclosed room as a storage of products for sale such as postcards, water, etc. and for the guard to rest. Furthermore, there is an open covered area with balcony and a large map of the village. The intention is to inform tourists going to the village and beach, selling items to yield an extra revenue for the community and at the same time discouraging those tourists seeking to buy or sell drugs. The latter is a significant problem in the village due to its great distance from the city centre Ubatuba (50 km) thus there is little to no police control. The vernacular construction technique wattle and daub was tried. This technique is traditionally used by Quilombos (descendants of African slaves), yet nowadays it is slowly disappearing. This design aims to point out to local inhabitants that these techniques are valuable and should not get lost.

Figure 6.18. 3D design of the information booth. 2005.

6.4.2 Construction

Again, with the aim to achieve a lower environmental impact, no pure concrete foundation was used, yet a stone base using the largest type of gravel with cement. The base was lifted 10 to 30cm from the ground to offer protection to the structure and to level the terrain. This time, it was opted to combine wood and bamboo; eucalyptus for the columns and bamboo poles for the roof structure. The eucalyptus columns were not chemically treated and therefore painted with tar as protection.

The roof structure is made in Moso (Phyllo. Pubescens) 10cm diameter. Both were acquired in a local wood store. The bamboo roof structure consists of a triangulated framework equal to a wooden roof structure. The three triangles were interconnected by a tie beam and longerons, using the same fish mouth connection technique as discussed in the previous sections. Although normally twigs are used to make the structure for wattle and daub walls, this time a bamboo framework was provided. Figure 6.20 shows the soil mixture made by mixing the red earth with a small amount of lime by feet. After this mixture is finished, the framework is filled by throwing small amounts simultaneously on both sides of the frame for a better cohesion while smearing it afterwards (Figure 6.21).

Figure 6.19. Bamboo frame for wattle & daub. 2005.

Figure 6.20. Preparation of the soil mixture. 2005.

Figure 6.21. Wattle and daub technique. 2005.

Figure 6.22. Completed information booth. 2005.

6.4.3 Analysis

Already four months after completion, the eucalyptus columns showed early signs of deterioration at the basis, more specifically where the eucalyptus pillar supports on the stone base presumably due to upward soil humidity. Also during heavy rains, the base of the pillars still got wet despite the provided roof overhang of one meter on each side. An even greater roof overhang might have been able to prevent this. Although, a greater roof overhang would have impacted the structure below. It would have been better to provide the eucalyptus columns on a steel pin hovering about 15cm above the stone base to minimize possible contact with water. This technique is commonly applied for wooden pillars on porches. Finally, the tar did not offer any effective protection. Another problem was caused by the ecological corrugated panels that appeared to be of inferior quality and lost their shape (strength) after approximately two years, especially where these panels did not have enough support. The corrugated sheets of the handicraft shop had the same problem. Shortly after, this type of cecological roof panels was taken from the market.

In 2013, Bamboostic project member Liselotte Delobelle executed a new bamboo construction project combining the functions of the previous two constructions (handicraft shop and information booth) on the location of this information booth. The renewed construction was provided in a bamboo structure and rammed earthen walls. As this new construction was not designed nor built by the PhD researcher, this construction will not be further elaborated on in this research. Noteworthy however is the fact that this handicraft shop is still in a reasonable good state (after seven years), although it can use some maintenance.

6.5 **Cylindrical bamboo canopy, Almada, 2006**

6.5.1 Introduction and Design

While building the community centre in the beginning of 2006, another smaller construction was built for a private commission by only a small part of the team in the neighbouring village Almada. The hotel owner of Pousada Casa Mila approached the bamboo team to build a bamboo canopy on top of an existing cylindrical stone tower structure. The owner wanted her guests to be able to relax and sit on top of the tower regardless of the weather conditions. This was a perfect opportunity for the team to put their bamboo knowledge into practice and was a first step towards private commissions. The 3D design of the bamboo structure can be found in Figure 6.23.


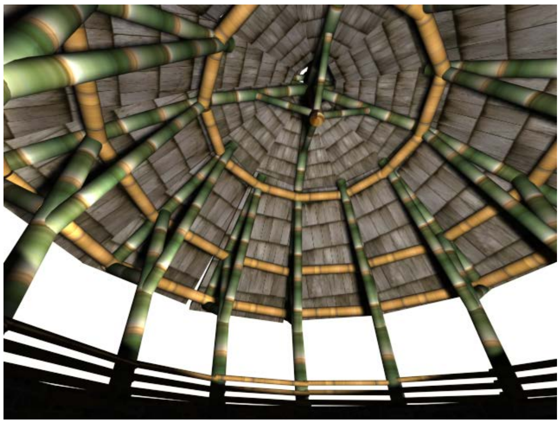

Figure 6.23. 3D design for the bamboo canopy. 2006.

6.5.2 Construction

A typical 'kingpost' structure was provided with a triangulation at the base and a sufficient inclination for a thatched roof. A central post in the top connects the other bamboos in a ringed form, while at the lower side this ring converges to a single point. This triangulated structure facilitates the connection of the upper parts of the bamboo culms. When looking at one of the beams, this forms a singular frame with two triangles. It is nearly impossible to have twelve beams connected together at the top. A central kingpost resolves the connections in a ring rather than to one single point as can be seen in Figure 6.24. For the base columns, the bamboo species Dendrocalamus with a diameter of 16-18cm was used and for the roof structure Moso (12-14cm) because of its smaller (finer) structure. A leftover of the bamboos from the community centre was used and its treatment is discussed in section 6.6.2. The base columns are connected to the brick tower by drilling an armed steel rebars of 30cm length into the bricks. A bamboo culm is put on top of the remaining 70cm wire rod after which the culm is filled up with mortar. The thatch reed is fixated between two small bamboo strips located at 30cm distance from each other. In Figure 6.25 the completed bamboo canopy is illustrated.

Figure 6.24. Kingpost bamboo structure. 2006.

Figure 6.25.Completion of the bamboo canopy. 2006.

Figure 6.26. Bamboo canopy at Casa Mila in Almada.. Retrieved from https://www.tripadvisor.be/Hotel _Review-g303633-d1380374-Reviews-Pousada_Casa_Mila_Ubatuba State_of_Sao_Paulo. (09/10/2019). Posted in February 2019. Copyright Julieta Bueno.

Figure 6.27. Bamboo canopy at Casa Mila in Almada. Retrieved from https://www.tripadvisor.be/Hotel_Review-g303633-d1380374ReviewsPousada_Casa_Mila_Ubatuba_ State_of_Sao_Paul (09/10/2019. Posted in January 2016. Copyright Sara Sampa.

6.5.3 Analysis

This hotel owner was very satisfied and the bamboo canopy stands to date (2020) in relative good condition. Several recent photos were found on Tripadvisor.com posted by guests. The original thatch roof has been replaced by corrugated sheets (Figure 6.27). Otherwise nothing appears to have been modified. The bamboo structure under the roof is maintained as it was originally built. Figure 6.26 illustrates better the current condition of the bamboo culms. Although the bamboos show signs of mold, the varnish seems to have been peeled off by the radiation and some cracks can be noticed, the bamboos do not seem to have been attacked by insects and no other significant problems could be detected on these photos. Maintenance can make the bamboos look new again.

6.6 **Community Center, Camburi, 2005-2006**

6.6.1 Introduction and Design

The community center as it is known to date is built in four different stages. The main building of 172m² was finished in June 2006 and contains an open multifunctional area for community meetings, other type of gatherings and cultural festivities. Adjacent to this multifunctional area, a small kitchen, two toilets and a covered atelier for the bamboo team are foreseen. Furthermore, a separate classroom for the preschool was provided. In August 2009, a smaller and separate bamboo unit was added as office space for the local organization (AMBACA). In September 2011, three extra rooms were built in annex to the main construction of which a computer classroom, a storage room for the work supplies of the bamboo team and a storage room for sport materials (surfboards and footballs) from other community projects. Figure 6.28 shows these three buildings with the dates of conclusion marked. In April 2018, an additional project, a community bakery, was completed.

The decision to provide in a community centre was taken by the community and its leaders. They aspired to bring the community closer together by enabling town meetings, local festivities thereby promoting self-decision on important political, self-governing, organisational and other issues. The requirements for the community centre were suggested and decided by the community members during several town meetings (Figure 6.29). The task of Bamboostic remains limited to tech-transfer and funding of community related projects. The bamboo team united themselves in a cooperative which still exists today (2020) and continues to perform private commissions. Most recent, the team has built a luxurious ecological villa in Itamambuca (Ubatuba) for a local architect, Argus Caruso (Archdaily.com, 2019).

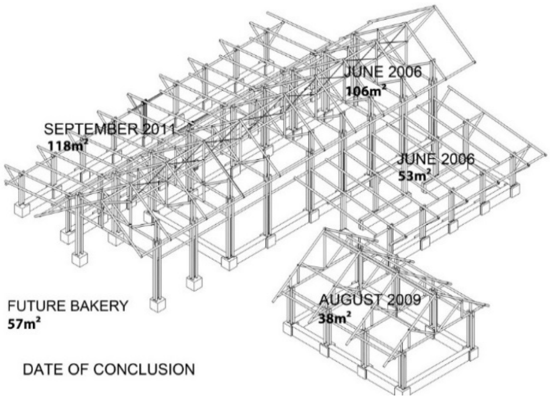

Figure 6.28. Construction dates of the different parts of the Community Center. 2016.

Figure 6.29. Town meeting on the requirements of the community center. 2005.

It was empirically experienced during the previous constructions that building in a tropical region connote humidity. Without proper and constant airflow, so-called wind shadows appear where mosquitoes and mold can proliferate. The main wind directions on the site (50m land inwards from the beach) either come from the sea or go to the sea by falling winds dropping from the mountain range behind. Optimal ventilation could be attained by orienting the community center in the direction of the sea combined with an elevated roof allowing free wind passage throughout the entire building. The design of the building also envisioned the upper part of the construction being open. Krautheim et al. (2014) describe how under warm and humid conditions, higher wind velocities have a positive effect on the physiological as well as psychological well-being. The height of the building aids the buoyancy or stack effect as air will flow in when the warmer indoor air rises up through the building and escapes at the top. The rising warm air reduces the pressure at the base of the building, drawing colder air in when there is a lack of natural airflow and stagnant air.

Another key element in bamboo architecture is proper protection against weather conditions. Such protection is not merely necessary for bamboo, but for any construction material, even more so for bio-based materials such as timber, hemp or straw bale. Only a limited amount of direct rainfall is tolerable for these materials (Quoc-Bao et al., 2014). Firstly, an inert base of at least 30cm needs to prevent moisture uptake from the soil and prevent the rain bouncing off from the ground thereby reaching the bottom part of the culms. In this case, a cement foundation of 50cm high was provided.

Secondly, sufficient large roof overhangs need to ensure protection against sun radiation and rainfall. Although the length of a roof overhang depends on the structural system and height of the building, ideally it is of such measure that in an angle of 45 degrees precipitation cannot reach the basis of the construction (Velez & Von Vegesack, 2013). However, bamboo has a limit to the load it can vertically bear without an extra support of a column or a bracket. In fact, each design is equilibrium between the desired roof overhang and the load-bearing possibilities of the material. When the required roof overhang cannot be obtained, the base should be lifted higher. Additionally, a roof overhang should protect the bamboo against radiation. Despite the fact that an overhang cannot prevent the low winter sun from reaching in during the evenings and mornings, this forms less danger because this radiation is not as strong. Bamboo is vulnerable to the strong sun radiation during middays because the sun slowly heats up the air inside the compartments causing the bamboo to crack (Minke, 2012). The cornice height of the main hall is 3m60 and the ridge height 5,95m with a free span of 4,95m (Figure 6.30). Although in this case the ideal roof overhang (under 45°) would be 1m65, a roof overhang of 1m20 was provided. The part of the bamboo culms still susceptible to rain and radiation were additionally protected by earthen bricks (pressed, unfired) that suffer little from rain abrasion or solar radiation. The cross section also illustrates how the truss is not completely symmetric, the far right corner has been eliminated and the columns are placed underneath the last vertical subdivision. This effect is not provided out of structural need, but to accomplish a visual effect for visitors, opening up the structure from the front side and giving the whole a lighter, aired and grand look. Two lower roofs were added for the classrooms and storage rooms. Thirdly, natural light and how to get the right amount into a building is of importance as well. In moderate climates there exists a need to bring in a maximum of natural light. In contradiction to Brazil where throughout most time of the year the sun radiation is so high that comfort is more associated with diffuse light. The design of the center, with its large roof surface and openings sideways of the building induces diffuse light to enter and avoids direct natural light.

Finally, the sheer force of the wind is another key design factor. Average wind loads in that region are estimated at 5,7m/s, while extreme wind gusts can be as much as up to 7.3m/s (Climatedata.org, 2019). As mentioned, the focus shifted towards a more straightforward architecture by providing a comprehensible framework that facilitated later replication by the low-skilled workers of Camburi. Scale models were applied to explain the idea behind triangulation. By pushing on every side of the scale model, it could be proven to the workers that a triangle is non-deformable. Every rafter consisted of at least one triangle to avoid deformation. The bamboo rafters were set up modularly which enabled prefabrication. The impact of the wind is larger when a construction gains in height therefore it can have detrimental consequences if a bamboo structure is assembled without the provision of wind braces from the start. Demedts (2006) concluded from his PhD on jointing systems for timber frame constructions that when lateral structures are placed in between four columns it becomes a wind brace in itself, much like the fixed connections of the spatial trusses developed by Prof. Eng. A. Vierendeel. Such trusses do not have the usual triangular voids as seen for typical wind braces, but rather employ rectangular openings and rigid connections in the elements which unlike a conventional truss must also resist substantial bending forces. Yet, such a rigid connection can also be formed by the four culms that are laterally cross connected as developed by Demedts. Figure 6.31 is an isometry of one construction module. The fixed connections with a minimum of loads to bear are only connected with wire rods, screws and bolds whilst those connections that capture higher stability forces are filled with mortar, especially when there are lateral forces at stake.

Chapter 3.2 discusses the strength and load bearing capacities of bamboo. The roof cladding of the main roof in ceramic tiles weighs 38,5 kg/m² which equals a total weight of 4.100 kg. Originally, the roof for the pre-school was covered with a green roof (55kg/m² or a total weight of 2.926 kg). However, due to heavy rainfalls and fierce solar radiation, the grass burned and the green roof was replaced by undulated plates (20kg/m²). The 3D design is illustrated in Figure 6.32.

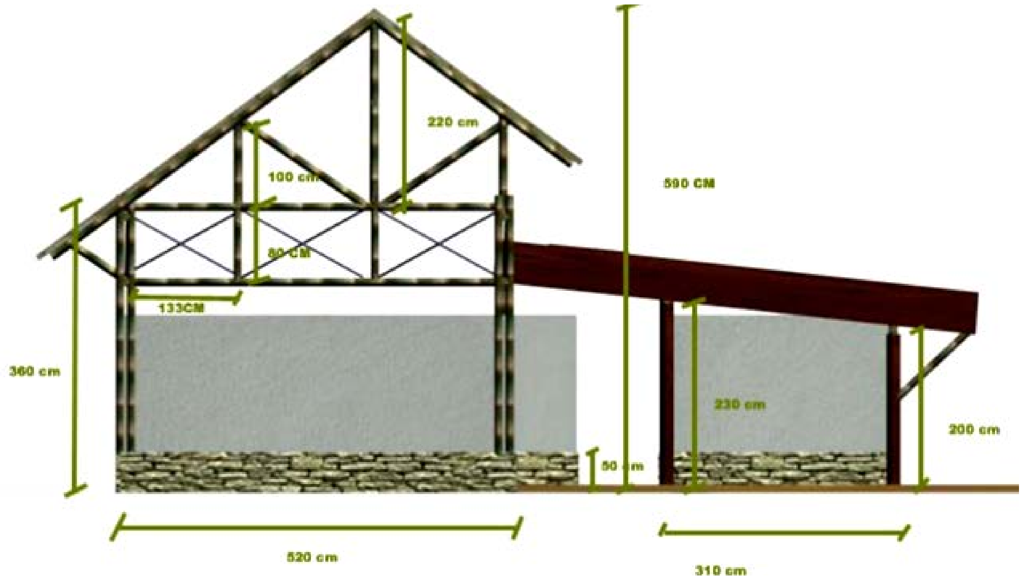

Figure 6.30. Cross section of the Community Center. 2005.

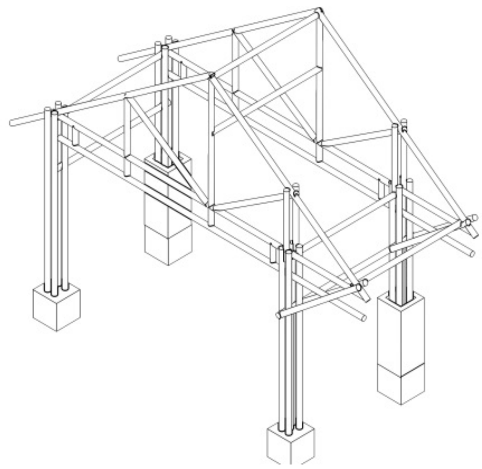

Figure 6.31. Isometry of one construction module.2005.

Figure 6.32. 3D design of the Community Center. 2005.

6.6.2 Preparation

The bamboos for the community center are harvested near the headquarters of the state park Serra Do Mar, situated 10km from the city centre Ubatuba. On this site, a majority of every occurring species in the Atlantic rainforest is planted enabling researchers to study hereon, including the bamboo species Dendrocalamus, Guadua and Phyllostachys. Twenty sufficiently aged Dendrocalamus bamboos were cut with an axe early in the early morning (5 till 7 o`clock) at a waning moon (Figure 6.33). The starch content in a bamboo culm is the lowest during the longer winter nights at the end of the night when it has the least reserves of minerals and starch (Van Lengen, 2008). Thereafter another non-chemical treatment was applied (clump-curing) were the freshly cut bamboos are left in the bush for another two week before the culms are taken out and cut into 4m lengths to transport the bamboos to Camburi (Figure 6.34). Additionally, a large amount of Phyllostachys Pubescens with a smaller diameter (8-12cm) was bought from a bamboo plantation in the interior of São Paulo. Both bamboo species subsequently received a treatment by diffusion in a borax solution of ten percent boric acid and ninety percent water. The bath contained 5000L of water (5m length x 2m width x 0,5m depth= 5m³) hence 20 sacks of 25kg were added (Figure 6.35). When the culm wall is not punctured, it is almost impossible to submerge the bamboo because the internodes are filled with air. Therefore small holes (6mm) at opposed sides were drilled in each internode. Still, even with these holes, it was necessary to bind rocks onto the bamboos to facilitate submersion. In order to maintain a constant percentage of the acid solution in the water, a plastic cover was provided. The other treatment techniques are discussed in detail in section 4.1.2. After 72 hours of submersion in the borax bath, the culms were placed above the bath allowing the solution to slowly drip out the culm. Finally, the bamboos were stacked upright in a tripod drying construction. The ideal drying time would be three months (guaduabamboo.com, 2020). In this case however, the bamboo stems were dried for six weeks in the stacking construction (Figure 6.36).

Figure 6.33. The harvesting of bamboo. 2005.

Figure 6.34. Transport of bamboo culms to Camburi. 2005.

Figure 6.35. The borax treatment by diffusion. 2005.

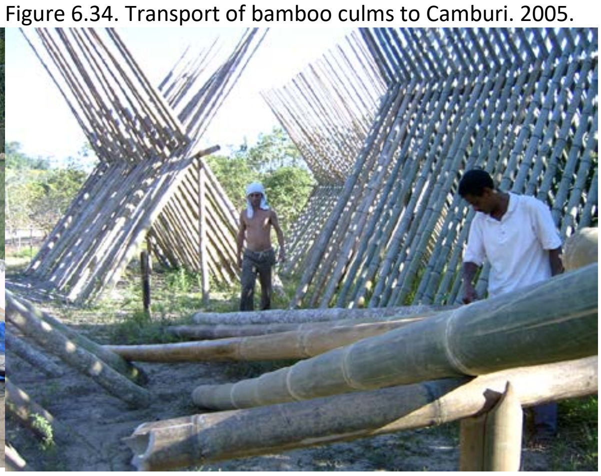

Figure 6.36. Stacking construction. 2005.

The stacking construction should be set up in the shade (the entire day) as radiation heats up the air inside the nodes (between two closed diaphragms) causing the air inside to expand which can lead to the bamboo to crack, sometimes ultra-passing several nodes (guaduabamboo.com, 2020). In most cases, these cracks do not cause a direct danger to the stability, but when rain water enters the culm via these cracks, bamboo can rot from the inside (Minke, 2012). A possible countermeasure is to puncture the diaphragms allowing free transport of air throughout the culm. However, in that case the load-bearing joint connections can no longer be filled with cement.

6.6.3 Construction

At the time of construction, there did not exist specific building codes for bamboo in Brazil. The most appropriate building codes were the Colombian NSR-10 code or the ISO22156 (2004) discussed in section 3.3. The material for the foundation (cement, gravel, sand and reinforced steel) was funded by the municipality of Ubatuba. They provided such a large quantity of materials to construct firm and extended foundations that we questioned if they had little faith in the bamboo construction and wanted certainty that they could easily replace it with a normal brick construction without having to redo the foundations. For each bamboo column, a column foundation of 50cm deep was foreseen with four reinforced steel bars extending 60cm in order to place the bamboos on top. The column foundations are interlinked with a strap beam of 30cm deep. They all protrude 30cm above floor level. Each enclosed space is filled with sand and a final layer of compacted soil. The visible areas of the foundations are finished off with large gravel stones similar to the information booth (section 6.4). The process of the foundations is shown in Figure 6.37.

Figure 6.37. Process of the foundation. 2006.

Only bamboo with a culm diameter over 20cm is utilized for the main columns. The first three to four internodes are punctured to enable placement on top of the steel bars. Especially the first columns need to be carefully positioned and potential deviations caused by the non-orthogonality of the material needs to be divided over all the columns. When measuring, the culms are held into place with wooden boards (Figure 6.38) and only once each bamboo column is properly arranged, the culms are fixated. First a hole of 5cm is drilled with a hole saw 60cm above floor level (size of the steel bar). Next the bottom part is filled with grout. When slightly 'hammered' on the sides, the concrete sinks in tight. Afterwards the drilled hole is tamped again using the same bamboo cap that was drilled out. The viscosity of the mortar (ratio 3:1) is important. When the viscosity is too high, the mixture contains too much water and the mortar will slowly drip out and more importantly the shrinkage of the mortar will cause empty spaces between the culm wall and the concrete which has a negative impact on the resistance to lateral forces (Minke, 2012). On the other hand, when viscosity is too low, the lack of water complicates the insertion of the mortar in the small hole. A good equilibrium is therefore essential. Also, the open endpoints of the bamboo culms need to be closed off to avoid water to remain stagnated inside thereby profilating mosquitos or other insects to breed (Minke, 2012). This was done by placing a piece of plastic on top (Figure 6.39). When small cracks appear, it is best to close these off without delay to avoid water from entering. It is nearly impossible not to have any cracks in the bamboo, yet when these are closed off, they do not pose a structural problem. The easiest, if the cracks are small, is to apply woody putty mixed with sawdust. Smear it into the crack and remove the excess with a damp cloth (Figure 6.40). In case a crack proceeds over more than three nodes, the bamboo culm is best replaced entirely.

Figure 6.38. Placement of the bamboo columns. 2006.

Figure 6.39. Plastic to cover the bamboo ends. 2006.

Finally, the columns are jointed on top with an interspace in the middle for a laterally put bamboo allowing for cross connections. The rafters are attached in one direction whilst the wind braces are put in the opposite direction. As such a fixed joint equal to the Vierendeel framework is retrieved (Demedts, 2006). The bamboos are interconnected with wire rods at every intersecting bamboo. With a large drill bit of at least 30cm, three bamboos are punctured simultaneously. It is nearly impossible to drill each culm separately in advance when these need to be connected in the exact same angle. It has to be done in one movement. Amid the transversely bolted connections, hex nuts and washers are put to keep an equal interdistance. If no nuts and washers would be used in between, the bamboos would be pushed together making the column skewed. Every hollow internode in this connection needs to be filled with mortar to limit displacement and prevent cracking. The distance between the columns (and the rafters) is 2,5m. Not only because commercially available distances are often sold at 2,95m, but also because longer lengths seem to buckle more, deforming the lateral wind braces (Wellington et al., 2007). The multifunctional area consists of 9 trusses supporting on 18 columns.The trusses are prefabricated on the ground. A scale model with the indication of the exact dimensions was used to guide the workers throughout this production process (Figure 6.41. Scale model to help prefabrication of a module. 2006 6.41) and as a casting wooden sticks were put in the ground according the correct dimensions and angle. These tools proved to be beneficial to the construction speed, consolidating the fact that prefabrication is a good solution to accelerate the production process. The rafter is a-symmetric and has a span width of 4,95m. For the trusses, plain fish mouth connections were used. When perfectly executed, this forms a considerably strong connection, but attention has to be given to its detailing, curving it to the exact diameter of the ‘receiving’ bamboo, otherwise uneven forces will cause the culm wall to split. The system of the fish mouth is explained in detail in section 3.5.2. on jointing. Whenever multiple culms need to be jointed in one point such as for example in Figure 6.42, it complicates the execution of the joint. In this case, the holes opposite of these fish mouth joints needed to be exact otherwise the wire rods would contravene. Such a complex joint should better be averted by using another type of jointing method e.g. by inserting or adding another connector piece.

Figure 6.40. Mixture of sawdust and glue to close off cracks. 2006

Figure 6.41. Scale model to help prefabrication of a module. 2006

Figure 6.42. Fish mouth joints in the truss. 2006.

Figure 6.43 demonstrates the placement of the trusses in the main hall. Due to the lightweight of the material, these were lifted manually on top of the columns. After the placement of five trusses, a ridge beam and lateral wind braces were put to interconnect these trusses. Every additional connection enlarges the possibility to withstand wind forces. Halfway the construction, the Brazilian summer with its inherent fierce radiation often followed by tropical rains, proliferated cracking of those bamboos already in place. Loud cracking sounds could be heard throughout the day as a consequence of the air heating up inside the compartments. Although the cracks were miniscule, the urgency to prevent this made the team resort to wrapping the culms in yellow plastic. Nonetheless, this proved ineffective as the cracking continued, albeit at a lower rate. Finally, it was opted to finish the roof on the first five trusses before putting the remaining trusses. For the battens, Phyllostachys Pubescens of a smaller diameter (10-12mm) was used. While several workers varnished the bamboo structure, others already started placing the roof tiles (Figure 6.44 and Figure 6.45) or continued the prefabrication of the missing trusses. Once the bamboo structure was covered by the roof cladding, the loud cracking of the culms stopped.

Figure 6.43. Process of the placement of the trusses. 2006.

Figure 6.44. Varnishing of the bamboo. 2006

Figure 6.45. Placement of the roof tiles. 2006.

Another setback occurred when, due to an improper execution, one of the supporting joints in the top of a column failed. The failure in Figure 6.46 caused one of the trusses to capsize on one side for about 5cm accompanied by a loud cracking until it was stopped by the second connection. The local workers were quite shocked when this happened and started to have second doubts. Upon closer investigation, this poor executed joint was discovered that had no longer resisted the huge forces exerted on it shortly after the placement of the roof tiles. When this error in execution was demonstrated to each of the workers individually, the confidence was slightly restored. Luckily, no real damage had occurred to the roof itself and the joint could be repaired. The team suggested implementing an extra beam beneath all the trusses for cross bracing and extra support.

Figure 6.46. Joint failure (on the left) and the repair thereof (on the right). 2006.

Figure 6.47. Bamboo roof structure. 2006.

Figure 6.48. Completion of the main roof. 2006.

Figure 6.47 shows the bamboo structure from underneath. There is no interior finishing foreseen in wooden planks or drywall. In the first because this is not necessary (only a visual effect) nor very common in this region. Secondly, bats, rats and other animals can nest in between the roof tiles and the roof finishing and finally, maintenance would be difficult considering the great roof height. When the first part of the roof was finished, the remaining trusses could be put into place and the final part of the main roof completed (Figure 6.48).

The pre-school was provided with a green roof. A straightforward construction method sufficed because of the limited roof surface. Every 30cm a bamboo batten was fixated onto a supporting bamboo beam carried by two rows of bamboo columns. On top, wooden boards were put, finished off with a plastic canvas and a thin layer of earth with lawn turf on top (Figure 6.49).

For the ventilation flow, the walls were foreseen with a maximum height of 2m. The gap above the walls was either left entirely open or closed off with a mosquito net infill. Earthen bricks were laid around the bamboo columns after it appeared that some were still exposed to weather conditions. These one-meter high earth brick walls were filled up with beach sand to avoid voids where rodents or other insects could nest in. The community center was completed in June 2016 (Figure 6.51) whereafter a grand opening was organized by the community itself with representatives of the local government, the national park, the PUC University and the Bamboostic team of course.

Figure 6.49. Construction of the green roof for the preschool. 2006.

6.6.4 Analysis

The Bamboostic team started the construction with forty-five workers that had to work according a rotation system due to their large quantity. Each week they had to alternate as only fifteen workers were accepted on site. Payments were done weekly. Already for the previously built smaller bamboo constructions, a salary was paid to the workers. However, when the construction of the community center started, even more locals became interested in participating because it enabled them to earn a wage during a period of eight months in their hometown without the necessity for displacement. Because of the large turnout, the community leaders advised us to lower the wage to a minimum. For one day of work 40 reals was paid, which is about 10€ per day. This and also the hard work that requires a minimum of technical insight and skills reduced the group by a natural selection. By the end of the construction, the team consisted only of sixteen workers (Figure 6.50).

During the eight months of construction, a genuine team spirit arose and practical jokes were daily practice. The members of Bamboostic worked every day together with the team. This hands-on mentality aided much in the acceptance of the project. By building together the endurances were shared. This might not seem important, but it is this specific construction period that the workers still refer to. Some adaptations to the design were made during the construction phase, but always in dialogue. Even the workers made proper suggestions which were often followed. All these aspects induced the fact that the local workers feel responsible for the construction.

Although no severe problems or setbacks occurred during the construction, certain issues were susceptible to improvement. Besides a proper bamboo design, the construction also needs to be carefully executed. When heavy loads or forces are put on a poorly executed joint, this can lead to bending or even to structural failure. The latter occurred in one of the joints after the placement of the roof tiles. Even though that particular joint was repaired the same day and there was no other damage, the local workers lost their confidence which had to be regained by showing exactly what had caused this dysfunction to each one of them separately. When additional support was foreseen, they slowly regained their confidence. This demonstrates the importance to design the joints as such that members can become replaced. Also, a correct planning appeared to be more important than anticipated. Many of the bamboos cracked under the hot summer sun and no precautions had been taken in advance to avoid this. The intention was to start with the foundations approximately in April-May and to complete the roof before the beginning of summer (November-December). However, the building permit had taken longer than expected and preparatory work could only start in September and the actual assembly of the bamboo structure took place the beginning of the summer (November) which increased the urgency for additional protection of the bamboos. An attempt was made by wrapping the bamboos in plastic, nevertheless the heat continued to remain trapped inside. A provisional shed or plastic covering tightened over the entire worksite would have been a better solution. Because the large part of the bamboo roof structure was nearly finished, it was preferred to complete the first segment of the roof rather than to provide for a temporary cover. The project demonstrated once more the influence of the weather conditions, humidity and material selection. For example, initially sisal rope was used to cover metal joints for aesthetical reasons, yet the bamboo beneath began to rot as moisture nestled in between. Although the rope was immediately removed, there had already been damage to the bamboo. It is also because of this experience that the PhD researcher is reluctant in the use of rope lashings. Perhaps, the quality and type of rope used are of great influence.

The local government's financial involvement only stretched to the payment of the foundations and the provision of a lunch for the workmen. Out of insecurity of bamboo, the city engineer had over calculated the amount of concrete necessary for the relative lightweight structure to be built. Yet, it is an illusion that a bio-based construction of a certain size could do without any concrete. In comparison to a conventional building, the amount of concrete (and its inherent pollution) is already reduced drastically. From an architectural and sustainable point of view, the application of concrete in a bio-based construction is not desirable yet from cost-effectiveness point of view concrete is the most logical option. The gravel stone finishing for the foundations proved to be labour intensive. Questions can be posed towards the 'honesty' of such a finishing as it hides the concrete inside. Moreover, the labour required to foresee this stone finishing would not have been financial viable in a commercial project, even despite the fact that labour costs are low-set in Brazil.

Despite the above-mentioned issues, the general feeling towards the Bamboostic project and especially the community center was very satisfactory, both to the project members as the assisting universities. The collaboration with the department of Engineering Sciences PUC-Rio (Prof. Ghavami) is exemplary of how academic know-how could be applied in the field. Only when tested in reality, theoretical knowledge can proof its value and become adjusted to reality. Even more importantly, getting knowledge of bio-based construction techniques to local communities substantially improves the acceptance of these techniques by people who could actually benefit from it, on the condition that it is done using well-designed and copyable examples.

Figure 6.50. The bamboo construction team. 2006.

Figure 6.51. Multifunctional area of the community center. 2018. Copyright Nelson Kon.

6.6.5 Durability analysis

There exists little research on the durability of bamboo in construction. However, in a realistic environment many factors have an impact on the life-span of a construction such as the wind, temperature, humidity, salinity, solar radiation, orientation and wear and tear of usage. This chapter aims to contribute by analyzing the performance of the community center in Camburi, Brazil ten years after the construction phase.

The community center consists of the bio-based materials bamboo, rammed earth and adobe bricks and is constructed in four different phases between 2005-2018. The most recently built construction, a communal bakery, is not elaborated on in this analysis. This section discusses which construction techniques were applied and studies the degradation of the bamboo culms and earthen walls after a decade being constructed. Conducting a destructive research was not possible as the community center is still in use. Therefore, the degradation is analyzed by means of a visual inspection and an interpretation of these observations by linking the findings to scientific knowledge present at the research institutes involved and based on the author´s proper expertise. Three visual inspections were performed between July 2016 and August 2017. The following aspects are outlined in the subsequent paragraphs: molds and fungi; cracking; attacked bamboo by insects; degradation of earthen walls; corrosion of steel connections; others. Every structural culm was closely observed and photographically documented. Figure 6.52 indicates the state of the degradation of each bamboo culm. Where severe degradation was found, the culms are annotated in red. Average to low degradation is marked in orange and yellow and a good condition in green. Overall, it can be perceived that the bamboo structure is in good condition, apart from some problem zones. It can be noted that bamboo in less ventilated spaces and exposed to weathering show more degradation and also that horizontal members suffered more than vertical ones.

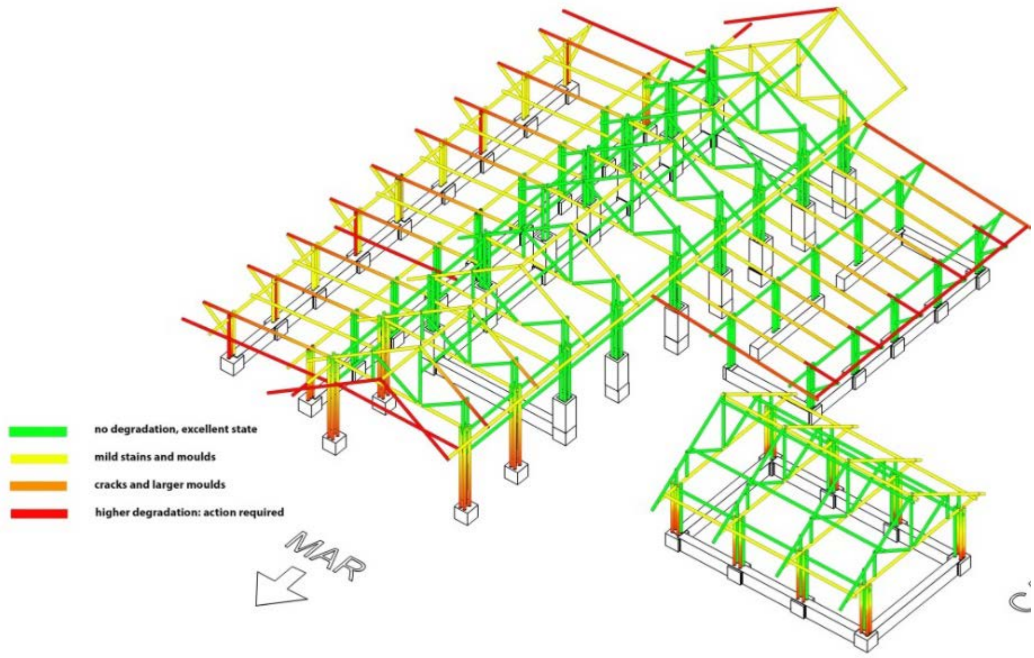

Figure 6.52. Overview of the degradation of bamboo culms. Visual inspection on May 2017.

6.6.5.1 *Molds and fungi*

In tropical climatological regions with high temperatures and a high level of humidity molds and fungi proliferate well. In general, molds are observed on the surface of the culms and at the cross-ends. A borax treatment largely prevents the proliferation of mold, however washing out by the rain reduces its protective efficacy (Tang et al., 2009; Liese & Kumar, 2003). Another determinant factor is the varnish layer that slowly disappears through uv light. Possibly, due to the lubricity of the outer bamboo layer, which is lower when the bamboo culm is unprotected and mold can attach itself more easily to the bamboo in comparison to when varnish is applied (Jianchao et al., 2014). In this case, a significant amount of green and white spots could be observed on the surface of the first truss nearest to the sea, and in a lesser amount on the second and third truss as well, indicating the presence of mold (Figure 6.53). In the design, timber sheathing was provided at the roof end in order to protect the front roof trusses. However, as a consequence of an untimely depart of the Bamboostic project members the sheathing was only provided on the other side. The front truss should be replaced entirely and timber sheathing or another permanent protection has to be put. Because the second and third bamboo trusses suffered considerably less damage, washing and varnishing these should already suffice. On the other end of the main roof, where the timber sheathing was placed, a mild deterioration was observed (Figure 6.54), indicating that although the timber sheathing offers considerable protection to the bamboos, it is still not foolproof.

Figure 6.53. Affected bamboo on the front truss closest to the sea. 2017.

Figure 6.54. Mild deterioration on the front truss closest to the school. 2017.

Figure 6.55. Rotting bamboo ends due to continuous exposure. 2017.

Figure 6.56. Fungi and mold on horizontally positioned bamboo members in a poorly ventilated area. 2017

Figure 6.57. Exposed vertical bamboo members in good condition. 2017.

Figure 6.55 demonstrates the state of decomposition (rot, turning black and easily salvaged) of the bamboo ends of the preschool indicating on an insufficient roof eave. The problem only arises on the outer end-parts of the bamboo culms whilst the remaining part is still of good quality. To solve this, the final counter batten should be inserted more in relation to the end of the roof panel and the affected tops should be sawn off. Optimally the endpoint of a culm has a node or is at least permeated for protection against insects.

The majority of the fungi that damage the cane require moisture content higher than the saturation point of the fibers (Minke, 2012). The combination of the high humidity level and little ventilation in an enclosed area cultivated fungi and mold on the horizontally positioned bamboo members in the storage rooms (Figure 6.56). In contrast to the daily usage of the main building, the storage rooms are predominantly closed off in order to protect the materials stored inside. In addition, the roof height of the storage rooms needed to be lower than the outer left side of the main roof. Therefore the roof of the storage rooms is at its highest only 2,60m sloping to 2,20m. The low height and the closed character of the area foster the relative humidity in the air which results in fungus and darkening of the bamboos. Nonetheless, no cracks are observed. Besides the bamboo culms, also the adobe bricks in these rooms show signs of mold and fungi which is not encountered elsewhere in the construction. Canes with fungus or mold must be cleaned and varnished. In order to structurally remediate the lack of ventilation the walls are best opened up or mechanical ventilation should be installed.

Finally, it was noted that not every bamboo culm relatively exposed to the weather conditions shows signs of decay. Exemplary are the bamboo culms in the association´s office and the columns in the main building. In Figure 6.57 it can be noticed that these are in relative good condition despite their exposure. Horizontal members seem to suffer more easily than vertical ones, probably because of the accelerated water run-off on vertical members whereas horizontal members endorse stagnant moist.

6.6.5.2 Cracking

As a consequence of the longitudinal orientation of the fibers and its low shear strength parallel to the grain, bamboo can easily split. The presence of the nodes does not significantly affect this. Splitting of bamboo is mainly induced by two reasons. Firstly, by a rapid change in the moisture content. Repeated humidifying and drying of exposed bamboo creates cracks in the surface of the bamboo (Figure 6.58). Bamboo is a hygroscopic material which means that it will absorb or expel moisture from or to its surroundings until equilibrium is reached. Water is either retained in the cell cavities (free water) or in the cell walls themselves (bound water). The moisture content is the highest in the growth phase of a bamboo (70%) diminishing to 20% after four to six years when it hardens. Because the moisture content of bamboo also varies in relation to the humidity in the atmosphere, bamboo shrinks and swells accordingly and stresses caused by this sudden drying and/or direct exposure to the sun induces cracking or splitting (Hidalgo-Lopez, 2003; Minke, 2012). As mentioned in section 6.6.3, the latter happened during the construction of the community center. Bamboo behaves best in an average air-humidity between 60-80%. When humidity level drops below 40% cracking is initiated, which was empirically perceived by the author while constructing in bamboo during wintertime in Europe with relative air humidity between 25-35%. Some bamboo species are more prone to splitting than others and a thinner walled bamboo is more susceptible as well. Also, the septum in a bamboo can cause splitting, even if the bamboo dries slowly, because the septum does not shrink along with the rest of the bamboo and when it resists, it can cause a split right at the node. Puncturing or drilling out the diaphragm can offer remediation, yet without this septum mortar can no longer be used as filler in the connection of joints when the natural boundary is disposed of.

Although cracks caused by sudden changes in the moisture content are mostly small of nature, these have to be filled with woody putty or filler. A mix of a two-component wood glue mixed with bamboo or wood sawdust to give it a similar colour is a simple and solid solution to fill cracks and even small holes in the culms. However, when an exceeding load force or direct exposure to sun remains, the crack will return or even aggravates. This solution has to be regarded as filler, not as a permanent adhesion that rectifies design or execution flaws. In the event a crack is wider than 1cm, runs over multiple nodes or occurs in a load-bearing position, the bamboo requires replacement.

Figure 6.58. Cracks that pose no structural problem but need to be adjourned. 2017.

Figure 6.59. Cracks that do pose a structural problem and need to be resolved. 2017.

Secondly, splitting of a bamboo can be caused by poor execution. Perforations can produce cracks. Forcing nails into a bamboo will lead to splitting. Screws are preferred on the condition that first a slightly smaller hole is predrilled. Also, joints designed for contact need to be executed exact. If there is insufficient contact between the culms, forces will be transferred only by the screw and when a joint is subject to high loads, the screw will split the bamboo (Minke, 2012). Cracks caused by improper execution can lead to a precarious stability and should be redeemed immediately, such as the crack in Figure 6.59. Because there was a small cavity in between the upper and lower bamboo, the underlying culm did not offer any support for the upper one once the roof load was put and the weight was carried merely by a laterally placed wire rod causing the culm to crack. This unforeseen load distribution succumbed in time to the weight. From the eighteen equal connections in the main building, this occurred only in one of them and it can therefore be concluded that it was an execution error and not a design error. An agile yet temporary solution is to provide splints to support the top and bottom of the cracked bamboo, yet replacing this particular bamboo culm is inevitable. Noteworthy is the flexibility of bamboo. Even though this deficit had caused a severe crack, this joint never produced a structural problem to the rest of the construction.

6.6.5.3 *Insect attacks*

The large quantity of starch attracts termites and borers that eat the soft inner part of a bamboo, yet also open endings, cracks and holes offer an ideal place for insects, rodents and other animals to nest. In order to guarantee durable constructive bamboo elements, an adequate treatment has to be given to the bamboo. The possible treatment techniques are discussed in section 4.1.2. In this case, a borax treatment by diffusion was given. During the visual inspections, no signs of termites, powder post beetles or other insects that eat the inside were detected. Nonetheless, a visual inspection cannot give a 100% certainty as these insects do not eat the outer hard silica skin but the soft inner layers of the bamboo (Liese & Kumar, 2003). The danger of the infiltration of such insects is that they attack the material from the inside and their presence remains largely invisible, except from leaving small traces (powder dust, miniscule holes and a light ticking noise), only to be noticed when the damage is already being done. Because none of the above traces were found during the examination, it can preliminary be concluded that the borax treatment was effective. It is however of utmost importance that this is regularly monitored. On the other hand, it was perceived that the bamboo rafters in the storage rooms still have the small drilling holes of the borax treatment exposed and signs of small insects (species unknown to author) nesting inside could be encountered. Regardless the fact that these insects would only nest inside, this also spoils the soft inner part and a potent solution of borax/water should be injected and thereafter sealed off with wood glue as described beforehand. Finally, in the top of the main roof structure two nests of wasps were identified hanging from the bamboos (Figure 6.60). These nests need to be removed before becoming a danger to the users of the community center, even though they are hard to reach. The wasps may become hazardous to the people, but in fact these nests do not pose a structural danger to the construction.

Figure 6.60. Nesting of wasps. 2017.

Figure 6.61. Vandalized rammed earthen wall. 2017.

6.6.5.4 *Earthen walls*

The rammed earthen and adobe brick walls, built according the indications of CRATERRE (Guillaud & Houben, 2006), have withstood time and weathering well regardless the mild exposure to radiation and precipitation. The colour and the quality are largely similar to when it was recently built. Obviously, children have tried to scribble on the rammed earthen walls thereby vandalizing them slightly (Figure 6.61). Despite the fact that the walls show marks of writings and some corners are crumbled, the walls could not truly be salvaged. In the rammed earth mixture, no large gravel was used and as a result a smooth and strong surface was obtained that is hard to penetrate. The disadvantage of repairing such walls is the difficulty to obtain the exact colour of the primary wall, which makes repairs very visible. Furthermore, some of the earthen walls from the storage rooms manifest mold near the bottom indicating on a lack of ventilation (Figure 6.62). The closed character of the storage rooms and the fact that these walls stand on the edge of two terrains where plants and trees grow in between blocking air ventilation, favors mold. The mold should be washed off with water and chlorine and the area on both sides of the walls should be cleared from its vegetation.

In regard to the adobe brick walls, it could be observed that those walls that are too narrow to truly imbed the adobe bricks firm enough, have become dislocated, probably caused by children picking at these bricks (Figure 6.63). Two out of fourteen adobe brick walls built around the bamboo columns to protect these were vandalized as well. For the placement of the adobe bricks, an earth/ sand and lime mortar was used that can be damaged effortless. The missing pieces or broken walls should be redone. Figure 6.64 demonstrates that there is nearly no difference in appearance between the culms in- and outside the sand except the omitting varnish. The salty beach sand used as filler seems to have offered an additional protection against (a)biotic attacks and might offer a solution to future constructions were a similar base protection is required.

Figure 6.62. Mold on rammed earthen walls. 2017.

Figure 6.63. Detached bricks. 2017.

Figure 6.64. Bamboo poles protected by square brickwork made of adobe and filled with beach sand. 2017.

6.6.5.5 Others

The corrosion of the galvanized wire rods, hex nuts and washers is in an advanced state due to the high salinity proximate to the ocean, as can be seen in Figure 6.65. The condition of the steel elements inside the bamboo columns cannot be examined, but most likely it is not as corroded as the salted moist air cannot penetrate the bamboo culm. In consideration of armed concrete degradation where only exposed steel corrodes, it can be assumed that likewise the wire rods inside the internodes permeated with grout are better protected because of the mortar. For the construction of the bakery (a community project executed in 2018) fire-treated galvanized steel was used. Fire-treated galvanized steel is mainly used in the naval industry and is half the price of stainless steel. As the project is situated in the coastal region where fishery is predominant, the availability hereof in is not a problem. Treatment of the abrasions with a corrosion resistant protective finish (such as Hammerite©) or daubing the galvanized steel elements with a corrosion inhibiter (WD-40©) as a regular maintenance procedure could alleviate this problem, even after the corrosion has set in.

Figure 6.65. Corrosion of galvanized wire rods, hex nuts and washers. 2017.

Figure 6.66. Darkening of bamboo poles. 2017.

Figure 6.67. Inferior quality corrugated sheets. 2017.

A darkening of the bamboos was observed in correlation their location. Merely the culms in the storage rooms, without exception, have become darker than in the rest of the construction (Figure 6.66). The specific nature of this darkening is unknown to the author, yet most likely it is a consequence of the higher humidity inside the storage rooms. At first sight, this darker colour does not pose any structural problem, but a destructive laboratory test should be performed in order to examine the proper impact of this modification on the inner wall structure.

The corrugated sheets proved to be of inferior quality. After a certain time, they lose their strength and deform completely as illustrated in Figure 6.67. If future budget allows, these corrugated roof panels should be replaced with more durable ones. It will not only benefit the appearance of the building but also better protect the bamboo structure underneath.

6.6.5.6 Conclusion

The main factors that cause deterioration of bamboo are known to be solar radiation, precipitation, humidity, moist soil and insect attacks (Hidalgo-López, 2003). This section illustrates that it is not just one but a combination of these factors that induces bamboo to decay. Contrary to the exposed front trusses of the main building and the bamboo ends in the preschool with obvious signs of decline, other similarly subjected bamboos such as the columns in the associations´ office and main building are largely unaffected. The question hereby rises what factors endorse this duality? Is it provoked by the difference in quality or species? Can it be attributed to its positioning inside the construction (vertical vs horizontal)? Is it the amount of exposure to the weather conditions and does these all have an equal impact (sun vs rain vs humidity)? It is assumed that the age of the bamboo construction determines the decay of the bamboo and that its decline is accelerated when poorly designed or executed which was affirmed during the durability analysis. The visual inspection detected that although the storage rooms were built in 2011, the stage of decay of the culms, being poorly ventilated, is greater in comparison to the deterioration of the bamboo from the main building built five years earlier. The association office built in 2009 appears to be in the best condition showing the least signs of decay.

Traces of small and more elaborate linear cracks were observed throughout the entire construction and albeit these cracks are not a risk to the stability, these could become problematic when rain water enters the culm and starts to rot. Also small insects can infiltrate the bamboo through the cracks and attack it from the inside (where the fibers are weaker than the lubricated outside). Also, when the bamboos no longer have the finishing layer of varnish (peeling off under UV radiation) a more advanced state of deterioration could be noticed. This could possibly be attributed to the fact that the varnish only peels off in places where weathering could take place (insufficiently protected through design) or to the effectiveness of a varnish finishing layer itself when it comes to the protection of the bamboo. It has been perceived that not all varnish types are as efficient. The brand that has given the best result so far is OsmoColour©. An oil-like varnish that penetrates into the pinholes is perceived to be more successful than one that forms a peel. Maintenance of the construction is crucial to avoid or at least reduce the structural capacity of bamboo. The bamboo culms must therefore have adequate spacing for cleaning and removal of mold and should always be foreseen with a finishing layer of varnish, repeated at least every five years (Remadevi, 2015). Also, cracks need to be filled with woody glue mixed with saw dust to avoid insect attacks or rain/humidity from entering (Minke, 2012). Proper maintenance will augment the durability of any bamboo structure but it cannot resolve problems caused by bad designing. Overall, besides small failures, the community center can be considered a well-preserved success. After more than a decade, the construction shows no severe defects and is stilled used on a daily basis.

The durability analysis furthermore underlined the importance of the used connection materials. Galvanized steel proved to be insufficient against the salinity of the sea air. A destructive investigation should be done in order to examine whether the wire rods inside the bamboo are corroded in the same way as this could pose a structural problem. A possible solution could be stainless steel or fire-treated galvanized steel.

6.7 **Veranda, Picinguaba, 2016**

6.7.1 Introduction and Design

The veranda was built annex to the PhD researcher´s house in Picinguaba, a small coastal town located in the municipality Ubatuba. Picinguaba and Camburi are neighbouring towns (15km apart), hence the climatological context as discussed in section 6.1.3. is applicable to this case as well. The main requirements were to extend the indoor with an outdoor living area that offers protection from weather conditions and to implement a laundry area. A light bamboo structure was designed to maintain a spacious area and the laundry was visually separated from the rest by a bamboo wall. The orientation of the veranda was positioned at the back of the house accessed by two sliding doors. An additional advantage was the fact that this location was oriented away from the main sun direction and enclosed that no high wind velocities could affect the structure. Providing sufficient ventilation was not an issue as the entire structure was maintained open. The veranda measures 10m x 3m. The bamboo species Phyllostachys Aurea with a diameter of 50mm was applied. There are eight trusses of 3m length with 1,25m interdistance whilst 4 columns are placed alternately at 2,5m. Hence, a supporting column is only provided every two trusses and the other truss supports on a laterally placed bamboo serving as wind brace. The columns put on the outer line consist of four bamboos each. The trusses sided with the house are attached to the wall of the house (no supporting columns) indicated in the section and isometric view in Figure 6.68.

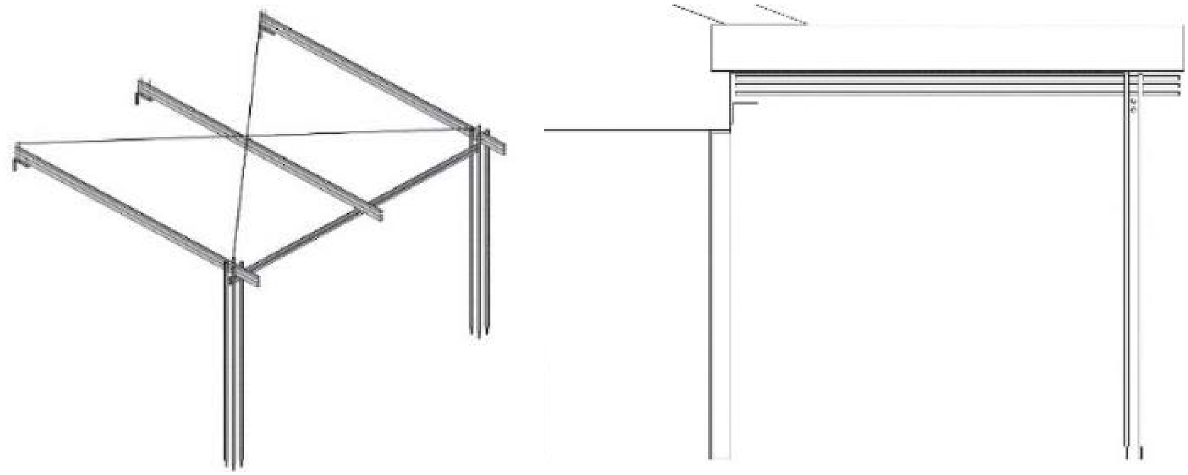

Figure 6.68. Isometric view of one module and a section of the veranda. 2016.

6.7.2 Construction

It is a common bamboo knowledge that bamboo needs to be lifted from the ground for protection, the challenge however is to do this in an aesthetical and elegant manner. In this case, wire rods ½ serve as a connector piece between the floor and culm giving the impression that the bamboos are 'floating'. Because tile flooring and a 10cm thick screed was already existing, no extra foundations were foreseen. Merely 10cm deep holes for the wire rods were drilled into the flooring which were subsequently filled with an epoxy injection before inserting the wire rod that stretched out for about 20cm. Stainless steel was used because of its higher resistance to salinity. Once the epoxy emulsion is completely dry, a hex nut and a 60mm diameter washer are screwed onto the rod, about 15cm above ground level. The bamboo put on top rests on this large washer and hex nut (Figure 6.69). Normally grout would be inserted for stabilization of the wire rod inside the culm. Nevertheless, in this case none of the bamboos were filled with cement. The method of construction employed the present compression where the weight of the roof holds the bamboos down onto the washer and dislocation of the bamboo culms is no longer possible. It has to be noted that given the specific location, no high wind velocities could extract the wire rods from the ground. Therefore, this system cannot just be implemented anywhere. Local wind velocities have to be carefully investigated. Before finalizing the roof, movement of the bamboo structure is still possible but the further in the building process the firmer the structure gets.

The advantage of using a nut and washer to support a bamboo culm is that it can be screwed up or down to align to the targeted culm height and roof inclination. By screwing upward also the pressure is increase and inherently the rigidity of the structure. Replacing the washer by a hard wooden circle with an equal diameter is also possible. Using such kind of connection offers several advantages over a grouted connection. Firstly, it is much easier to replace a member if needed. Secondly, the insertion of cement is a time-consuming process and the construction phase could be accelerated when this can be avoided. Finally, without concrete, the environmental impact of the construction is possibly lower as is calculated in chapter 7 on LCA. Tests on the Chinese Pavilion built by Heinsdorff, where joints with a typical concrete infill were used, pointed out that a longitudinal crack was formed by pushing the steel connector and concrete infill into a bulge in the node when high compression load was applied (Heinsdorff, 2011). The issue is that in this type of connection the loads are not placed on the outside wall where most of the fibers are located, but on the internal internode filled with concrete. It is assumed that concrete forms a 'unity' with bamboo connecting to its wall, however when opening an internode with a concrete infill, this can be taken out in its whole without any adherence to the internal wall. Widyowijatnoko (2012) points out that high compression loads should therefore not be inflicted on the internal diaphragm. Normally, the trusses would require a large diameter bamboo, yet by interlocking 3 slender bamboos with the insertion of two wire rods 3/16, these bamboos co-operate as one. The trusses are prefabricated and then lifted onto their place. One side of the truss rests on an iron hook which is bolted onto the outside wall of the house while the other is alternately supported by a column or the wind brace. A traction cable (5mm) is stretched diagonally between the trusses. It is necessary to put sufficient tension on the traction cables before functioning properly. Only when stretching these cables, the construction becomes rigid. The jointing method used to connect the columns to the trusses is similar to the one used in the community center (section 6.6.3.). A rigid connection can also be composed by providing horizontal cross connections arriving from two different sides in between four vertical bamboo members thereby creating a wind brace in itself as illustrated in Figure 6.70. It is a straightforward jointing system according the fixed connections of spatial trusses by Prof. Eng. Arthur Vierendeel (Figure 6.72). Such trusses do not have the usual triangular voids as seen in typical wind bracing, but rather employ rectangular openings and rigid connections in the elements, which unlike a conventional truss must also resist substantial bending forces. Once again no concrete filling was applied in these connections. Figure 6.72 shows the roof structure in more detail. The roof height of 2m60 was determined by the height of the roof from the house. Atop of the bamboo structure thin whitewashed bamboos were fixated with a 30/4.5 screw onto the upper culm of the truss. The receiving bamboo was predrilled to avoid cracking. Subsequently, OSB plates were placed, finished off with a bitumen layer with an aluminium coating. This coating provides a cooling effect through the reflection of solar rays thereby reducing the heat below. The total roof weight is 28kg/m² and another load of 6kg/m² of expanded clay grains were added for aesthetic and water draining reasons. Hence, the total roof load is 34kg/m² x 30m²= 1.020kg, carried by seven trusses connected to the wall and four columns. Wind load as stated before is negligible because of the specific enclosed location (in a non-hurricane zone).

Figure 6.69. Column base supporting on wire rods. 2016.

Figure 6.70. Detail of top of the column. 2016.

Figure 6.71. Roof structure. 2016.

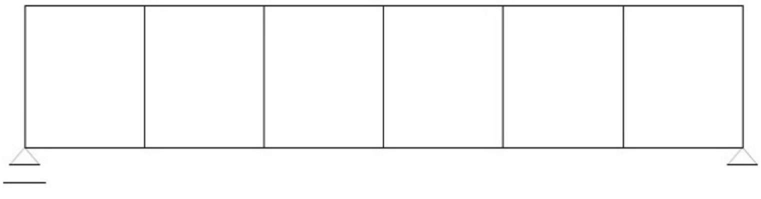

Figure 6.72. Spatial truss by A. Vierendeel. 19 April 2017 Article on the Vierendeel Truss by J.M.Pons-Poblet. http://revistas.unisinos.br/index.php/arquitetura/article/viewFile/arq.2019.151.11/60746935. Copyright J.M.Pons-Poblet.

6.7.3 Analysis

Whereas in the previous cases constantly the specie Dendrocalamus with a diameter between 12 and 20cm was used, the veranda was built with Phyllostachys Aurea of 5cm diameter in order to obtain a more slender architecture. The light appearance of the structure and the ease of construction due to the lightweight of the material were perceived to be advantageous. Besides the architectural aspect, the application of small diameter bamboo also offers additional benefits. Contrary to Dendrocalamus and Guadua that have limited availability in the region concerned, multiple small diameter species such as Bambusa TuldoIdes (Taquaral) or Phyllostachys Aurea (Mirim) are widely spread and free of cost. Especially in tropical countries, small diameter bamboos (4-8cm diameter) are easily found near roads and in smaller forests while large diameter bamboos are mainly located on private domains or commercially exploited bamboo forests (Loboviko et al., 2007). Only a few architects built with small diameter bamboo as it is normally used for furniture or decoration. Vo Trong Nghia, a Vietnamese architect and well-known early adaptor, bundles multiple small diameter bamboos to compose a thicker column. He mainly employs 5cm diameter culms of the native species Bambusa Oldhamii (VTN Architects, 2019). In section 2.1, his work and techniques are briefly discussed. Another benefit is the fact that the purchase cost of a thicker bamboo culm (> 12cm diameter) is nearly equal to the cost of six smaller ones (< 6cm diameter). At a wood supply store in the coastal region of Ubatuba for example, an average of 32R$ is paid for a single 18-20cm culm compared to 28R$ for six smaller ones. Besides the lower material cost and the wider availability, also the greater adaptability is advantageous. The fact that multiple culms are required to assemble one ´thicker` diameter culm, makes it possible to take out a ´bad` bamboo and replace it with another without compromising the structure. All these factors facilitate the application of bamboo, certainly in West Europe where small diameter bamboo grows naturally as well.

The completed veranda is presented in Figure 6.73. The first year after being constructed, mold began to develop on assorted areas of the bamboo culms. As a corrective measure the mold was washed off and the varnish was locally scraped off whereafter the entire structure was varnished anew. The question arises whether this proliferation of mold was generated by the harvest of unripe bamboos, inadequate treatment or the misapplication of the varnish. However, it seems doubtful that the mold was induced by a lack of ventilation because at present the mold did not reappear. Over time, as a consequence of brief yet torrential rainfall that is common in this tropical zone, the water drainage proved to drain insufficiently rapid and the temporarily increased load caused a caused a light subsidence in the middle of the roof. The truss and wind braces in the middle of the roof buckled as can be seen in Figure 6.74. The total roof weight was calculated at 1.020kg, yet when the roof is filled with water an additional 1.500kg (30m² x 5cm – height of the sideboard) is added, meaning almost 150% extra to the original weight. The diameter of the bamboos is at a minimum to receive such high supplementary loads. This bamboo structure was designed based on the experience of the PhD researcher. Calculations with an extra ‘safety-coefficient’ could avoid applying too small diameters in future constructions. In spite of not being very aesthetical, it does not cause any danger because none of the bamboos have cracked. The most appropriate solution would be to replace the bamboos with a larger diameter or to provide a column that supports the center of the wind braces and pushes it back into its original position.

About three years after being built, the truss in the center of the roof requires urgent replacement. In addition to the subsidence described above, the bamboo was attacked by the power dust beetle which correspondingly caused such severe cracks that replacement of this truss became inevitable. The power dust beetle attack was already perceived because of small ticking sounds indicating larvae were eating the inner bamboo and bamboo dust on the floor. Most likely, this insect attack can be attributed to the bamboo treatment because the bamboo was acquired at a wood supply store in the

Figure 6.73. Finished veranda with a light buckling in the middle. 2016.

Figure 6.74. Buckling of a truss. 2018.

center of Ubatuba. The vendor informed us that the bamboo came from a plantation near São Paulo and had begotten a vapour treatment, yet more detailed information was retained nor did the vendor provided the name of his supplier. This case emphasizes again the importance of a proper treatment and when there appears to exist any ambiguity regarding the treatment method, it is best to redo the bamboo treatment to be entirely sure. A contingency plan had to be performed with an insecticide treatment and the replacement of the cracked truss. First, minuscule holes were drilled into every internode of every bamboo in the construction whereafter an undiluted and strong insecticide was injected. This proved to be a very time-consuming process as the veranda is provided with an underroof of numerous smaller whitewashed bamboos. As there exists no guarantee that the larvae have been effectively eliminated, the construction has to be monitored continuously to be able to act immediately when indications of these insects reappear. A quality label for proper harvested and treated bamboo should become norm similar to timber products. This way a consumer is aware of the quality of the bamboo being cut and treated according the correct procedures. The replacement itself was straightforward. As stated earlier, a bamboo design should foresee and allow the replacement of the bamboo members. Because no concrete was used for the fixation of the joints in the veranda, it sufficed to support the roof whilst the nuts/wire rods were simply removed and the bamboo truss was taken out. The insecticide only had a limited effect and in the summer of 2021 the bamboos of the veranda were all replaced by bamboo acquired directly from a bamboo plantation with a chemical treatment. By replacing one column or truss at a time, the structure was never compromised.

6.8 **Art Gallery, Catuçaba, 2016**

6.8.1 Introduction and Design

In general, designing with bamboo can be reduced to the following three parameters:

1) the selection of the bamboo species and its diameter

2) choosing a structural system

3) the design of the joint.

During the previous case, the small diameter bamboo (5cm) proved to contain several advantages in comparison to the application of large diameter bamboo. As a consequence, the author continued to experiment with the Phyllostachys Aurea species in the art gallery and the guesthouse and only the other two parameters varied. For the art gallery, a combination of the bamboo species Phyllostachys

Aurea and Bambusa Tuldoides Munro was employed. These species are both from the Poeceae family, leptomorphic and monopodial, or more popularly referred to as ‘runners’. Because runners pose a problem towards aggressive overtake of other species, they have to be carefully planted and monitored. These species grow best in semi-tropical climates, although they are widely cultivated around the world. Their diameter ranges from 40 to 60mm (Ghavami, 2009). The Phyllostachys Aurea, even though locally available, was bought at the same local wood supplier as the bamboo for the veranda (section 6.7.) at a standardized length of 300cm. According to the vendor, the bamboo comes from a plantation in the countryside of São Paulo where they got a vapor treatment. The Bambusa Tuldoides Munro was harvested at the farm where the art gallery is erected and received a baking treatment, carbonizing the starch and carbohydrates with a blowtorch (Minke, 2012). Laboratory testing in order to determine the exact mechanical properties of the used bamboo is beyond the scope of this research. Therefore, there is referred to existing data such as the research done on the mechanical properties of Phyllostachys Aurea bamboo used at the St Joseph´s school in Mungpoo, India. These results show a highest load of 13.57kN with very little displacement due to the shear failure of the bamboo. Tension tests demonstrate an average load of 2,84kN with an average displacement of 9mm (Sharma et al., 2009). Although other bamboo species can withstand a higher resistance in relation to the culm and wall thickness, this species is widely spread and therefore more easily available. Further research is necessary on the mechanical properties when three of four of these culms are combined into one column.

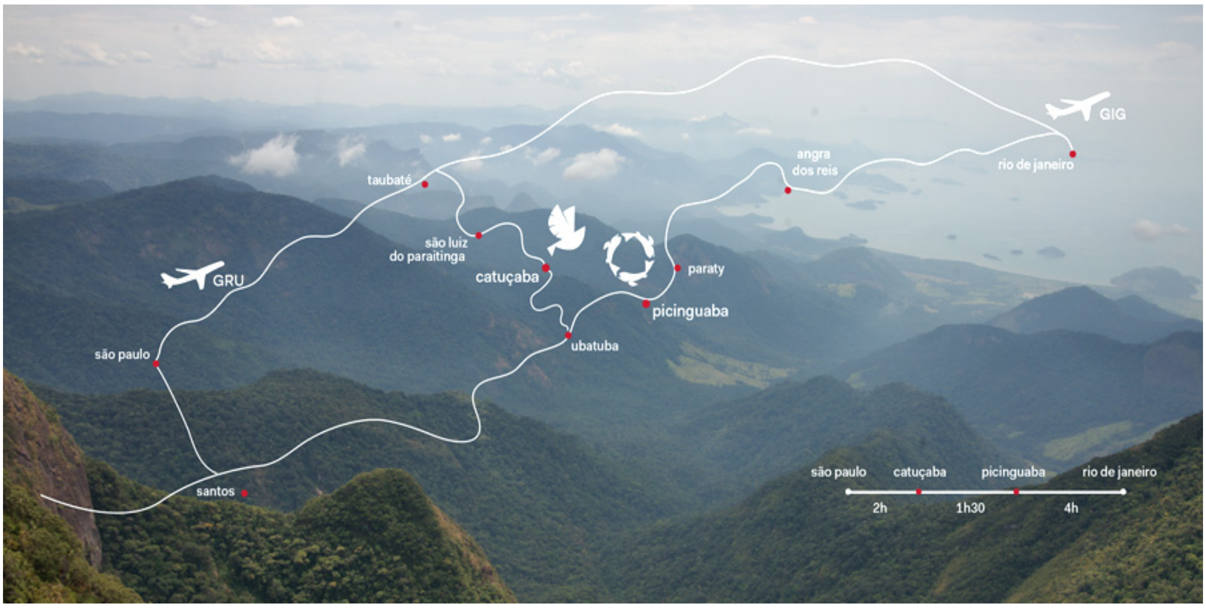

Figure 6.75. Location of Catuçaba in comparison to São Paulo, Rio and Ubatuba (Picinguaba). Retrieved from Fazenda Catuçaba website on 03 June 2017. http:www.catucaba.com.br/location.

Figure 6.76. Hotel Fazenda Catuçaba and the Occa. Retrieved from Fazenda Catuçaba website on 03/06/2017. http/catucaba.com.br. Copyright Ruy Teixeira.

The art gallery is built at Fazenda Catuçaba, a 450-hectare coffee farm turned into a luxurious hotel in the mountain range of the Atlantic Rainforest, three hours' drive from São Paulo. Catuçaba is a modest community and part of the larger municipality São Luis de Paraitinga located at 20km distance (Figure 6.75). In the 19th century, this Paraiba valley was responsible for over 90% of the coffee production of the world, until in 1888 the prohibition of slavery ended this. The mono coffee culture and the influx of European immigrants from the beginning of the 20th century have been the basis of the prosperity of São Paulo. The hotel is located in the Serra do Mar State Park, which stretches out to the coastline in the municipality Ubatuba 50km further (Catuçaba.com.br, 2019). São Luis de Paraitinga is located in a Cfb climate zone or a temperate oceanic climate according the Köppen classification. This is a typical climate of west-coasts in higher middle latitudes and generally features cool summers and cool but not cold winters, with a relatively narrow annual temperature range and few extremes of temperature. It is a climate type comparable to Western Europe. Oceanic temperatures are defined as having a monthly mean temperature below 22° C in the warmest month, and above 0°C in the coldest month (Climate-data.org, 2019). The average temperature in São Luis de Paraitinga is 14.7°C in the coldest month July and 21.3°C in the warmest month January. The altitude of the town is 795m (2,608ft) above sea level. It typically lacks a dry season as precipitation is more evenly dispersed throughout the year. The highest average rainfall is measured 236 mm in January and the fewest in July with an average of 26 mm. (Wikipedia.org – oceanic climate, 2019). Contrary to the equatorial climate of Ubatuba, this area is much dryer and more moderate and hence easier to build in. The bamboo specie Bambusa Tuldoildes Munro vegetates well in this milder climate and can therefore be found on various locations at the farm.

Throughout the hotel property various art installations can be found because the hotel owner conveys that art and nature are intertwined and that art should be presented in a natural environment to become more receptive to see and feel the art. The art gallery hosts changing exhibitions offering hotel clients a changing variety of art. The location of the art gallery is set between the main farmhouse (colonial Portuguese style) and the Occa (Figure 3.0.82); a communal space built according the vernacular architecture of an Indian tribe from the Brazilian Amazon. Figure 6.77 is the 3D design and Figure 6.78 the AutoCAD drawings of the art gallery. The art gallery, arising between the colonial farmhouse and the indigenous communal space, had to unite these two completely different worlds. The design therefore displays the colonial Portuguese style on the outside with its white washed walls and blue doors equal to the farmhouse and shows its Indian heart/core on the inside being the bamboo structure. The narrow passage, the arcs and courtyard in the middle refer to ancient monasteries and hereby try to invoke a contemplative space. A small fountain is situated in the center of the patio from where the water runs back into the river. It is an infinite loop as the fountain water is initially pumped from the river. The art gallery is nearly quadratic (15m x 11m) with a passageway of 2.10m wide. These measurements follow the golden proportion (discussed in detail in section 5.4). The floor plan is divided into 15 squares of 2.10m x 2.10m and every square, except the latter two, has a centered door. By providing thirteen doors, one can enter the gallery from each position augmenting the transparency and simultaneously creating curiosity to discover what is inside. The floor level on one side extends from the building and partly floats over the river giving a visitor the ability to look at the art gallery from a distance and experience better the nature around him. A flat roof of 2.9 m height was foreseen to keep a modest profile, offering the farmhouse and the Occa a primary role. Three existing six-meter high palm trees are integrated in the design and even one of these palm trees goes through the roof. The passageway is covered but maintained open sideways towards the patio. Because the climate conditions are moderate, this open character does not affect the art exposed inside the gallery. If in the future it appears necessary, the art gallery can be closed off with glass sliding doors for which the required foundations have already been put. The floor level is elevated 30 cm from the ground for protection.

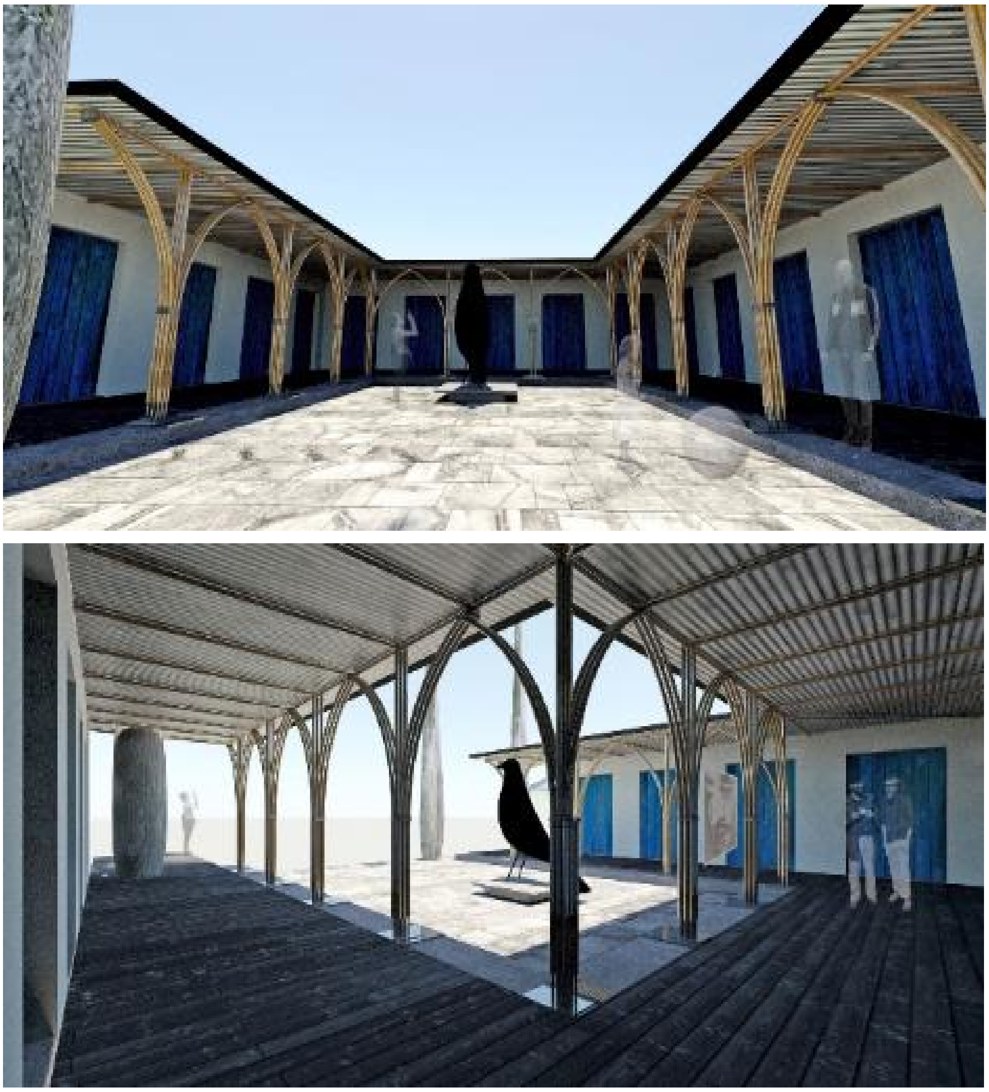

Figure 6.77. 3D design for the art gallery. 2016.

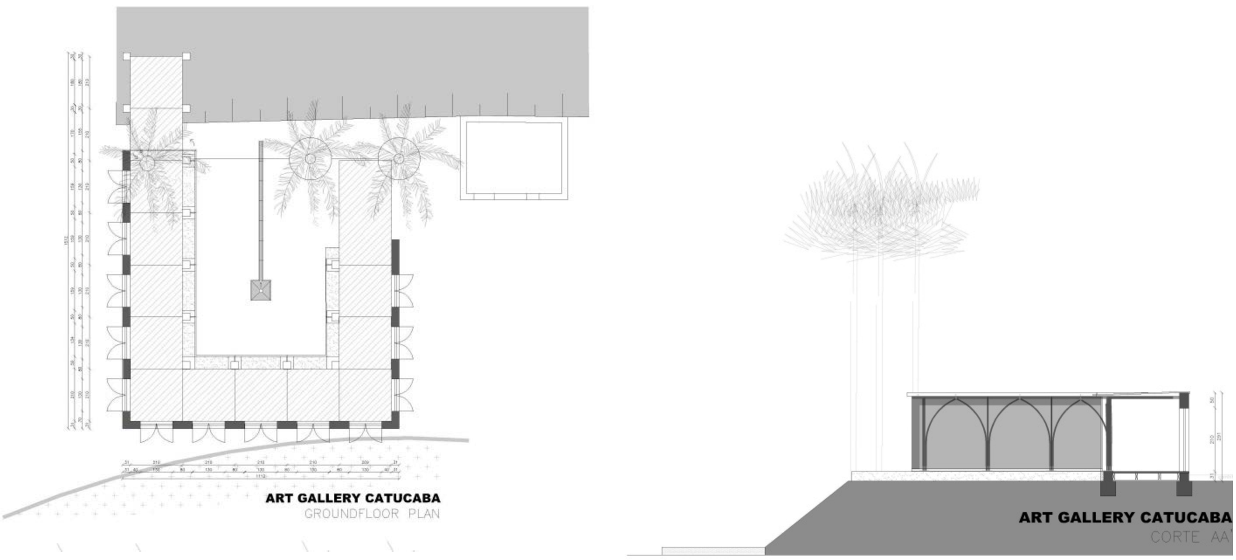

Figure 6.78. AutoCAD drawings of the art gallery. 2016.

6.8.2 Construction

Anew, four bamboo culms are combined to compose a supporting column using the same hex nut and washer system as applied in the previous case studies. A concrete foundation trench of 30cm is provided where galvanized steel wire rods 5/8 are inserted about 20cm into the cement while still wet. These rods extend for 30cm that afterwards the bamboos can be put atop. The concrete foundation is finished off with a hard wooden plate of 20x20x2cm. For the remaining 80cm broad border a combination of blue stone interspersed with weathering steel is used. In Figure 6.79, it can be seen how the hex nuts and washers lift the bamboos another 15cm from the floor level. Phyllostachys Aurea was used for the structure and the locally extracted Bambusa Tuldoides Munro for the arcs.

Figure 6.79. Detail of the foot of a bamboo column. 2016.

In the passageway, three different types of joints are utilized. The isometric view in Figure 6.80 provides a clear picture hereof. First, the four culms are interconnected to a laterally placed truss supported by contrary adhered wind braces according the Vierendeel connection principle. Advantageous to such a joint is that it avoids too many connections arriving at one bamboo thereby weakening it. Moreover, it is a firm connection that is able to withstand wind forces already after two columns are put into place (Demedts, 2006). The second joint connects the arches on top of their curve with a specifically designed 'violin'-shaped hardwood connector piece (Figure 6.81). The third joint is the connection of the underside of the arch with the column (1m from the floor level). The arches support the wind braces and trusses between every two columns and as such become a part of the structural system. Designing a bamboo structure also means designing its connector pieces by drawing straight lines from the direction of the columns, trusses and arches to 'sculpt' the point where they need to connect to each other while simultaneously provide a safe passage of the transferring forces. In the joint design process, one needs to give attention to the possibility of screwing the nuts tight. In the case of the ´violin-shaped joint` a spherical hole was drilled out to enable the attachment of the hex nuts. Also the strength of the wood is essential. No softwood should ever be used, only hardwood of the first durability-class (Sassu et al., 2012). In this case, the Brazilian hardwood Cumaru was used. Connector pieces in joints are of high importance to deduct tension and compression forces onto the bamboo members and generally they are made of steel, aluminium, bamboo or even rubber but very few times of hardwood, although the environmental and cost factors obviously favour wood above metals (Minke, 2012). Although strength tests need to be conducted for the individual design of each connector piece, it is perceived that a hardwood connector is far from the weakest part of the structure. Bending the dried poles of Phyllostachys Aurea appeared to be impossible because the required curve could not be attained to its full extent before cracking of the bamboo occurred. Whilst some sources advice to insert fine sand into the culm to avoid wall-cracking (Guaduabamboo.com, 2020), this also did not suffice. The bamboo Tuldoides Munro was harvested at the farm site as only with fresh cut bamboos ('green') bending can be achieved for these fibers are still flexible. The diaphragms were punctured and in every internode a small hole was drilled in order to release hot air inside (guaduabamboo.com, 2020). A formwork of rebars was put into the ground in order to bend the pole piece by piece securing it in between. A blowtorch, while anointing with gasoil, was moved up and down, only continuing to the next node when it felt the node 'gave way'. Cutting the pole to the right size was only done when a satisfactory curve was obtained enabling to choose the best piece. As one arch is formed by three pieces, each bend culm was left inside the rebar formwork while adding the following one and only take out the formed arches when all three were interconnected by wire rods 3/16 inch. Merely after the interconnection of these arches a rigid shape was obtained. Separately they still wanted to return to their natural shape. A small wooden connector-piece for the top and bottom of the three arches was used to subsequently connect them as a whole to the ´violin` connector piece.

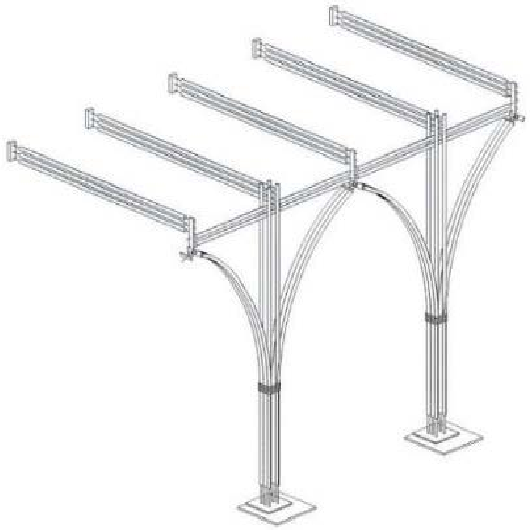

Figure 6.80. Isometric view of the columns. 2016.

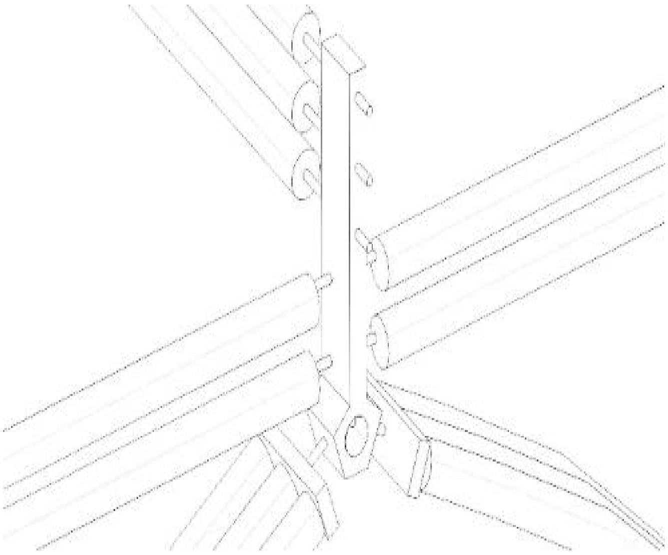

Figure 6.81. Violin connector piece. 2016.

The trusses are assembled by the connection of three small diameter bamboo culms and a wooden batten (50mmx20mm) placed on top, equal as was done in the veranda described in section 6.7. Two holes about 2m apart were drilled through these bamboos and batten at once whereafter a 5/16 inch galvanized steel wire rod is inserted and fixated without the usage of grout or cement. Between the upper bamboo and the wooden batten two hex nuts and washers are foreseen to enable the alignment of the roof. The wooden batten is also required to ensure a flat surface that allows the placement of the roof cladding. The trusses are prefabricated on the ground before lifting onto their place. Similar to the veranda as well, the bamboo trusses are on one side connected to the wall and on the other side supported by a bamboo column, with the difference that in this case a wooden block of 20x10x5cm is encapsulated into the brick wall onto which the trusses are bolted. The advantage of this the roof weight onto each other as was the case in the veranda. The two diagonally system is that the three bamboos of the truss are all separately connected to the wall and do not transfer placed trusses in the corners have a free span of 3.2m, the other 25 trusses have a length of 2.7m. Figure 6.82 illustrates the completed art gallery in 2016.

The walls of the art gallery are built with reused bricks from the site and painted in white. On the outside the wall has a cement finish while the bricks on the inside are left in sight. The roof is covered with aluminum prefab plates of 300x100x6cm that are afterwards covered with Bambusa Tuldoides Munro culms for aesthetical reasons. The bamboos on the roof did not get any treatment as they do not have any load-bearing function, these are merely aesthetical. In case photos are taken from above, the bamboos are visible instead of the aluminum roof. As the art gallery is a freestanding construction, higher wind velocities can add loads to the building, even lifting it. The weight of the aluminum panels is 15kg/m². When adding the weight of the trusses and the bamboo roof-covering it reaches 23kg/m². For the total area of 68.9m² this signifies a total weight of 2.618kg which is sufficient for prevailing excessive wind-loads, aided by the mountainous environment which already offers a natural protection to the construction.

Figure 6.82. Completed art gallery. 2016.

6.8.3 Analysis

The design of the art gallery is based on the human mean (section 5.4.). The height of the bamboo columns, the interdistance between the columns, the width of the passageway and the size of the patio are according the proportional measurements. Despite the fact that whether the application hereof could lead to aesthetical beauty or not, the art gallery appeared in multiple international media such as ArchDaily.com, Designboom.com, Epoca (magazine in Brazil), Architectura.be and others thereby indicating a certain level of architectural quality. The bowed arches refer to ancient monasteries and add value to the building. However, much time and effort went into the bending process and one should question whether this is justified for his/her specific project. Bending a sharp curve is only possible with green bamboo and therefore not always feasible. Moreover, it is difficult to achieve an equal curvature for all the culms. The bamboo stem wants to return to its natural state, which is straight, and needs to be consolidated in its curved state. These elements need to be considered when designing bamboo buildings.

Mechanical testing on the validity of the applied techniques is necessary before transferring them to larger constructions. Large free spans, such as in the projects of Vo Trong Nghia, are generally composed of bundles of small diameter bamboos tied together with ropes or tensioning band whereas these case studies assume the usage of similar techniques as would be used when designing with larger bamboo diameters yet by doubling or tripling the number of culms. The exact amount of load the employed columns, trusses and ´violin` shaped joint can withstand, need to be examined. No buckling, mold, cracks or other signs of deterioration have been registered. Unlike the bamboo from the veranda (section 6.7), the art gallery shows no signs of powder dust, small holes nor ticking sounds that are an indication of insect attacks. It can be questioned whether this can be attributed to the fact that this was another batch where arguably the treatments had led to a better protection or due to the fat that the art gallery is built in another climate zone, being a less humid, more moderate climate with presumably less insects. However, the bamboos need to be monitored regularly because the possibility remains that borers might attack. A small repair to the roof is required since in one of the corners a leak was noticed where the panels do not connect properly. This leak damaged the dry wall plates underneath where signs of molds could be noticed. The bamboo structure however remains unaffected.

6.9 **Guesthouse, Picinguaba, 2017-2018**

6.9.1 Introduction and Design

The location of the guesthouse, equal to the veranda (section 6.7), is the coastal town of Picinguaba. This village is situated at the coast, 40km from the city center of Ubatuba. Picinguaba has identical climatic conditions as Camburi, its neighboring town, being tropically warm and humid as explained in section 6.1.3. In comparison to the veranda, the guesthouse is less protected by existing structures therefore wind loads are higher and a higher roof load is necessairy. The main requirement is to provide in a multifunctional guesthouse where family and friends can stay over for a short holiday while in the meantime the construction can also be used as an additional room to work or for the children to play. The guesthouse should include one bedroom with an adjacent bathroom that is comfortable but not too large. The living room should be spacious and provide for a simple kitchen that makes guests independent from the main house. It is also essential to have a soundproof barrier in order to guarantee the privacy of both the residents and guests.

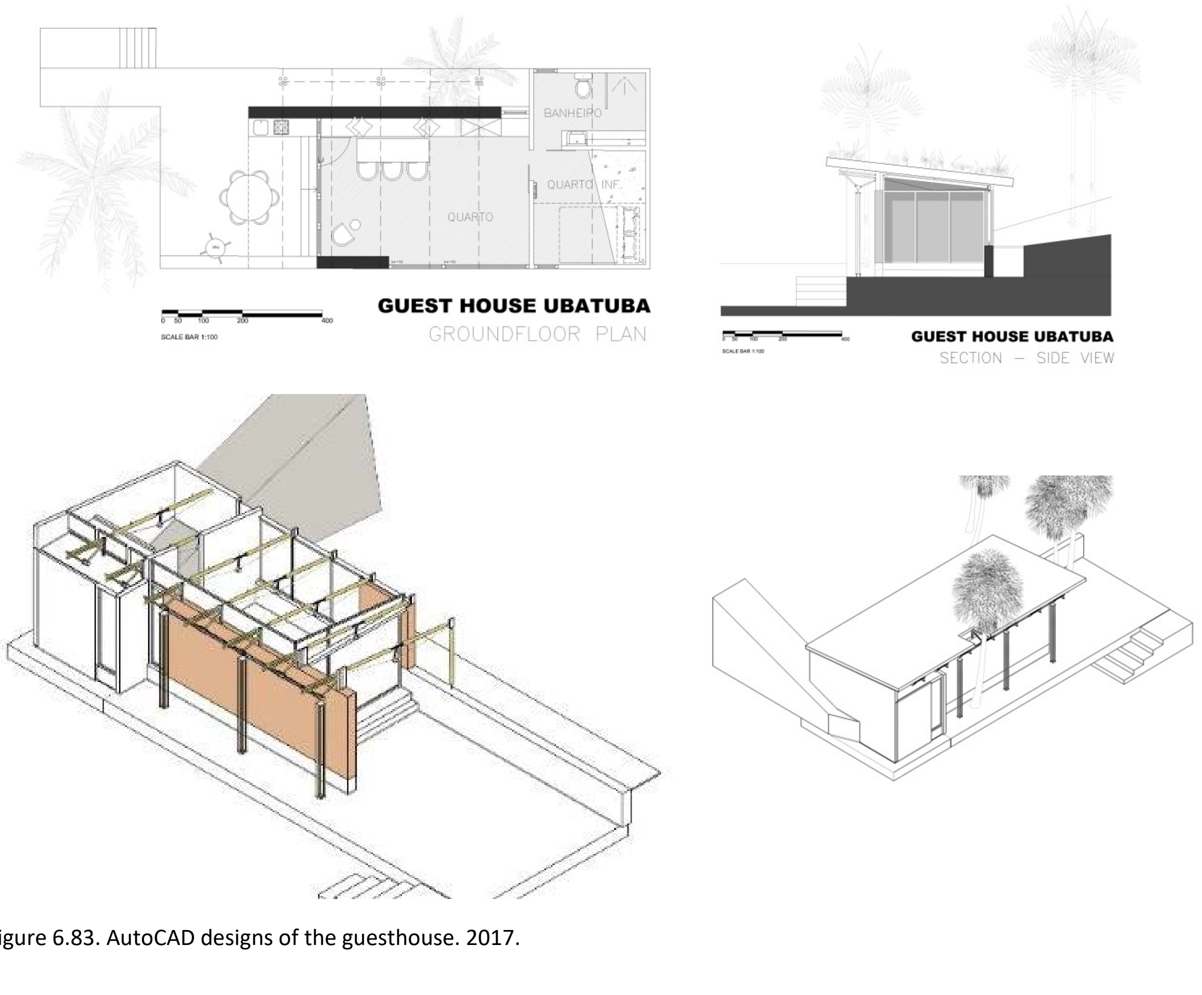

Figure 6.83. AutoCAD designs of the guesthouse. 2017.

Given the project's location remote from the city centre amplified by the fact that the house has no car access and construction materials need to be carried to the site, the idea is to use as little construction material as needed by re-using materials and applying bio-based materials extracted from the site. The rammed earth wall serves as noise barrier and is made with locally excavated red earth. As the terrain lies on a slope, levelling of the terrain was required thereby delivering base material without the input of extra energy. The wooden panels of the formwork used to produce the rammed earth wall were later on applied in the roof structure. The beams holding the framework together became the ring beam. Locally found black earth and plants were implemented for the green roof. A large granite rock present on the left side of the terrain was integrated in the bedroom and in order to maintain an existing palm tree, a square was cut out of the roof. Bamboo was used for the roof structure. To ensure privacy, the large windows were positioned at the back and right side of the building, the front was maintained relatively closed. Figure 6.83 presents the AutoCAD plans (isometric views, floor plan and a section of the house).

Because of its thermic inertia, a green roof produces a difference in low and high-pressure areas in and around the construction encouraging the ventilation (Mertens et al., 2006). The small windows on top of the rammed earth wall provide for cross-ventilation. In every room, the windows can be opened to ensure ventilation, but can also be closed whenever it is colder outside. The roof has a 1.10m eave to the front and a 2m 'free-hanging' eave to the right. Together with a 1,70m extension of the rammed earthen wall, it offers the guesthouse a small private courtyard. As the site is situated on a slope, running rainwater from the mountain needed to be deviated. This was done through a 50cm broad canal behind the house, which later was finished off with a wooden 'walkway/deck`. This was necessary to avoid water from entering during heavy rainfall.

6.9.2 Construction

The guesthouse has a total surface of 36,80m² with a living room/kitchen of 8,50m length by 3,50m enlarging to 5,00m width for the bathroom and bedroom. The walls are either made with cemented bricks or rammed earth. The extended rammed earth wall has a length of 6,30m and is 2,45m high (2.9m including its foundation). There are four bamboo columns. Three of them support the 1,10m roof eave at the front of the guesthouse. The basis is again identical to the previous case studies (section 6.7 and 6.8) because this proved to be an easy and adjustable working method. Yet, the connection on the top differs from the Vierendeel principle of the previous cases. In this design, the four bamboo culms are connected to a steel plate (150x150x8mm) where a wire rod in the middle runs to the joint above, making the whole work as one column. Figure 6.84 illustrates the connector piece that resembles a little ´twitter` bird. It is the second time hardwood is used for the connector piece, although this time the piece is three-dimensional whereas the one in the art gallery was two-dimensional. The upper bamboo culms going to the front of the roof are connected to a small steel plate on top of the wooden sculptured ´twitter` bird and the culms that support the back are connected to a small steel plate at the back of this ´bird`. This upper bamboo structure is not interconnected, only the lateral placed wind braces. On one side these are connected to the ´twitter bird` by a wire rod (1/2 inches) running entirely through fixated on both sides to secure its proper location. On the other side, a wooden plug is inserted in the culm for about 5cm. Timber cylinders inserted in the culm avoids the fragility resulting from longitudinal fracture of bamboo fibers (Sassu et al., 2012). Filling the open end-internode of a bamboo cane also avoids water or insects entering in the bamboo, similar to what a concrete infill would do. Wooden plugs have been used before (Widyowijatnoko, 2012), but rarely with wire rods, hex nuts and washers for tensioning them against another material. As this is a 'new' kind of jointing, it is not safe to apply them without proper testing. In this case, it was an experiment. Following the NSR-10-code from Columbia, a joint either has to be performed at least twenty times or it has to be tested in a laboratory before it can be accepted as a 'conform' joint (ICONTEC, 2006). The final column is composed of a single bamboo culm, species Phyllostachys Pubescens with a diameter of 120mm instead of 50mm. This column is connected on the bottom and top by a wooden plug with an outside diameter equal to the diameter of the bamboo and the inner part less than the internal diameter, wherein a galvanized wire rod 5/8 inch is drilled and secured by means of a hex nut and washer. The steel parts in this project are fire-galvanized as commonly employed in the naval industry. None of the joints have a grouted or cemented infill.

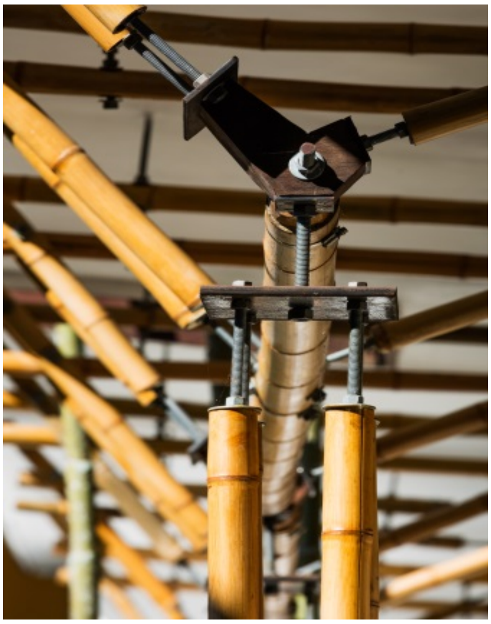

Figure 6.84. Detail of the bird joint. 2018. Copyright Nelson Kon.

Figure 6.85. Bamboo column. 2018. Copyright Nelson Kon.

The trusses can be divided into internal and external trusses, seen in Figure 6.86 . The configuration of the trusses at the front of the house (on the outside) is similar previous two cases where multiple small diameter bamboos are joined to support the roof. About 1/4 of the entire weight of the green roof is transmitted to these seven trusses and three columns in front of the rammed earthen wall (Figure 6.87). For the interior trusses, a new technique was tested; an inverted truss. The bamboo species used is Phyllostachys Pubescens, diameter 12-14cm. The weight of the green roof demands a larger diameter indicating the importance of using the ri ght diameter at the right place. The inverted truss is an innovative solution to prevent buckling in the middle of a horizontal bamboo member. A bamboo culm in a horizontal position, like any beam, is most lokely to deform in the center. This can be observed in a typical bending moment and shear force diagram (Sharma et al, 2011). Instead of an obvious solution to this problem such as the typical triangulated truss or augmenting the diameter/section of the beam, this deformation can also be countered by providing an 'inverted truss' illustrated in Figure 6.88. An inverted truss is a reference to triangulated steel structures. In this case, a 20cm wire rod is foreseen in the middle of the bamboo culm with two tensioned cables running to each endpoint, decreasing the load of the middlepoint. Because these tensioned cables are brought to the point where the bamboo truss is connected to the wall, it cannot modify its position in this orthogonal field thereby preventing bending of the bamboo in the central point. Using this technique, a slightly smaller diameter of bamboo culm can be foreseen, because the bending does not have to be taken into account anymore when designing the total section. Clearly, the total 'strength' of the truss needs to be calculated carefully because failure would be more sudden as there is no possibilty of bending before failure. The result however is a 'lighter' look where otherwise two or three large diameters would have been required to compose a triangulated truss. Jointing the outer ends of the inverted truss to the ring beam is resolved by inserting a wooden 'plug' of which a wire rod is put in the centre hereof. Because of the considerable weight of the green roof, the internode is filled with cement to fixate the wooden plug thus making a stronger connection. The wire rod is subsequently bolted onto the wooden ringbeam by a small steel plate (Figure 6.89). Tension bands are a necessity in this kind of truss because the moment force in the endpoints enlarges the risk of cracking. With a tension band, the structural integrity of the bamboo stem is maintained and all forces can be transferred correctly.

Figure 6.86. Interior and exterior trusses. 2018. Copyright Nelson Kon.

Figure 6.87. Detail of exterior truss and column. 2018. Copyright Nelson Kon.

Figure 6.88. Inverted trusses. 2018. Copyright Nelson Kon.

Figure 6.89. Wooden plug detail. 2018. Copyright Nelson Kon.

Figure 6.90. Earth layer for the green roof. 2018.

Figure 6.91. Green roof. 2018. Copyright Nelson Kon.

The green roof (Figure 6.90 and Figure 6.91) consists of the following layers; (1-) wooden battens that hold up (2-) multiplex boards (formerly used for the casting of the rammed earth) which serve to attach the (3-) dry wall panels for finishing off the ceiling. Above these multiplex boards (4-) a waterproof layer of PDA was placed with sufficient overhang to form upstanding boards at the borders. Above this waterproof layer, (5-) expanded clay granulates were placed to form a water retaining buffer, divided by a (6-) root proof geo-membrane from the (7-) earth layer with sufficient humus for (8-) plants to grow. This total package equals around 82 kg/m², making the total load of the roof 4.206 kg, which is substantially higher than the previous two cases. The roof height slopes from 4,00m to 3,30m which is an inclination of 6% on the total length. Preferably, a green roof has an inclination between 0 to 15% (Mertens et al., 2006).

6.9.3 Analysis

Similar to the bamboo from the veranda (section 6.7), also the bamboo from the guesthouse manifests signs of power dust and miniscule holes indicating an invasion of borers. It is unknown to the author whether these agents first appeared in the bamboo from the guesthouse and then lunged to the veranda, vice versa or if it happened simultaneously. Nevertheless, the proximity of these two constructions plays an important role. In addition, both constructions are surrounded by tropical rainforest where these agents naturally reside. Together with the bamboo of the veranda, these bamboos were injected with insecticide to eliminate the agents. Nonetheless, one of the inverted trusses had been attacked too much and in combination with the substantial roof load finally cracked. No damage to the roof structure occurred and there was immediately put a tension band around the cracked bamboo to secure the integrity. Nonetheless, the culm needs to be extracted and replaced by a new one. Besides this culm, also some of the smaller bamboos in the upper roof structure in the front eave have been attacked by the borers and require replacement although their replacement is less urgent as the inverted truss. The design enables the replacement of one or several bamboo elements. It is of course better to avoid any insect attack and in case the treatment method of the acquired bamboo is not entirely clear, one should treat the bamboo additionally to avoid similar problems. A normative treatment with a quality guarantee could also avoid this. In the summer of 2021, all the bamboos of the guesthouse were also replaced by new ones bought directly from a plantation. The new bamboos have a slightly larger diameter being 6 cm for the smaller ones and 20 cm for the thicker ones.

Unlike the bamboo from the veranda, the bamboo from the guesthouse do not display signs of mold or fungi. Probably because of the positioning of the guesthouse towards the main sun direction and/or the adequate ventilation because of the higher roof height. Nevertheless, the dry wall on the exterior part of the roof demonstrates mold or fungi on the edges yet this can be washed off with water and chlorine. This can probably be attributed to the partial exposure to precipitation The bamboos in the front of the guesthouse that are exposed to the sun, require to become varnished more often as varnish slowly peels off as a consequence of UV radiation. Another culm that suffered over time is the wind brace in the front of the guesthouse where the roof has been cut out for a palm tree. Because this bamboo has no roof protection, it suffered significantly more from weathering decay. This culm has locally become vale and grey/black. In order to protect this culm, it was covered with polyester fibres glued with a raisin. Currently, the weathering has stopped, yet the appearance of the bamboo remains grey/black. Better would have been to protect this bamboo in a better way.

After the positive experience of the hardwood ´violin` connector piece from the art gallery (section 6.8), Parana Pine was applied again for the connector pieces in the guesthouse. This time not only for the joints, but also for the connection of end parts to the wall, the floor or the roof. The ´bird` is a firm joint and poses no problems. Also the wooden plugs in the wind braces (horizontal) and in the single vertical column operate accordingly. Nevertheless, some (not all) of the wooden plugs in the inverted trusses made a slight kink. Probably, the connection of the wooden plug inside the bamboo culm was not entirely perfect indicating the outmost importance that the ´wooden plug` becomes an extension of the bamboo culm and the cohesion of the ´plug` to the bamboo needs to be a hundred percent. Nonetheless, this slight buckling does not pose a structural danger, merely an aesthetical issue. The green roof proves to be successful. The multiplex boards remain their stiffness and do not transport humidity to the dry wall underneath. The OSB panels in the veranda (with a lower roof load) knew a slight buckling indicating that the stiffness of OSB panels is less reliable. The originally planted green, even though largely overgrown by weed, still grows and the roof is relatively green throughout the year. The layer of expanded clay granulates and earth appeared to be sufficient to retain humidity and water for the plants.

6.10 **Bamboo canopy, Guaporé, 2019**

6.10.1 Introduction and Design

The bamboo canopy is designated to serve multiple purposes such as yoga practices, festivities, community meetings in a private, high-end alternative community located in Guaporé (Rio Grande do Sul), Brazil. The bamboo structure had to be provided atop of twenty existing eucalyptus columns. The shape of these columns suggested an oval shaped construction. Advantageous for the design was that these eucalyptus columns ensured a good protection of the bamboo. Even the low summer sun cannot reach the bamboo poles. No walls had to be foreseen as the average temperature in this region is between 10.3°C and 29.6 °C (Climate Data, 2019). A geometrical spaceframe was designed with sculptural truss elements. A flat roof made is foreseen made of MDF plates with an EPDM cover. Figure 6.92 illustrates the 3D design.

The community is situated in the small town of Guaporé in the state of Rio Grande do Sul in Southeast Brazil. Porto Alegre is the capital of Rio Grande do Sul and is situated about 200km from Guaporé. According to the Köppen climate classification Porto Alegre belongs to the Cfa category. A subtropical zone characterized by hot and humid summers and mild winters with an average annual temperature of 19.5°C. The summer temperatures often rise above 32 °C (90 °F). High levels of humidity make the season very muggy. Precipitation is high and regular during all seasons, around 1.348 millimeters annually. This is slightly wetter than Rio de Janeiro with 1.172mm, yet considerably drier than São Paulo (1.457mm) or Brasilia (1.557mm). The winters are mild to cool, rainy and changeable. In the coldest days of the year temperature can fall slightly below zero. Nonetheless, snowfall is very rare, although it has already 229occurred in the past (Climate Data, 2019).

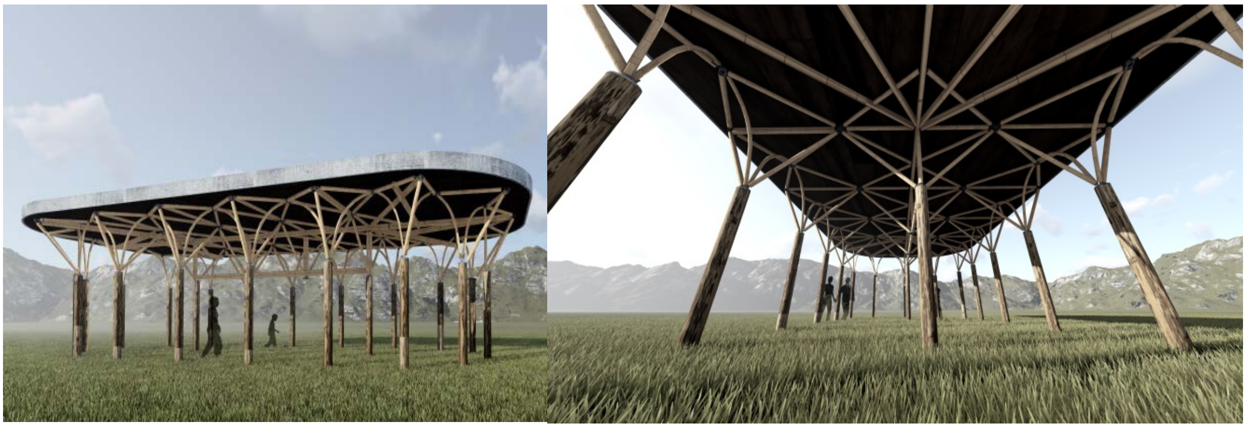

Figure 6.92. 3D design of bamboo canopy in Guaporé. 2019

6.10.2 Construction

Phyllostachys Pubescens with a diameter of 10-12cm was acquired at a bamboo plantation in the region. The bamboo received a borax preservation treatment and in contradiction to the bamboo purchased in Ubatuba, this time the treatment was proven to the author. The design is composed of eighteen modules that can be built on the ground before lifting on top of the columns. There are two rows of four similar modules and the two outer ends each exist of five similar modules, totalling in eighteen modules. In the middle of the construction two additional columns serve as a middle connection point (Figure 6.93). Because of the remote location from the region where the community project members and the PhD researcher reside, the design focused maximally on prefabrication and modularization in order to reduce the construction time. The construction included six different joints which are elaborately discussed in section 3.5.2. Every connector piece was produced beforehand in a local carpentry shop to save time. The construction had to be built in three weeks' time by six workmen; the PhD researcher, one workman from the community project in Camburi and four workmen provided by the client. However, due to circumstances no extra workmen were foreseen and the entire structure was built only by two men in a period of five weeks.

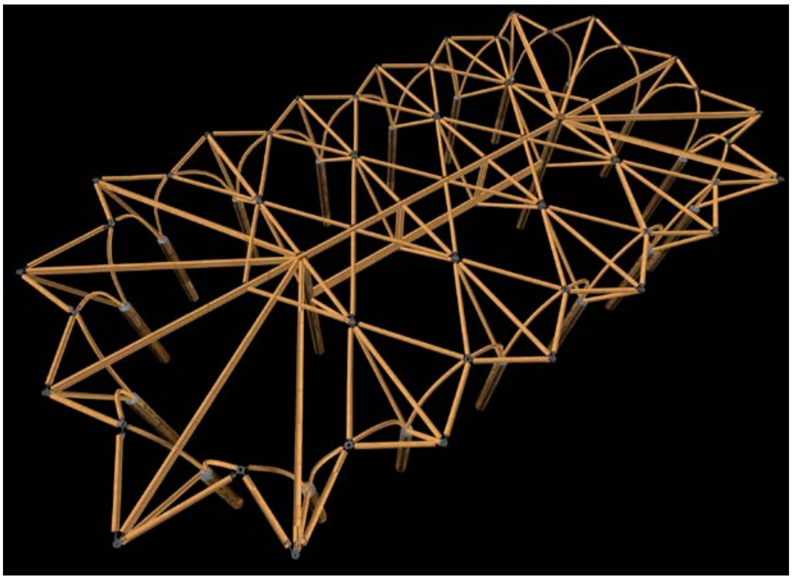

Figure 6.93. Overview of the bamboo structure. 2019.

Each module resembles an angel with its wings pointing backwards and included four different connector pieces. First, a round footing piece that resembles a cake forms the base of the module. This connector piece permits the assembly onto the 3m high eucalyptus columns. These columns have a diameter of 30cm and therefore this connector piece as well. In this piece, four bamboos are connected by a wooden plug secured by a wire rod 5/8 puncturing this connector and fixated on the bottom edge. These joints are filled with cement to secure the poles in the correct angle and to withstand better tensile and moment forces. The second connector piece forms the 'head' of the module pointing forwards. A hardwood round timber piece of 12cm diameter, equal to the diameter of the bamboos, is used to connect the four culms that arrive at this piece by a similar wooden plug and wire rod going through and bolted on the other side. The third type of connection joints the left and right side of the module and is similar to the previous, with this difference that it connects only three arriving bamboos and its shape is slightly different. The fourth and final connector piece is a central key joint and connects four bamboos poles of the module itself and an additional four bamboos of the jointing module.

Figure 6.94. Construction process of the bamboo canopy. 2019.

The modules at the outer ends of the oval shaped construction vary a little with the above described module. The bamboo culms directed towards the eucalyptus columns in the middle needed to have a longer beam to span the distance. This beam is made of two bamboos that are interconnected by a wire-rod 1/2 inches without the use of an external connector piece. Subsequently, five double bamboo beams arrive at each of those two central eucalyptus columns. This would be impossible without placing them at a certain distance from the intersection point. Therefore a bent steel plate is bolted onto the side wall of the eucalyptus column enabling the wire rods to be connected. In Figure 6.94 the construction process of the bamboo canopy in Guaporé is presented. Due to the distance and relatively young age (1 year) of the construction, no analysis was conducted for this project.

6.11 **Conclusion**

The PhD researcher gained substantial practical experience building these bamboo buildings, more than would be the case when just designing them. In every construction, attempts for innovative improvements were made either to facilitate the construction process, to reduce the building cost, to diminish the environmental impact and most importantly to eliminate design errors. Designing with a bio-based material such as bamboo in a tropical humid climate requires detailing and affinity with the material. In every construction, other issues as well as malfunctions appeared. The need for improvement remained, even more because various ‘new’ techniques were introduced such as the application of small diameter bamboos, the hardwood connector pieces and wooden plugs, the combination of the washer, hex nut and wire-rod basis to support a bamboo culm support and the inverted truss. Each of these techniques proved to have strengths and weaknesses regarding the potential for prefabrication, construction quality, adaptability, building cost and environmental impact. These descriptive case studies are presented to show how and with which species and diameter was build and which lessons were learned, hopefully inspiring others to do the same and incentive more research on the architectural side of the subject.

The bamboo species employed in most of the cases is Phyllostachys Pubescens 12 to 20cm and Moso, diameter 8 to 12cm. In the latter three case studies, small diameter bamboo species with a diameter between 4 and 6cm were applied. It is perceived that the use of small diameter bamboos can be as successful as large diameters. The structural strength of the small diameter columns and trusses appeared to be equally good as the larger culm diameter columns, although further engineering test are needed to determine their loadbearing capacity and shear strength. The most important benefits are the lightweight of the material which facilitates the construction process and a more lighter type of architecture can be achieved. Because the availability of particular bamboo species vary depending on the region, it is believed that each case is specific and one should work with what is most logic (geographically and financially). Moreover, also personal preferences play a role. The specificity of working with small diameter bamboos differs only in a few aspects with large diameter bamboos. Where normally one large diameter bamboo culm is sufficient for a truss or a beam, now three or even four culms have to be foreseen, implying a greater creativity in connecting these together. The Vierendeel principle proved to function well for large diameter bamboos (i.e the community centre discussed in section 6.6), as well as for small diameters (i.e. the veranda, art gallery and guesthouse, respectively in section 6.7, 6.8 and 6.9) and appears to be an endorsed system for jointing columns, wind braces and trusses. It can be concluded that three main factors play a main role in designing with bamboo; defining the structural design method, choosing the bamboo type, the diameter to work with and design of the joints. When a specific structural method requires a large diameter bamboo, as was the case with the inverted truss in the guesthouse, one should not limit oneself. Different species and diameters can easily be combined. In the next chapter the environmental impact of both types of columns is assessed in detail in chapter 7 to gain insight in the pros and cons of both types from an environmental point of view.

Regarding the ´new` implemented techniques, a wooden connector piece has been proposed because it is cheaper than a steel connecter piece. It is moreover assumed that the environmental impact of such wooden connector is lower. This will be further assessed in the next chapter. As every building is however different, inherently every connector piece is as well. Nonetheless, several guidelines for architects and/or bamboo builders regarding the use of hard wood connector pieces can aid the designer and might be important to increase the application of wooden connector pieces. Subsequently, it can also be interesting to investigate the possibility and cost of 3D printing of connector pieces with bamboo or wood fibres. This is however outside the scope of this PhD research.

The method of the inverted truss proved beneficial as it contravenes buckling of the bamboo culm in the middle whereupon there can be worked with a smaller diameter and less bamboo culms are required as a triangular frame is no longer necessary. In the case of the guesthouse, the roof inside is carried by merely six bamboo culms of 2.95 meters. The material and labour cost are minimum to build such a light roof structure.

It is furthermore deemed essential that joints are designed in such a way that they allow for replacement and adaptability. This has consequences towards the chosen types of jointing as not all joints allow adaptability and often have to be demolished along with the bamboo member if structural failure appears or changes have to made to the construction. The case studies revealed that the advantage of using washers or wooden cylinders to support the base of a vertically positioned bamboo culm is its adjustability. At any given time, the washers or wooden cylinder with a hex nut beneath can be screwed up and down, adjusting the roof height. This method does not require cement, only the natural load of the roof. It is important that the wall of the bamboo culm is completely supported in order for forces to be transferred evenly to the soil. An imperfect horizontal cut could induce cracking because some parts would be supported more than others or could transfer the loads askew to the foundations. Even though in none of the three cases this problem arose, this could also be the result of the relatively light roof loads. Care should be taken when transferring the proposed connection methods to larger or heavier constructions, which are subdued to large upward wind loads, for it is mainly by the correct amount of compression by weight that the proposed jointing/footing methods have proven valid. The constructions only gained complete rigidness after applying the full roof weight.

Prefabrication of structural bamboo elements is a key factor to reduce construction time and inherently building cost because of time efficiency. In the above cases, the trusses and wind braces were always assembled on the floor while other connections were made at full height. More prefabrication is possible but limits the adjustability during construction. A correct balance in each specific project needs to be found. Prefabrication is design dependent and needs to be well thought of in the beginning of the design.

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CHAPTER 7 LIFE CYCLE ASSESSMENT OF TWO BAMBOO COLUMNS

A life cycle assessment (LCA) can be used in order to quantify the environmental benefits and damages (impact) of a building or a particular construction material. LCA has been established as the main methodology to quantitively assess environmental impacts related to the production and use of goods throughout all stages of a product´s life cycle such as acidification, toxicity, depletion, land-use, waste,… The model reveals a cause-effect relationship between human activities and the environment (Escamilla et al., 2018; van der Lugt & Vogtländer, 2015). The advantage of this method is that it considers the broad range of environmental impacts that may occur over the full life cycle of a building or a material so that the assessment does not remain limited to the operational energy use and the related greenhouse gas emissions (Ramon & Allacker, 2019).

This chapter assesses the environmental impact of two prefabricated bamboo columns as applied in the case studies. Subsequently these bamboo columns are compared to the impact of similar columns in conventional materials in order to understand the pros and cons. There have already been conducted several LCA studies on bamboo, of which the most relevant one is the INBAR technical report nr. 35 by van der Lugt & Vogtländer. However, Van der Lugt & Vogtländer (2015) mainly focus on engineered bamboo products such as flooring and laminated boards whereas this chapter assesses columns in raw bamboo including its steel and wooden components, with and without a concrete infill. Despite the fact that van der Lugt & Vogtländer (2015) mainly focus on engineered bamboo products, the input data and life cycle inventories they use remain relevant for this LCA research. Another difference between both studies is that they have used the data from Idemat 2014, a life-cycle inventory database developed at the Delft University of Technology and for this research the Ecoinvent v.3.0 and the ELCD database serve as a basis for the inventory data. Finally, the INBAR report nr. 35 uses a damage based model (Eco-indicator 99) and in this case the MMG (TOTEM) method is used as the latter considers a wider range of environmental indicators. For the LCA, the SimaPro v.9.1.0.8 is used. Special attention is given to the effect on climate change in line with the IPCC 100a method because this is one of the most problematic environmental issues the world is facing today. Therefore long-term emissions are excluded because it gives a somewhat false idea on ecology.

According to the ISO standard 14040, an LCA study should include the following steps: definition of goal and scope, definition of the life cycle inventories, impact assessment and finally interpretation of the results (ISO, 2006). Section 7.1. describes the **goal and scope** of this LCA alongside the set-up of the research. **The life cycle inventory** is listed in section 7.2. and in section 7.3 the **impact assessment method and its results** are presented. In the final section (7.4.), the **interpretation and conclusions** of the findings are discussed.

7.1 Goal and scope

The aim of this LCA study is to analyze whether a prefabricated modular bamboo column as proposed in the case studies is beneficial with respect to its environmental impact. For the assessment, a column is opted as it is seen as a representative element, i.e. it can be used in any orthogonal bamboo structure or skeleton. The reason that a column is preferred over a beam is the fact that in practice bamboo is more frequently used as loadbearing element along its fibers (both in tension and compression) than perpendicular to its fibers. The elasticity of bamboo also provides a differentiated outcome with regards to other materials when used as a beam. Bamboo demonstrates a linear elastic behavior as the internodes take the weight addressed to it while these forces are deduced in a straight line to the ground.

Two types of prefab columns are analyzed, i.e. a single pole bamboo column and a column made by the jointing of four smaller bamboos. These columns are compared to each other and also to variants hereof; with vs without a grouted infill, treated vs untreated. In order to make a meaningful comparison, a good comparative base needs to be defined beforehand, called the functional unit (FU). The FU in this study has been defined based on the loadbearing capacities. Both bamboo columns have a height of three meters because this is a standardized size at which bamboo culms are commonly sold as larger lengths complicate transportation. From literature and the Columbian norm NSR-10, we can derive an average working loadbearing capacity for the selected bamboo (section 120/10mm) of 13,73 kN for a column of 3m height (1373kg), based on the critical factor (buckling). Whilst the average compressive strength of the bamboo is 63 N/mm² or 6.3 kN/cm² (see chapter 3.2.1), the buckling-limit at this height determines the load that can be taken. This hence leads to a loadbearing capacity of 13.73 kN as functional unit for the height of a 3 m bamboo column.

The bamboo columns are prefabricated as one piece hence the connections on top and at the bottom are included in this analysis. For the assembly, steel wire rods, nuts and washers are used as well as a Parana Pine wooden end-piece that transfers the load that passes the wire rods to the walls of the bamboo. In neither of these bamboo columns concrete was used to fortify the joint connection. In many cases, the weight of the roof can play the same role as a concrete infill; holding the bamboo into place. Nevertheless, whenever strong uplifting winds are to be expected in combination with a low roof weight, the joints are reliant on a concrete infill. In order to gain a better insight in the exact impact of concrete, the column is modelled with and without a grouted infill. Figure 7.1 illustrates the life cycle processes of raw bamboo.

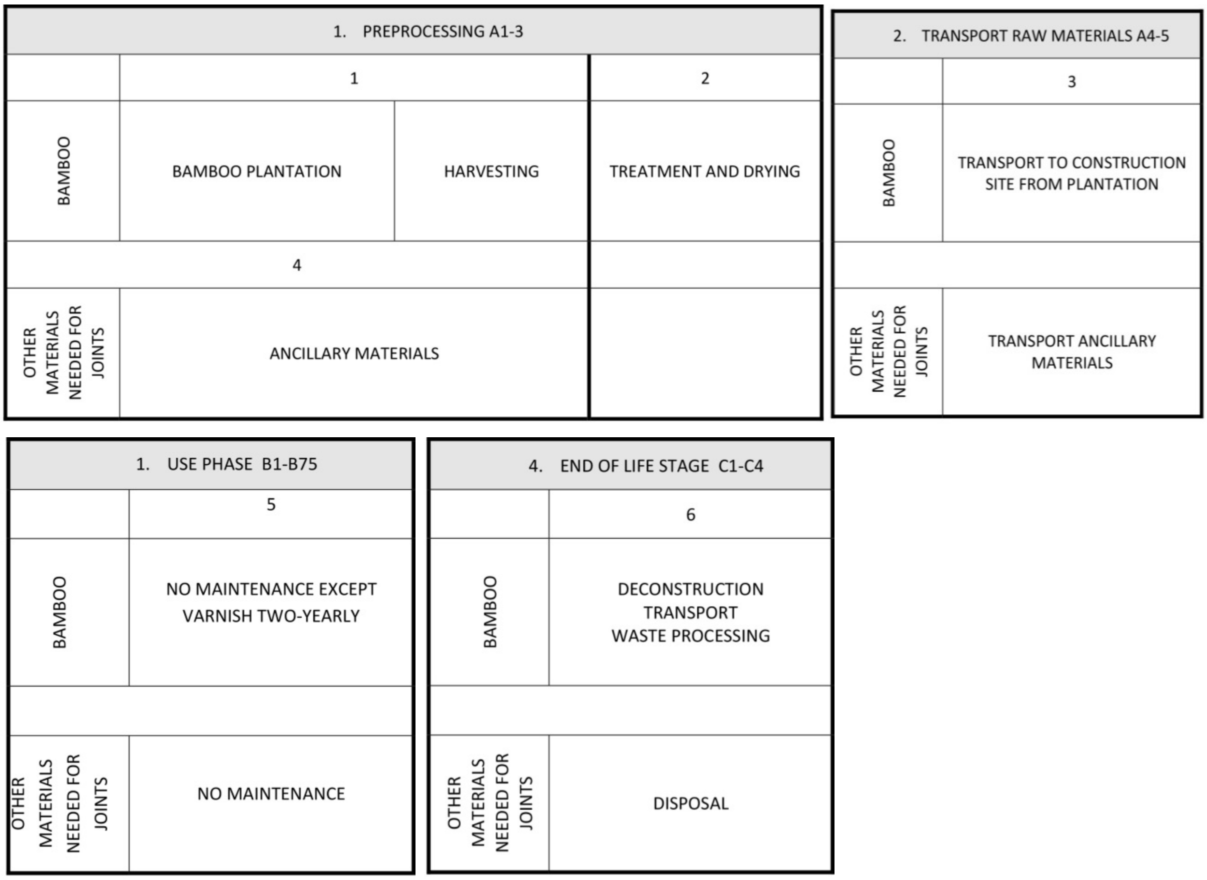

Figure 7.1. Included phases in the LCA of the bamboo columns. 2018. Retrieved from Industrial or Traditional Bamboo Construction? Comparative Life Cycle Assessment (LCA) of Bamboo-Based Buildings. E.Z. Escamilla et al. 2018. pp. 4.

For comparison, also an overview of the life cycle stages for conventional materials is given below in Figure 7.2.

A1-A3: The main difference in the preprocessing or product stage is the fact that the product stage of conventional materials already need to include transport of the raw material supply and the manufacturing process hereof whereas the preprocessing stage for bamboo encompasses only the plantation, harvesting and treatment/drying method. With Ecoinvent v.3, market and transformation processes were introduced meaning that the input from production in other countries as well as the transport-processes is included (Ovam, 2012).

A4-A5: The product stage for bamboo and conventional materials is equal and contains transport to the construction site. For each product group or material category, average transport distances and means of transport have been determined according to whether the product is taken directly from the factory to the site, or from the factory to an intermediate building merchant and from there to the building site (Ovam, 2012).

B1-B7: Also the use stage for bamboo and conventional materials are similar. In both cases the use, maintenance, repair and replacement are considered, although for bamboo refurbishment is not an option.

C1-4: Finally, the end of life stages is aligned in terms of deconstruction, transport and waste processing. The reuse, recovery and recycling potential of each material are different. With the exception of soil, all construction and demolition waste, whether or not sorted on site, needs to be transported from the construction/demolition site to a sorting facility/collection point (e.g. metal dealer or crusher) and from there it is eventually further dispatched to recycling, a reuse facility, incineration, energy recovery or landfill.

D: The benefits of energy utilization (i.e. the avoided impacts of e.g. the Belgian electricity mix or the production of heat from gas) are estimated in Module D. This data has however not yet been taken into account in MMG-method due to its voluntary nature, the still ongoing methodological discussion and developments regarding the formula within CEN and the fact it exceeds the system boundaries of the building (Ovam, 2012).

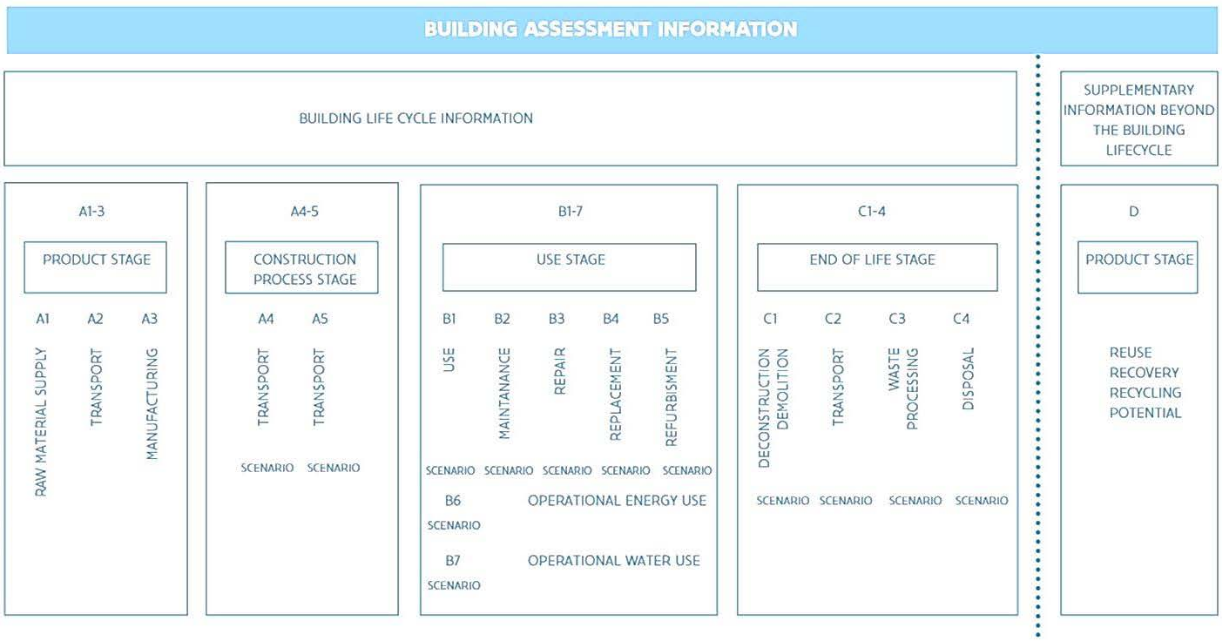

Figure 7.2. Overview of the life cycle stages and system boundaries within the European standard EN 15978:2011. Retrieved from Environmental profile of building elements. Ovam. 2012. pp. 15.

The modular approach of the EN15804 for the declaration of the impact per life cycle stage is followed. Applied to the bamboo columns of this LCA, the preprocessing, construction and use stages are located in Brazil. The bamboo was purchased by the local timber store at a managed plantation in the surroundings of São Paulo. The estimated transport distance is based on a presumed distance between the location of the plantation and the city of Ubatuba. It is also assumed that the bamboo is transported by a freight lorry to the local wood supply store in Ubatuba and also the timber store delivered the bamboo poles to the construction site by means of a lorry.

Although the MMG method takes the end of life stage into consideration, this indicator was not activated in this analysis. The end of life will normally occur in the future and it is unpredictable what aspects will play a role in relation to deconstruction, waste processing and disposal at that time. Module D (i.e. loads and benefits due to recycling) is also not included in the study.

For a better comparison and understanding whether the studied bamboo columns are a valid alternative for a column made of a conventional material in terms of environmental impact, the bamboo columns are compared with a column in concrete, wood and steel. These alternative columns fulfill the same requirements, i.e. height of 3 meters and a loadbearing capacity of 13.73 kN. Identical system boundaries have been assumed: i.e. the columns have been analyzed including the connections on top and at the bottom, yet excluding module C and D.

7.2 Life cycle inventory

During the Life Cycle Inventory (LCI) all flows related to the various elements of the functional unit are being inventoried. For the LCI of each bamboo column, an overview of the materials needed to fabricate this column should be listed including a calculation of the exact amounts required. Additionally, the processes occurring during the service life of the columns need to be defined.

Before describing the inventory of each column separately, the next two paragraphs first describe the modelling of a wet and untreated bamboo stem versus a treated, dried and transported bamboo stem. These extracts form the basis for the further modeling of the bamboo columns.

In Figure 7.3 the inventory of 1m³ **wet and untreated bamboo** is shown. A bamboo stem requires generally a growth period of 4 years before it can be harvested. Extraction of the bamboo generally occurs by means of a chainsaw. According to the Ecoinvent v3.3 database, 0.12 minutes of sawing is needed per m³ of bamboo. The land-use is calculated assuming an area of 0,5m x 0.5m per bamboo stem and a value of 1,84m² is given for the transformation of unused grassland into forest.

Inputs								
Inputs from nature	**Sub-compartment**	**Amount**	**Unit**	**Distribution**	**SD2 or 2SD**	**Min**	**Max**	**Comment**
Occupation, forest, intensive		7,368284402	m2a	Undefined				Sven Mouton (0,5 m x 0,5 m per bamboestengel + 4 jaar nodig om te groeien vooraleer kan worden gerooid)
Bamboo, unspecified, standing/m3		1,00	m3	Undefined				copy from 'wood, unspecified, standing/m3'
Transformation, from grassland, natural (non-use)		1,842071101	m2	Undefined				Sven Mouton (0,5 m x 0,5 m per bamboestengel)
Transformation, to forest, secondary (non-use)		1,842071101	m2	Undefined				Sven Mouton (0,5 m x 0,5 m per bamboestengel)
Add								
Inputs from technosphere: materials/fuels		**Amount**	**Unit**	**Distribution**	**SD2 or 2SD**	**Min**	**Max**	**Comment**
Power sawing, with catalytic converter {RoW}| processing | Alloc Rec, U		0,120165919	min	Undefined				

Figure 7.3. Extract from SimaPro: inventory of 1 m³ of wet and untreated bamboo stem.

For the life cycle inventory of **1 m³ of dried, treated and transported bamboo stem** (Figure 7.4), three processes are added to the wet and untreated bamboo, i.e. the drying process, the treatment and the transportation. The drying process requires no additional energy as it suffices to put a bamboo pole upright in the shade in order to dry. Based on the limited data provided by the supplier, the treatment was done by means of the boucherie method where boric acid is injected under compression into the stem. The data on the amount of treatment material is based on 1m³ of bamboo. In a later stage in the LCA, this m³ of bamboo is related to the amount that still contains this treatment material. For the transport of the bamboo poles, the actual distance is calculated from the plantation to the construction site; transport by a freight lorry (weight of 7,5-16 metric ton) over a distance of 226,2km whereafter this outcome is reduced by a correction factor per volume based transport.

Inputs								
Inputs from nature	Sub-compartment	Amount	Unit	Distribution	SD2 or 2SD	Min	Max	Comment
Add								
Inputs from technosphere: materials/fuels		Amount	Unit	Distribution	SD2 or 2SD	Min	Max	Comment
bamboo culm (wet + untreated)		1,00	m3	Undefined				
Boric acid, anhydrous, powder {RoW}| production | Alloc Rec, U		33,76013944	kg	Undefined				source: own measurement Sven Mouton
Air compressor, screw-type compressor, 300kW {RoW}| production | Alloc		4,00E-4	p	Undefined				source: Escamilla and Habert (2014 - J of Cl Production)
Transport, freight, lorry 7.5-16 metric ton, EURO3 {RoW}| transport, freight,		85,96	tkm	Undefined				226,2 km (Sven) x correction factor (volume based transport)
Electricity, low voltage {BR}| market for | Alloc Rec, U		96,46	kWh	Undefined				source: Pablo

Figure 7.4. Extract from SimaPro: inventory of 1 m³ of dried and treated bamboo stem.

Although a relatively small amount of electricity is required to process a raw bamboo pole (only for the utilization of power hand tools & the boucherie treatment), general information on the Brazilian electricity mix is provided. Figure 7.5 provides an overview of how the electricity production in Brazil is divided in the year 2012. The main source to generate electricity in Brazil is hydropower (76.9 %). Together with biomass (6,8%) and wind power (0,9%) these renewable sources represent 84,6% of the overall Brazilian electricity production. Presumably these percentages have changed in the past years, especially because Brazil has been or is still constructing twenty new thermoelectric stations that are either natural gas-fired or petroleum derivatives-fired. Nevertheless, it can be presumed that renewable energy sources will continue to account for the highest percentage of electricity generation (Da Rocha et al., 2015).

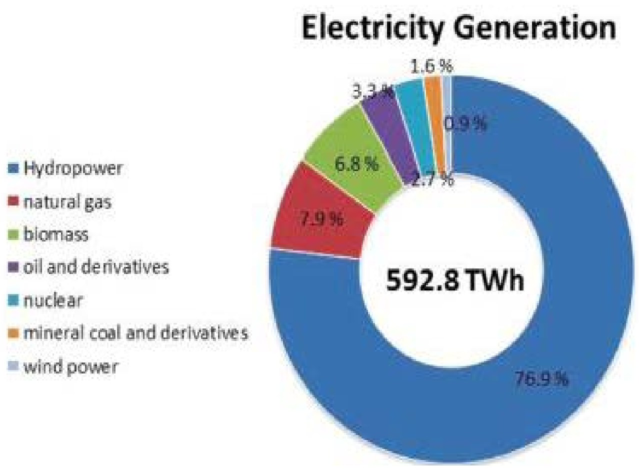

Figure 7.5. Overview of electricity generation in Brazil in 2012. Retrieved from Energy trends and the water-energy binomium for Brazil (p. 577) by G. Da Rocha, J. Dos Anjos and J. De Andrade. 2015. Annals of Brazilians Academy of Science.

7.2.1 Column type 1 - single bamboo pole column

The first type of bamboo column assessed consists of a single bamboo pole of 3m height with a loadbearing capacity of 13.73 kN. This type of column is applied as such in the guesthouse (section 6.9). It is important to note that the load on the column in the specific case of the guesthouse (coming from the roof) is lower than 13.73 kN (not considering any other loads such as wind, fire or other forces). Figure 7.6 demonstrates this bamboo column from different angles.

The column consists of a rectilinear bamboo element with a connector piece on each end which enables the attachment to another constructive element such as a wooden beam, the foundations or the roof. In this case, the column is attached to a concrete foundation wall on the bottom and a wooden ring-beam on top. The species used for the column is a treated Phyllostachys Pubescens, also called ´Moso`, with a diameter of 12cm, a length of 3m and a wall thickness of 1cm. For lack of testing in this case study, it is assumed from literature that its compressive strength is anywhere between 48 and 108 N/mm² (see chapter 3.1.1). The bamboo is applied in its original raw form without the addition of any engineering processes and extracted 226km from the construction site. The bamboo species is equal to the one assessed in the technical INBAR report by van der Lugt & Vogtländer (2015) and therefore the data from this study serves as a basis for data that is lacking in the LCI database. In general, Phyllostachys Pubescens has a density of 700kg/m³, a growth length up to 15m, a diameter on the ground between 12-14cm and a wall-thickness of 9mm. The LCI database proceeds from a diameter of 10-12cm (2016).

Figure 7.6. Single bamboo pole column used in the guesthouse in Brazil.

The connections (Figure 7.7) are made from a combination of timber and steel parts. The timber is Parana Pine wood that is acquired at a local timber trader (the location of origin undisclosed by the vendor). The diameter of this timber piece is one centimeter larger than the outer diameter of the bamboo pole at the bottom (14cm). Hence, the timber piece has a diameter of 15cm and a thickness of 10cm, resulting in 0,001916m³. At least half is made smaller than the inside diameter of the bamboo pole in order to function as a wine bottle cork. The bamboo wall rests on this wooden plug that provides for an equal surface in the load-transfer to the wooden plug. Subsequently, a hole is drilled in the middle of this wooden piece to insert a wire rod. The size of the wire rod is 5/8 pol (M16) and has a length of 30cm for each joint. Hex nuts and washers keep the wooden piece into place. In order to calculate the amount of steel used for the wire rods, a wire rod of 60cm length (2x 30cm) has been weighted, illustrated in Figure 7.8. For the Parana Pine and the steel elements, the Ecoinvent v 3.3. dataset has been used. At the base of the column, a left-over square metal plate was placed on top of a wooden base. As this element is not part of the column itself, but merely an Aesthetical addition, it is not considered in the LCI of the column.

Figure 7.7. Detail of timber joint.

Figure 7.8. Weighting 60cm long 5/8 inch wire rod.

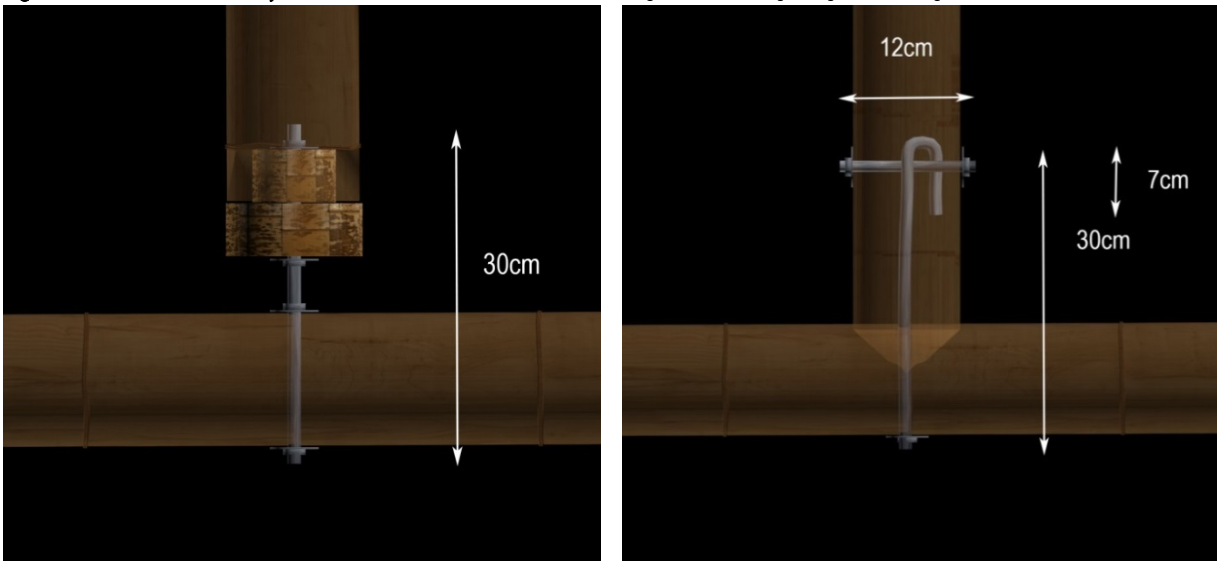

Figure 7.9. Comparison between a connector piece from this research and a traditional fish mouth connection.

Figure 7.9 illustrates the connection of the studied object of the LCA on the left and a traditional fish mouth connection on the right. When comparing both joints, it can be noticed that the amount of steel required to produce a fish mouth joint is greater. A fish mouth connection requires a hook and a laterally positioned wire rod whereafter the hook can be placed. This joint requires approximately 49cm of steel for one connector piece (98cm for both outer ends) whereas the proposed joint requires 30cm of steel (60cm for both ends). Due to the fact that the steel part is more visible in the proposed joint, it might generate the wrong perception that the amount of steel needed is higher. One could argue that the perpendicular connection of the proposed joint can possibly rupture the wall of the ‘receiving’ bamboo and therefore requires concrete/grout inside the compartments. Nevertheless, in the case of a fish mouth connection, a similar rupture can occur. Furthermore, when there is no excessive load applied on the bamboo, both connections can be provided without the insertion of concrete as there exists little to no danger of rupture of the bamboo wall. In Figure 7.10 and Figure 7.11 an inventory for both an ungrouted and grouted joint is presented, although in the bamboo column from the case study no grout was used. The Parana Pine plug along with the applied roof weight already prevents possible dislocation. The grouted version is calculated as a variant in order to assess the possible impact of the application of grout in a joint. The Ecoinvent v3 database records for unreinforced concrete with cement CEM II/A from primary aggregates is used, without the input of recycled gravel or sand. The amount of concrete for one grouted joint is determined at 0.012 m³ of concrete (final row in Figure 7.11).

Inputs

Inputs from nature	Sub-compartment	Amount	Unit	Distribution	SD2 or 2SD	Min	Max	Comment
Add								

Inputs from technosphere: materials/fuels	Amount	Unit	Distribution	SD2 or 2SD	Min	Max	Comment
dried and treated bamboo stem	0,033929201	m3	Undefined				
Roundwood, meranti from sustainable forest management, MY, debarked	0,001916	m3	Undefined				own measurement sven mouton
Steel, chromium steel 18/8 {RoW}| steel production, electric, chromium ste	0,5	kg	Undefined				rod - measurement sven mouton
Steel, chromium steel 18/8 {RoW}| steel production, electric, chromium ste	0,128	kg	Undefined				4 nuts 5/8 inch - technical sheets
Steel, chromium steel 18/8 {RoW}| steel production, electric, chromium ste	0,00472	kg	Undefined				4 washers 5/8 inch - technical sheets

Figure 7.10. Extract from SimaPro: inventory of a single pole bamboo column type 1a with ungrouted connections.

Inputs

Inputs from nature	Sub-compartment	Amount	Unit	Distribution	SD2 or 2SD	Min	Max	Comment
Add								

Inputs from technosphere: materials/fuels	Amount	Unit	Distribution	SD2 or 2SD	Min	Max	Comment
dried and treated bamboo stem	0,033929201	m3	Undefined				
Roundwood, meranti from sustainable forest management, MY, debarked	0,001916	m3	Undefined				own measurement sven mouton
Steel, chromium steel 18/8 {RoW}| steel production, electric, chromium ste	0,5	kg	Undefined				rod - measurement sven mouton
Steel, chromium steel 18/8 {RoW}| steel production, electric, chromium ste	0,128	kg	Undefined				4 nuts 5/8 inch - technical sheets
Steel, chromium steel 18/8 {RoW}| steel production, electric, chromium ste	0,00472	kg	Undefined				4 washers 5/8 inch - technical sheets
Concrete, normal {CH}| unreinforced concrete production, with cement CEI	0,024	m3	Undefined				2 grouted connections at joints 2x0,012m³

Figure 7.11. Extract from SimaPro: inventory of a single pole bamboo column type 1b with grouted connections.

7.2.2 Column type 2 - column consisting of four small diameter bamboo poles

The second type of column consists of four small diameter (5cm) bamboo poles of the species Phyllostachys Pubescens that form a coherent whole as illustrated in Figure 7.12. As there is no specific data on the properties of Phyllostachys Pubescens with a diameter of 5cm available, the LCI data from the INBAR technical report 35 (van der Lugt & Vogtländer, 2015) on density (700kg/m³), growth length (15m) is anew assumed here. The studied column has a height of 3 meter and a maximum loadbearing capacity of 13.73 kN. However, the load from the roof of the veranda is much less than this maximum loadbearing capacity. The harvesting, treatment and transportation methods are similar to the previous column type. There are some minor differences in the jointing principle compared to the single poled bamboo column. Whereas the first column supports on a wooden plug, in this case steel hex nuts and large washers are used to secure and support the culms. In both cases, a wire rod is inserted inside the bamboo pole, however the size differs. As these bamboos are very lightweight, a wire rod of 3/16 inches (M5) is already sufficient. The length of each wire rod is 25cm. The Ecoinvent v.3 record of ´steel, chromium steel 18/8 [RoW] is used to calculate the impact of the wire rods. The other end of the wire rod can either be inserted into a wet concrete foundation, a wooden block/beam or ceramic flooring as was the case in the veranda (section 6.7). Another kind of connection method is applied on top of this column where two wire rods are inserted horizontally through two poles that are positioned in a transversal direction connected by means of hex nuts and washers. These wire rods are 3/16 inches as well and have a length of 18cm.

Figure 7.12. Four small diameter bamboos that form a coherent column in the veranda, Brazil.

Figure 7.13 lists the inventory of column type 2a without the application of grout equal to the columns in the veranda and a variant with grouted joints is modelled in Figure 7.14. For the calculation of a grouted infill, concrete with cement CEM II/A and primary aggregates is assumed. Two times four bamboo poles need to be filled with each 0,0002m³ of concrete. This results in the almost negible amount of 0,0016m³ of concrete.

Inputs								
Inputs from nature	Sub-compartment	Amount	Unit	Distribution	SD2 or 2SD	Min	Max	Comment
Add								
Inputs from technosphere: materials/fuels		Amount	Unit	Distribution	SD2 or 2SD	Min	Max	Comment
dried and treated bamboo stem		0,015079645	m3	Undefined				measurement sven mouton
Steel, chromium steel 18/8 {RoW}| steel production, electric, chromium ste		0,88	kg	Undefined				4 rods base - technical sheets
Steel, chromium steel 18/8 {RoW}| steel production, electric, chromium ste		0,056	kg	Undefined				2 rods top - technical sheets
Steel, chromium steel 18/8 {RoW}| steel production, electric, chromium ste		0,052	kg	Undefined				4 nuts 3/16 inch (base) - technical sheets
Steel, chromium steel 18/8 {RoW}| steel production, electric, chromium ste		0,044	kg	Undefined				4 washers 6 cm (base) - technical sheets
Steel, chromium steel 18/8 {RoW}| steel production, electric, chromium ste		0,104	kg	Undefined				8 nuts 3/16 (top) - technical sheets
Steel, chromium steel 18/8 {RoW}| steel production, electric, chromium ste		0,01328	kg	Undefined				8 washers 3/16 (top) - technical sheets

Figure 7.13. Extract from SimaPro: inventory of the bamboo column type 2a with ungrouted connections.

Inputs from nature	Sub-compartment	Amount	Unit	Distribution	SD2 or 2SD	Min	Max	Comment
Add								
Inputs from technosphere: materials/fuels		Amount	Unit	Distribution	SD2 or 2SD	Min	Max	Comment
dried and treated bamboo stem		0,015079645	m3	Undefined				measurement sven mouton
Steel, chromium steel 18/8 {RoW}| steel production, electric, chromium ste		0,88	kg	Undefined				4 rods base - technical sheets
Steel, chromium steel 18/8 {RoW}| steel production, electric, chromium ste		0,056	kg	Undefined				2 rods top - technical sheets
Steel, chromium steel 18/8 {RoW}| steel production, electric, chromium ste		0,052	kg	Undefined				4 nuts 3/16 inch (base) - technical sheets
Steel, chromium steel 18/8 {RoW}| steel production, electric, chromium ste		0,044	kg	Undefined				4 washers 6 cm (base) - technical sheets
Steel, chromium steel 18/8 {RoW}| steel production, electric, chromium ste		0,104	kg	Undefined				8 nuts 3/16 (top) - technical sheets
Steel, chromium steel 18/8 {RoW}| steel production, electric, chromium ste		0,01328	kg	Undefined				8 washers 3/16 (top) - technical sheets
Concrete, normal {CH}| unreinforced concrete production, with cement CEI		0,0016	m3	Undefined				2 x 4 grout cilinder infill at joints (8x0,0002m³)

Figure 7.14. Extract from SimaPro: inventory of the bamboo column type 2b with grouted connections.

7.2.3 Variant: Wooden column (Parana Pine C24)

In literature, it can be found that a column of C24 has a comparable loadbearing capacity to the above described loadbearing capacity of 13.73 kN for the studied bamboo species, also with the buckling as limiting factor rather than compressive strength (EN1995-1-1, 2006) as a consequence of the length of 3m. In Brazil, the wood with strength class C24 that would be suitable and commonly available in the region of the case study is Parana Pine (Araucaria Angustifolia) in a standardized dimension of 71/196mm, 3m height. Parana Pine is softwood and not a true pine. It grows in Southeast Brazil and adjacent areas of Paraguay and Argentina, amongst which the state Paraná itself (Centrum Hout, 2017). The total volume of such a wooden column is 0,0417m³. Given the density of Parana Pine of 545kg/m³, the column weighs 22,7kg (Woodwork Details, 2021). For Parana Pine, the Ecoinvent v3 data record on round wood, Parana Pine from sustainable forest management, under bark (GLO) market, Alloc Rec, U' is used according the data set from Simapro Software.

Figure 7.15. Examples of commercially available connectors in wooden beams (Stainless Uk Ltd, 2019).

Similar to the bamboo columns, it is recommended that the hardwood column is not in direct contact with the ground surface in order to prevent rotting. A steel connector piece needs to be added at the bottom of the column lifting it a few centimeters. Very often this is done by slicing the beam in the center to insert a metal plate, with a perpendicular positioned plate welded onto it in order to facilitate the attachment of the column to the ground surface. Figure 7.15 in the middle and on the right demonstrate multiple possibilities. The total absolute minimal amount of steel used for such a ground connector piece that suits the regarded C24 71/196 would be a plate of 11x11x0.5 cm plus an equal sized plate at the bottom (2 plates). The size of these metal plates might vary, but for this study the size of 11cm by 11cm is assumed. This is considered an absolute minimum in order to secure the plates to the wooden beam for it has to be inserted into the 19,6cm length of the beam and has to have a sufficient height to attach two nuts whilst having ample distance from the ground in order to prevent upward moisture. It would make sense that this same 11cm is the size of the plate welded to it, with also ample space on both sides to prevent the connection from becoming a hinge. Less than 0.5cm thickness would result in a weak connection. The assumption results in a total amount of 121 cm³ of steel, which means 0.000121 m³ of steel multiplied by 7850kg/m³ or 0.942 kg of steel.

For the attachment to a beam at the top of the column also screws or nails can be used, often in combination with a 'horse-shoe', a metal-casing that supports the beam and is screwed onto it (Figure 7.15, left). For argument's sake this most common technique (that requires more steel) will not be assumed. Instead, the absolute minimum of 2 plates at the bottom will be used for the comparison, assuming that the connection at the top needs no extra steel to connect it to other materials. Figure 7.16 gives a summary of the inventory of the Parana pine wood column.

Inputs from nature	Sub-compartment	Amount	Unit	Distribution	SD2 or 2SD	Min	Max	Comment
Add								
Inputs from technosphere: materials/fuels		Amount	Unit	Distribution	SD2 or 2SD	Min	Max	Comment
Roundwood, parana pine from sustainable forest management, under barl		0.0417	m3	Undefined				sterkteklasse DC24 3m 71/196 parana pine
Steel, chromium steel 18/8 {RoW}| steel production, electric, chromium ste		0.942	kg	Undefined				measurement sven mouton

Figure 7.16. Extract SimaPro: inventory of a Parana Pine wood column.

7.2.4 Variant: Concrete column

The density of concrete is 2400 kg/m³ (or 24kN) and for steel 7850kg/m³ (or 78,5 kN). For the structural solutions needed in the case study, 1% of steel is assumed inside the concrete column. This is a conventional proportion of steel to concrete in order to produce an armed concrete column. For a concrete grade in M20, the following formula is applied P = (3.27p + 8) b D/1500 (Areemit & Faeksin, 2013). P refers to the percentage of steel in the concrete which is in this case 1 and 1500 is the column size in millimeters. In order to determine the volume of 1% of steel, this percentage needs to be related to the volume of the column (0,15mx0,15mx3m) being 0,0675m³. One percent hereof is a volume of 0.000675m³ of steel. The weight of the steel can then be found by multiplying this volume with the density of steel being 7850kg/m³ or 5,29kg. For a concrete column, 150x150mm is a minimum dimension, not only defined by the maximum load-bearing capacity (again limited by buckling), but also by the possibility to provide in a timber casting and the requirement to cover at least 30mm above the steel rebar. The reinforced concrete column requires sufficient steel to ensure the required strength-class of 20 Mpa amounting to 5,29kg of reinforcing steel. This data is displayed in Figure 7.17.

Bekende inputs uit de natuur (hulpbronnen)	Subcompartiment	Hoeveelheid	Eenheid	Verdeling	SD2 of 2SD	Min	Max	Opmerking
Toevoegen								
Bekende inputs uit de technosfeer (materialen, brandstoffen)		**Hoeveelheid**	**Eenheid**	**Verdeling**	**SD2 of 2SD**	**Min**	**Max**	**Opmerking**
Reinforcing steel {RER}| production | Alloc Def, S		5,29	kg	Ongedefinieerc				1% of the volume of the concrete column
Concrete, 20MPa {CA-QC}| concrete production 20MPa, RNA only | Alloc Def, S		0,0675	m3	Ongedefinieerc				column 15x15x300 for concrete M20

Figure 7.17. Extract from SimaPro: inventory of a reinforced concrete column.

7.2.5 Variant: Steel column

In order to carry a load of 13.73 KN, a round hollow steel tube S235 with a section of 48.3mm diameter and wall thickness of 4mm would be necessary. The dimension of the steel column is rather determined by the buckling factor than the compression strength or other mechanical properties. Such a steel tube weighs 4,4kg per meter (Metalsupplies, 2019; Eurocode Applied, 2019). The weight of the steel is calculated by multiplying the 3m length x 4,4kg/m = 13,2kg. First, 'virgin' steel (100% raw material) is assumed. The data "Steel, unalloyed {RER}| steel production, converter, unalloyed | Alloc Rec, U" was chosen from the inventory as illustrated in Figure 7.18.

Normally, a layer of coating should be applied as a fire protection. Such a coating is especially required for domestic or public areas before it can be considered as a fire-safe product. Including such a coating would augment the environmental impact of the steel significantly. However, this input is not considered in this study as such a fire-resistant coating is neither calculated for the bamboo.

Bekende inputs uit de natuur (hulpbronnen)	Subcompartiment	Hoeveelheid	Eenheid	Verdeling	SD2 of 2SD	Min	Max	Opmerking
Toevoegen								
Bekende inputs uit de technosfeer (materialen, brandstoffen)		**Hoeveelheid**	**Eenheid**	**Verdeling**	**SD2 of 2SD**	**Min**	**Max**	**Opmerking**
Steel, unalloyed {RoW}| steel production, converter, unalloyed | Alloc Rec, U		13,2	kg	Ongedefinieerc				round profile 48,

Figure 7.18. Extract from SimaPro: inventory of a steel column with virgin steel.

A sensitivity analysis has been made for the steel in relation to the type of steel used. If the steel were to be from a recycled source instead of 'virgin' steel as above, the element of 'recycled steel' should replace the virgin steel in the above inventory. When recycled steel is to be considered, it is assumed that it is melted electric in a steel mill. As 100% recycled steel does not yet exist, there is calculated with a sensitivity of 63% 'virgin' steel and 37% recycled steel according to Stroeckx (2020). The following Ecoinvent record is " Steel, low-alloyed {RoW}| steel production, electric, low-alloyed | Alloc Rec, U" is added for the part recycled steel.

Bekende inputs uit de natuur (hulpbronnen)	Subcompartiment	Hoeveelheid	Eenheid	Verdeling	SD2 of 2SD	Min	Max	Opmerking
Toevoegen								

Bekende inputs uit de technosfeer (materialen, brandstoffen)	Hoeveelheid	Eenheid	Verdeling	SD2 of 2SD	Min	Max	Opmerking
Steel, low-alloyed {RoW}| steel production, electric, low-alloyed | Alloc Rec, U	4,884	kg	Ongedefinieerc				round profile 48,3mmx3mm a 3,4kg/m = 13,2kg
Steel, unalloyed {RoW}| steel production, converter, unalloyed | Alloc Rec, U	8,316	kg	Ongedefinieerc				

Figure 7.19. Extract from SimaPro: inventory of a steel column with recycled steel.

Another sensitivity that should be considered is the life span of steel vs that of bamboo. It can be assumed that this is longer than bamboo, although no data on the durability of bamboo can be found. It is often said that bamboo buildings have a lifespan of 50 years, which is more or less equal to steel (Figure 7.20), however there is no scientific proof to back this statement, not in more nor less useful years. When a sufficient treatment and physical protection is provided as explained in the previous chapters, the wall of the bamboo 'woodyfies' and it can be assumed that bamboo can be compared to hardwood in terms of the life span.

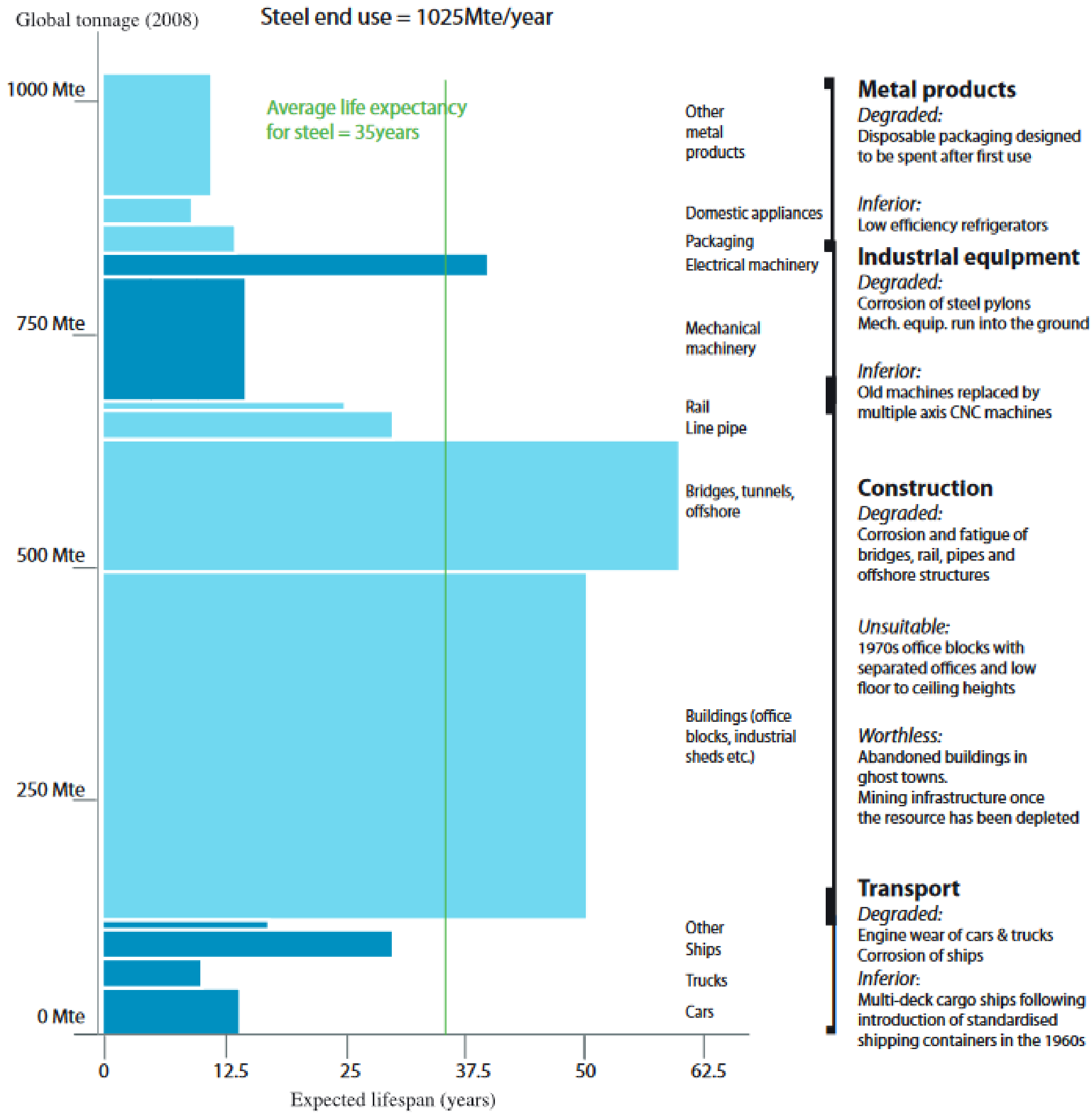

Figure 7.20. Expected lifespan and causes of failure of steel products (D.R Cooper et al, 2014, pp. 11).

7.3 Impact assessment

For the impact assessment, the Belgian LCA method for buildings and building elements is used, i.e. the MMG-method ("Milieugerelateerde Materiaalprestatie van Gebouwelementen"). The MMG method originates from a lack of environmental classification systems on building materials and components adapted to the Belgian context. In 2011, the Public Waste Agency of Flanders (OVAM) commissioned a research project in collaboration with the KU Leuven (ASRO), VITO and BBRI. They developed an expert calculation model (including assessment framework) for the quantification of environmental performance of different building elements. The model served as the basis for a database of 115 building elements representative in the Belgian construction industry. This model has been further developed since and currently the database contains over 500 building element variants. The MMG-method considers a wide range of environmental impact categories on human toxicity, ecotoxicity, particulate matter formation, radiation, ionizing, land use/ biodiversity and water scarcity (Allacker et al.,2020). According to the MMG method, the environmental impact can be expressed in characterized values (e.g. CO_2 equivalents for climate change) or in external environmental cost (single score). For each individual environmental indicator, the characterization values are multiplied by a monetization factor (e.g.: X kg CO_2 equivalents times Y €/kg CO_2 equivalents). This factor indicates the extent of the damage to the environment and/or humans, expressing it in a financial amount for the purpose of avoiding potential damage or settling any damage incurred. These aggregated environmental scores are also reported separately. The indicators with its monetization values are illustrated in Figure 7.21 (De Nocker & Debacker, 2018).

Environmental indicator (CEN)	Unit	Central (€/unit)	Low (€/unit)	High (€/unit)
1. Global warming	kg CO2 eqv.	**0.050**	0.025	0.100
2. Depletion of the stratospheric ozone layer	kg CFC-11 eqv.	**49.10**	25	100
3. Acidification of land and water sources	kg SO2 eqv.	**0.43**	0.22	0.88
4. Eutrophication	kg $(PO4)^{3-}$ eqv.	**20**	6.60	60
5. Formation of tropospheric ozone photochemical oxidants	kg etheen eqv.	**0.48**	0	6.60
6. Abiotic depletion of non-fossil resources	kg Sb eqv.	**1.56**	0	6.23
7. Abiotic depletion of fossil resources	MJ, net caloric value	**0**	0	0.0065
8. Human toxicity				
a. cancer effects	CTUh	**665109**	166277	2660434
b. non-cancer effects	CTUh	**144081**	28816	720407
9. Particulate matter	kg PM2,5 eqv.	**34**	12.70	85
10. Ionising radiation, human health	kg U235 eqv.	**9.7E-04**	3.2E-04	2.9E-03
11. Ecotoxicity:				
a. terrestrial	-			
b. freshwater	CTUe	**3.70E-05**	7.39E-06	1.85E-04
c. marine	-			
12. Water scarcity	m³ water eqv.	**0.067**	0.022	0.20
13. Land use: occupation:				
a. soil organic matter	kg C deficit	**1.4E-06**	3.4E-07	0.6E-05
b. biodiversity				
b1. urban: loss ES*	m².a	**0.30**	0.07	2.35
b2. agricultural	m².a	**6.0E-03**	1.5E-03	2.4E-02
b3. forest: biodiversity	m².a	**2.2E-04**	5.5E-05	8.8E-04
14. Land use: transformation				
a. soil organic matter	kg C deficit	**1.4E-06**	3.4E-07	0.6E-05
b. biodiversity				
b1. urban	m²	**n.a.**	n.a.	n.a.
b2. agricultural	m²	**n.a.**	n.a.	n.a.
b3. forest, excl. tropical	m²	**n.a.**	n.a.	n.a.
b4. tropical rainforest	m²	**27**	6.9	110

Figure 7.21. Overview of West-European monetary (central, low and high) values for the CEN-indicators (L. De Nocker & W. Debacker, 2018, pp. 12).

7.3.1 Impact assessment of the bamboo columns

7.3.1.1 Wet and untreated bamboo stem

The environmental cost of 1 m³ of wet and untreated bamboo stem equals 0.00288€ of which 0.00137€/m³ (48 %) is contributed to the land use occupation (biodiversity loss in a forest) and 0.00151€/m³ (52%) to the amount of energy needed for the power tools during harvesting. When only considering the impact on climate change, the main driver is the electricity usage of the chainsaw (100%). The impact of the electricity usage could be reduced when using a machete or handsaw instead of a chainsaw for the harvest.

7.3.1.2 Treated, dried and transported bamboo stem

The environmental cost of a dried, treated and transported bamboo stem equals 15€/m³ of which 0.00339€ is for the bamboo culm itself, 6.75€ for the boric acid (anhydrous) treatment, 2.88€ for the air compressor that operates the boucherie treatment, 2.42€ for the transport by a freight lorry and 2.96€ for the low voltage electricity required for the extraction process. This amount above is given for 1m³ treated and dried bamboo, further on amounts will be given per single stem as used per regarded column. Figure 7.22 shows the drivers for each environmental impact category in relative terms. The electricity use is indicated in light blue, transport in dark blue, the air compressor 300kW in yellow and the boric acid solution in orange. These results outline the importance to search for alternative treatment substances and methods in order to reduce the environmental impact as the factor treatment is distinctly the most impactful. The natural process of soaking culms in a boric acid solution for several days instead of mechanically pushing the solution through the stem already results in a considerable improvement. The bamboo for the community center in Camburi (section 6.6) was treated as such and these bamboos still show no signs of insect attacks.

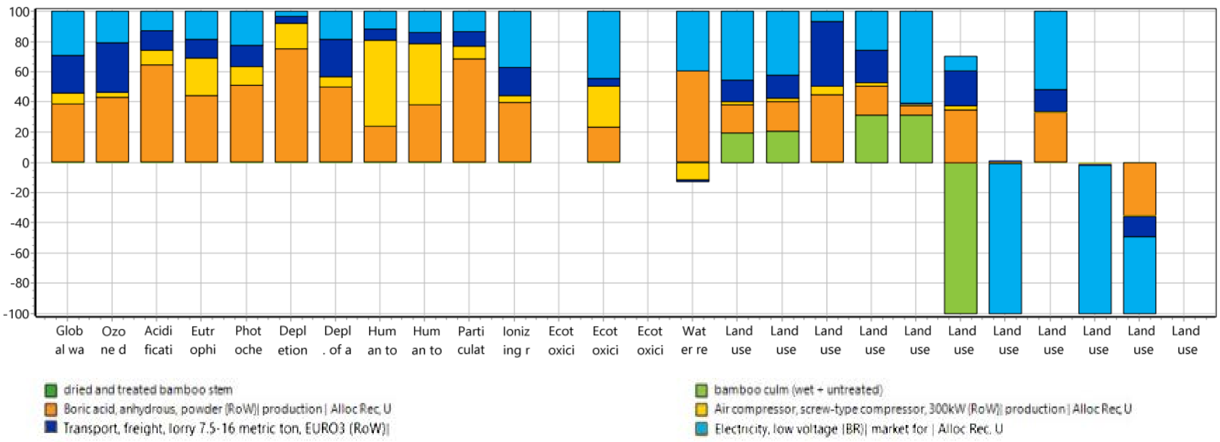

Figure 7.22. Environmental impact of 1m³ dried, treated and transported bamboo stem using the MMG method.

Counterintuitively the impact of transport appears to be substantially lower than the impact of the treatment when considering both the treatment product (acid borax) and the electricity needed to implement it. Transport in this graph refers to the transport from the plantation to the construction site by means of a freight lorry within Brazil. The results show that national transport has a relatively low effect on the environmental impact. In case sea transport would be required, the eco-burden of transport would be much greater. In the figure above, transport is responsible for about 25% of the impact on global warming. As will become clear in the next steps of the LCA; when a dried, treated and transported stem is processed in a preassembled column, the effect of transport drops in relation to the steel, concrete or wooden components of the bamboo column. In order to make this difference visually explicit, Fig 7.23 singles out the factor of transport as a differentiating subpart. Dark green presents the dried and treated bamboo stem with transport and the light green without.

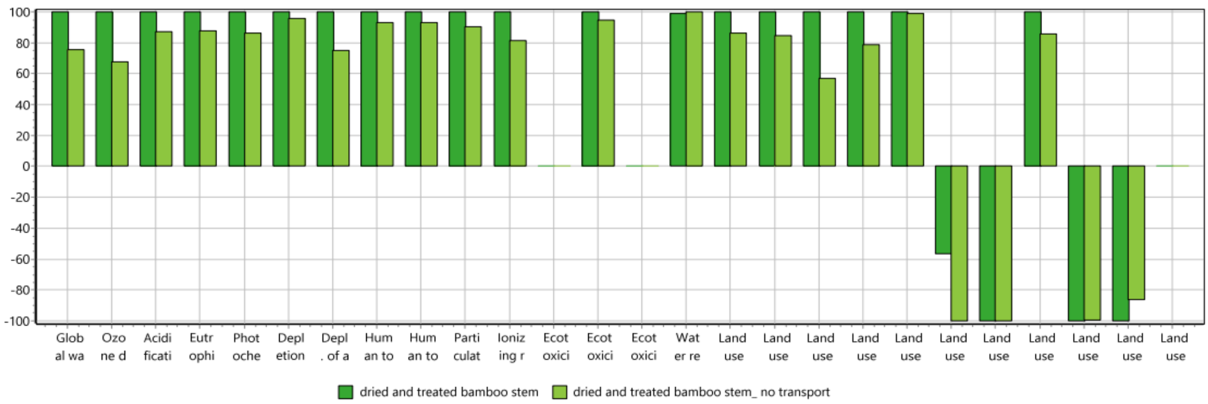

Figure 7.23. Environmental impact of 1m³ dried and treated bamboo using the MMG method on the factor transport.

7.3.1.3 Column type 1a: Single bamboo pole column

The life cycle environmental cost of the column composed of a single bamboo pole with connectors equals 2,51€. The single bamboo pole column consists of a dried and treated bamboo culm, the steel components and the Parana pine hardwood piece. Looking at the indicator global warming (first column in the graph of Figure 7.24), less than half of the impact is attributed to the bamboo stem itself (green), a small amount to the hardwood piece (orange) and almost the other half by the relatively small amount of steel in the total volume (chromium steel 18/8 RoW) for the wire rods, nuts and washers (yellow and dark and light blue). It should be noted that the suggested bamboo prototype columns require less steel than a traditional fish mouth connection. It is difficult to further diminish the amount of steel. A lashed connection would obtain better results, however lashings are not the most preferred solution from a durability point of view due to potential vandalism and other risks (e.g. fire, friction) which may cause loss of strength and other safety issues.

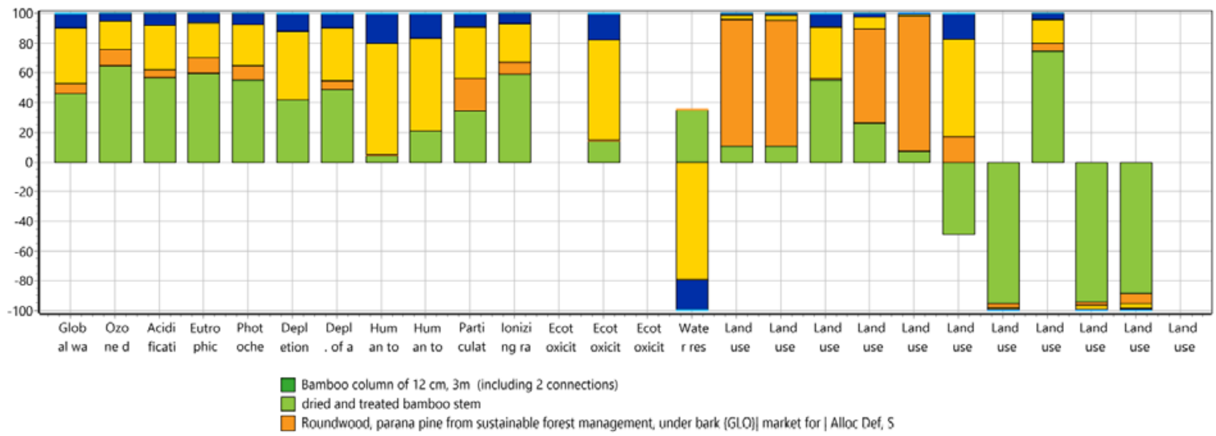

Figure 7.24.Environmental impact of the bamboo column type 1a (single, ungrouted bamboo pole) using the MMG-method.

Figure 7.24 emphasizes anew the impact of the treatment method. The boric acid solution in a dried and treated bamboo stem is responsible for the highest share of ozone depletion (second column), acidification (third column), eutrophication (fourth column), photochemical ozone creation (fifth column) and ionizing radiation (11th column).

The steel components are the most impactful in ‘human toxicity and cancer effects’. The steel wire rods (yellow) cause the second largest share of the global warming impact (after the dried and treated bamboo) and of several other impact indicators. An important remark in this context is the recycling potential of steel. Steel can be melted and re-used countless times. In this assessment, it is assumed that the stainless steel chromium 18/8 RoW consists of 60% recycled steel content. As in normal steel, 100% recycled steel is not possible in stainless steel, also because it would lose its anti-weathering properties that is needed for a durable bamboo construction. Stainless steel 18/8 is 304 grade stainless steel consisting of chromium and nickel which makes it very resistant to corrosion and oxidation (British Stainless Steel Association, 2020; Stroecks 2020). Not using the stainless steel chromium 18/8, but for example low alloyed recycled steel from electric melting would drastically reduce the effect, but then also a weathering agent should be applied that makes the steel withstand corrosion and other destructive impacts.

The impact of the hardwood (Parana Pine) on climate change is relatively limited. It is important to note that in this assessment, it is assumed that the hardwood comes from a sustainably managed plantation. If it were considered to be from an unmanaged tropical rainforest, this would result in a higher impact in terms of biodiversity loss and carbon emissions (considering the biomass would be counted as ‘lost’). This is also demonstrated in the land-use impacts that are already very high for hardwood from managed plantations.

The analysis of the global warming impact of the single bamboo pole column illustrated in the first column of Figure 7.24 and the tree model below in Figure 7.25 reveals that the steel components (wire rods, nuts and washers) represent over 50% of the impact although the amount of steel is relatively small. Therefore, where possible, virgin steel should be replaced by hardwood or at least by recycled steel. Lashings can also be considered if all safety aspects can be addressed.

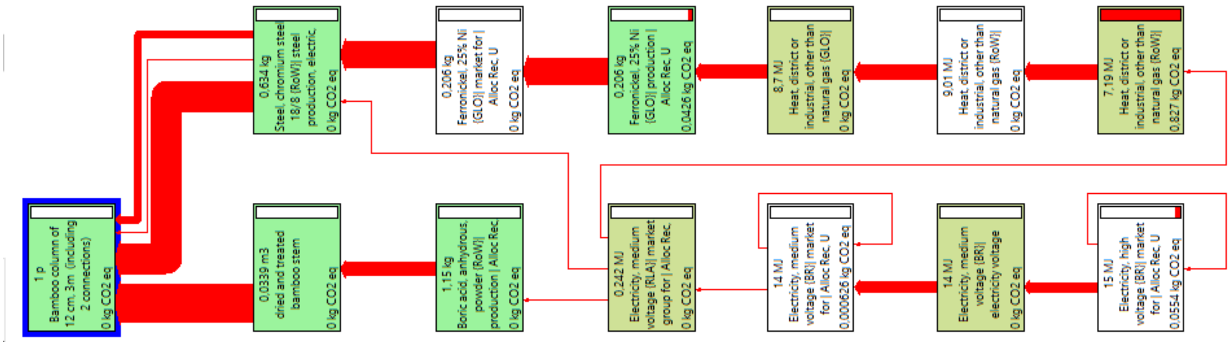

Figure 7.25. Tree model representation of the global warming impact of the bamboo column type 1a (single, ungrouted bamboo pole).

7.3.1.4 Column type 1b: Single bamboo pole column with grouted connections

Figure 7.26. demonstrates the environmental impact when the connections of the single bamboo pole column are grouted instead of ungrouted. It can be seen that the concrete infill marked in red has a relatively low impact when it comes to global warming, and even less when the other indicators are reviewed. Compared to the overal impact factor, the concrete infill is accountable for 6,04% of the impact. Considering the fact that its impact is rather low, it can be questioned whether leaving out the grout is even recommendable, certainly when there is a possibility of uplifting winds and little roof weight pushing downwards.

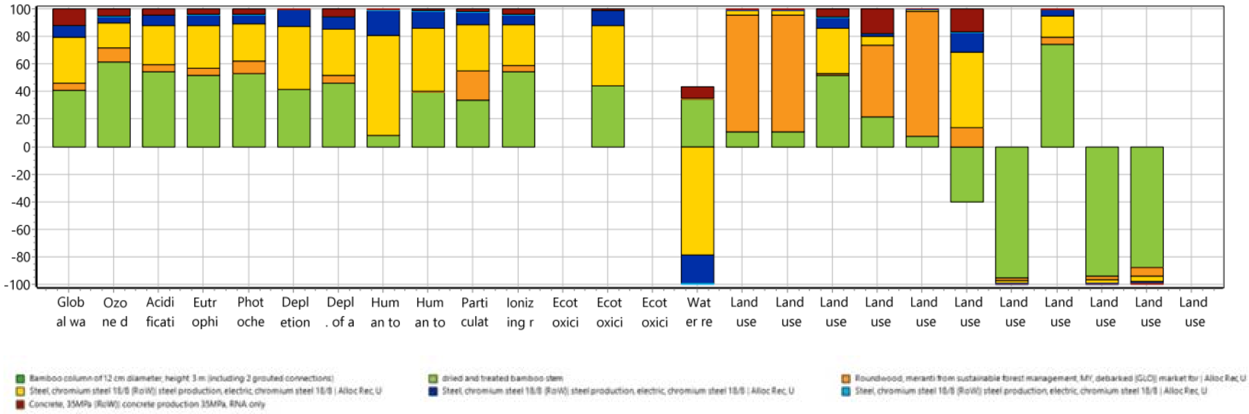

Figure 7.26. Environmental impact of the bamboo column type 1b (single, grouted bamboo pole) using the MMG-method.

Considering the grouted infill, an important side note has to be made. The concrete infill does not have a large impact when applied solely to the compartment of the joint itself. However, the consequences in case the entire length of the culm (3m) would be provided with a concrete infill instead of just the two nodes at the outer ends (15cm) are illustrated in Figure 7.27. In that case, the grouting displays a dominating factor when it comes to environmental impact, but also concerning the other factors.

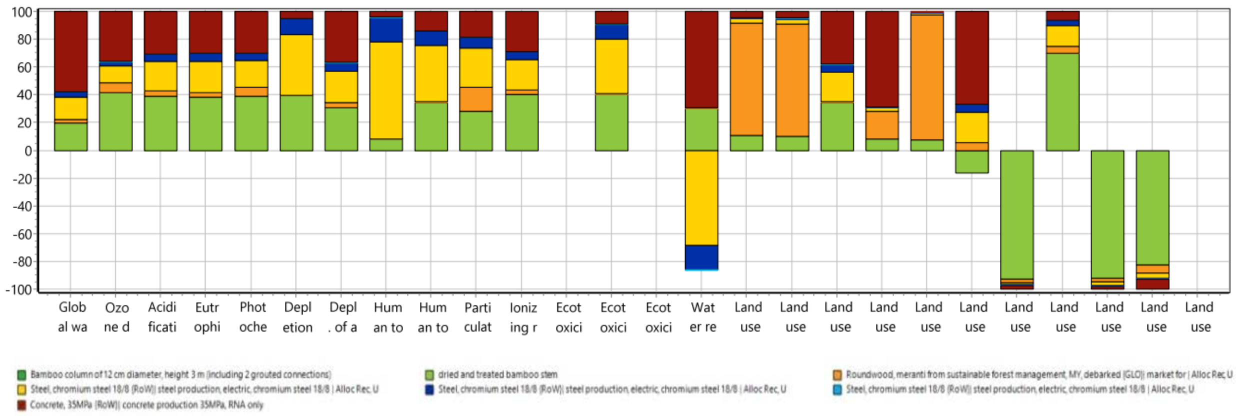

Figure 7.27. Environmental impact of the bamboo column type 1b using the MMG method in case of a complete grouted infill.

7.3.1.5 Column type 2a: column consisting of four small diameter bamboo poles

The second column prototype is the column composed of four small diameter bamboo stems (5cm) as described in section 7.1.2. Anew, the steel components for the joints are responsible for a large share of the impacts, for nearly all of the indicators (Figure 7.28). The wire rods are marked in orange, the hex nuts and washers are marked in yellow, light and dark red and light and dark blue. This column type requires four times the amount of bolts, nuts and washers compared to the previous column prototype, although the sizes are smaller. The combined impact of the steel parts is larger than the treatment of the bamboo stems. Figure 7.29 shows the contribution of the different elements to the total global warming impact of the column.

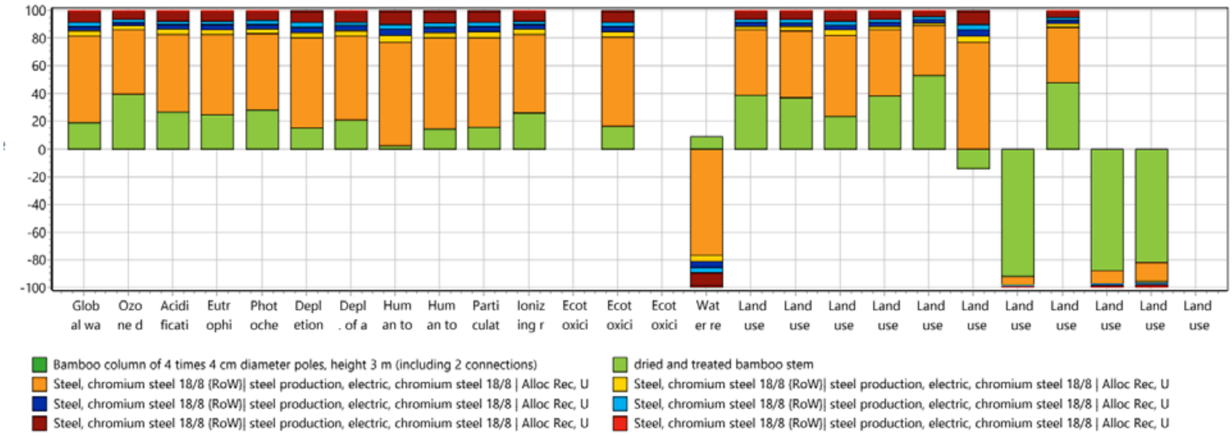

Figure 7.28. Environmental impact of the bamboo column type 2a (4 small diameter, ungrouted bamboo poles) using the MMG-method.

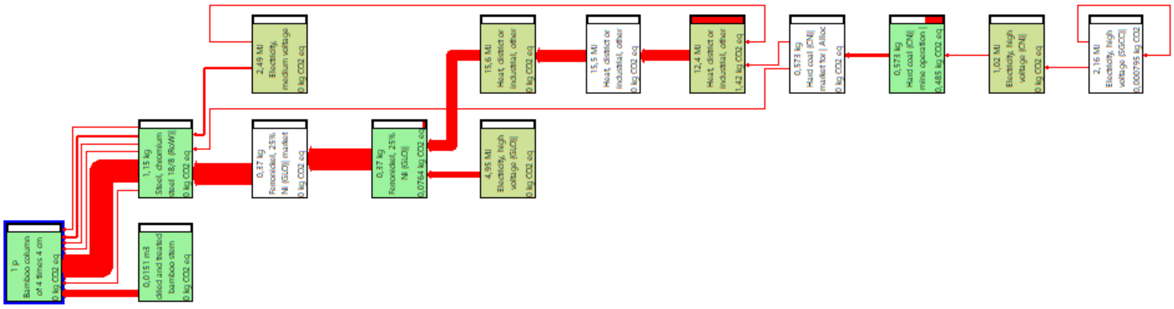

Figure 7.29.Tree model representation of the global warming impact of column type 2a (4 small diameter ungrouted poles).

7.3.1.6 Column type 2b: column consisting of four small diameter bamboo poles with grouted connections

Similar to the previous section, the effect of a concrete infill is assessed for this type of column. The impact of grouting is indicated in dark purple atop of each column in Figure 7.30. For most of the impact categories, the impact of grouting is less than 10%. Specifically looking at global warming (first column in the graph), the relative contribution of grouting equals 3,34%. The fact that the impact of the grout is even less than column type 1b can be attributed to the smaller diameter of the poles.

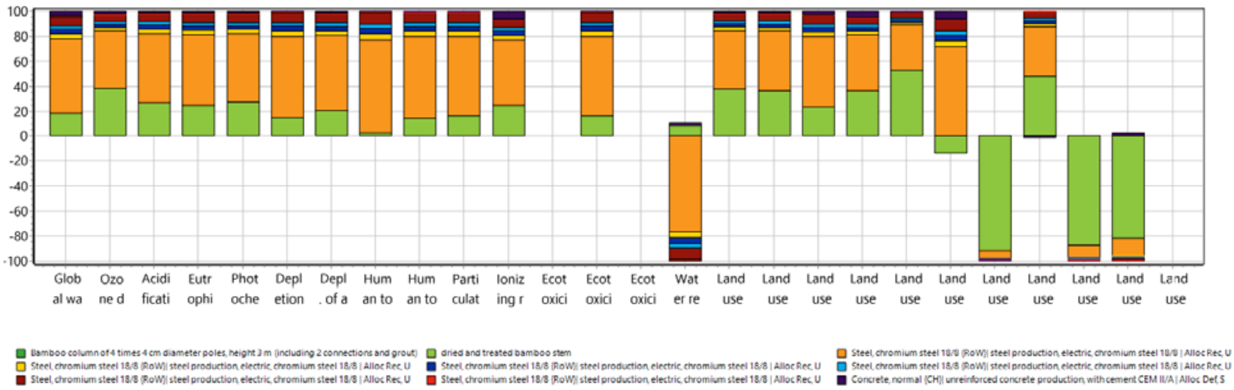

Figure 7.30. Environmental impact of the bamboo column type 2b (4 small diameter, grouted bamboo poles) using the MMG-method.

7.3.2 Comparative assessment of the various columns

In this section, first the two bamboo columns prototypes are compared to each other, secondly the traditional fish mouth joint is compared to type 1 of the proposed bamboo columns and finally the two bamboo columns are compared to the columns in conventional materials (wood, concrete and steel). For these assessments, it was also opted to compare the monetarized single scores as it is important to consider all impact indicators when comparing different materials. The monetary values used to calculate the single score has already been discussed in the beginning of section 7.3.

7.3.2.1 Comparison of the two bamboo columns

Figure 7.31 compares the environmental impact of the two proposed bamboo prototype columns according the MMG impact assessment method. On the left, in dark green, the environmental impact of the single bamboo pole column (type 1) is shown and on the right, in light green, the impact of the bamboo column consisting of four small diameter poles is represented (type 2). For the following indicators; depletion of fossil fuels, acidification, eutrophication, particulate matter and ionizing radiation, the impact of both column types is more or less identical (< 10%). For the global warming indicator, the first column type has a 10% lower impact, whilst the second column type has a 10% lower impact in regards to the photochemical ozone creation.

- The single bamboo pole column performs better in terms of the depletion of minerals, human toxicity (both the cancer and non-cancer effects) and ecotoxicity (fresh water).
- The four small diameter poles column performs better on the indicators of ozone depletion and land use.

Because of these conflicting indicators, the environmental cost in Figure 7.32 might help to reveal which of both column variants leads to an overall better score. The single bamboo pole column has been calculated to have a total environmental cost of 2,51€ and the four small diameter bamboo poles column a cost of 3,65€. Even though this might seem a considerable difference (nearly 50% more), it is a relatively small difference when compared to the other materials (see next sections).

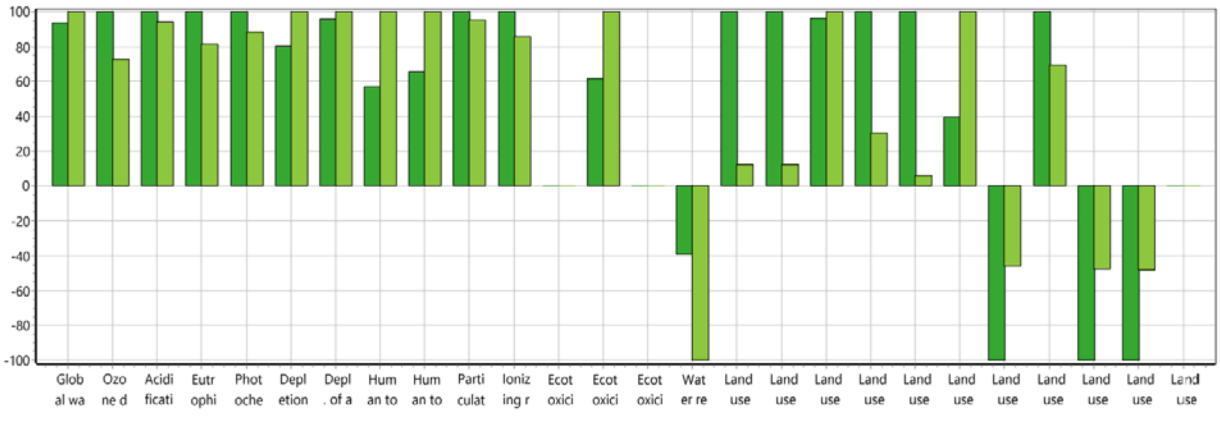

Figure 7.31. Comparative assessment of the two proposed bamboo columns.

Se	Impact category	Unit	Bamboo column of 12	Bamboo column of 4
	Total	EUR2017	2,51	3,65
☑	Global warming	EUR2017	0,273	0,302
☑	Ozone depletion	EUR2017	2,46E-5	1,93E-5
☑	Acidification for soil and water	EUR2017	0,0186	0,0182
☑	Eutrophication	EUR2017	0,0924	0,0809
☑	Photochemical ozone creation	EUR2017	0,00117	0,00111
☑	Depletion of abiotic resources-elements	EUR2017	0,000209	0,000259
☑	Human toxicity - cancer effects	EUR2017	1,2	2,1
☑	Human toxicity - non-cancer effects	EUR2017	0,487	0,742
☑	Particulate matter	EUR2017	0,387	0,365
☑	Ionizing radiation -human health effects	EUR2017	0,000225	0,000203
☑	Ecotoxicity - freshwater	EUR2017	0,000854	0,00138
☑	Water resource depletion	EUR2017	-0,000385	-0,00098
☑	Land use: occupation - SOM	EUR2017	0,000181	4,86E-6
☑	Land use: occup. - flows biodiv., urban	EUR2017	0,0355	0,0365
☑	Land use: occup. - flows biodiv., agric	EUR2017	4,72E-6	3,11E-6
☑	Land use: occup. - flows biodiv., forest	EUR2017	0,014	0,000175
☑	Land use: transformation - SOM	EUR2017	2,72E-6	8,59E-6

Figure 7.32. MMG impact assessment (monetary values) of the two proposed bamboo columns.

It can be concluded from this comparison that the amount of steel in the connections should be as limited as possible. This can possibly be done by cutting off the wire rod immediately after the hex nut that secures the hardwood piece or by replacing the steel with a more ecological material, or non-chromium steel with a high recycled content. For inside application where there are no oxidizing agents this could be considered. Further research into hardwood or other materials can even lead to other joint design solutions. Given the fact that the hardwood piece has a very low impact, it is also recommended to use it as an alternative for steel whenever possible. With the aid of a CNC-cutting machine, this hardwood connector piece can even be provided with an interlocking system much like traditional Japanese jointing methods.

7.3.2.2 Comparison of the proposed bamboo joint with a traditional fish mouth joint

A traditional fish mouth connection requires a greater amount of steel than the proposed connection in the bamboo column type 1 explained in section 7.2. Based on the results illustrated in Figure 7.33 and Figure 7.34, it can be noted that the proposed joint (type 1) marked in dark green scores better than a traditional fish mouth joint (light green) on nearly all of the aspects except for land use. The environmental impact of steel remains a point of attention in joint design. Besides the higher amount of steel, a fish mouth joint is also more time consuming to produce which makes it financially less interesting (**P**rofit) and moreover requires skilled knowledge which might lead to social exclusion (**P**eople). Considering all of this, the proposed joint connection is preferred over a fish mouth joint.

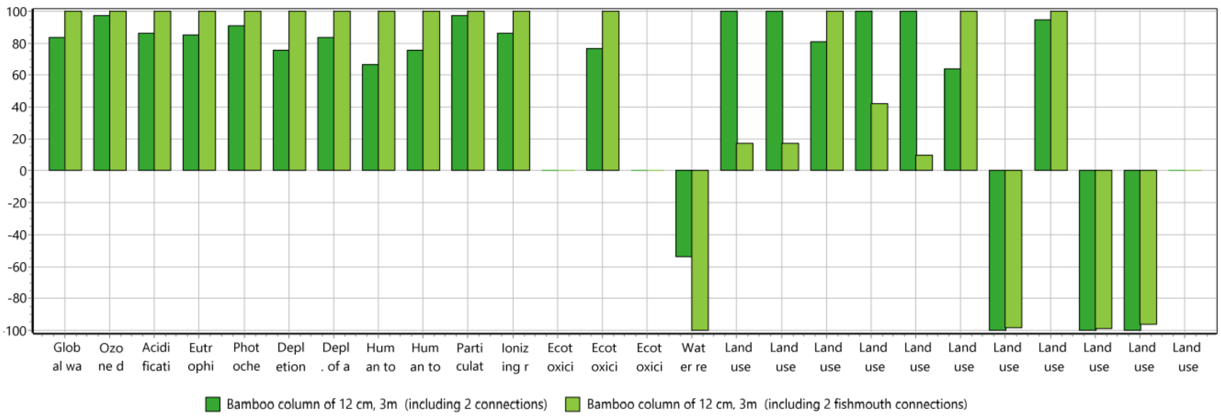

Figure 7.33. Comparative assessment of the proposed joint (left) versus a traditional fish mouth joint (right).

Se	Impact category	Unit	Bamboo column of 12 cm, 3m (including 2 connections)	Bamboo column of 12 cm, 3m (including 2 fishmouth
	Total	EUR2017	2,51	3,44
☑	Human toxicity - cancer effects	EUR2017	1,2	1,83
☑	Human toxicity - non-cancer effects	EUR2017	0,487	0,698
☑	Particulate matter	EUR2017	0,387	0,394
☑	Global warming	EUR2017	0,273	0,339
☑	Eutrophication	EUR2017	0,0924	0,106
☑	Land use: occup. - flows biodiv., urban	EUR2017	0,0355	0,0432
☑	Acidification for soil and water	EUR2017	0,0186	0,0223
☑	Photochemical ozone creation	EUR2017	0,00117	0,00138
☑	Ecotoxicity - freshwater	EUR2017	0,000854	0,00125
☑	Land use: occup. - flows biodiv., forest	EUR2017	0,014	0,000278
☑	Depletion of abiotic resources-elements	EUR2017	0,000209	0,000276
☑	Ionizing radiation -human health effects	EUR2017	0,000225	0,00026
☑	Ozone depletion	EUR2017	2,46E-5	2,71E-5
☑	Land use: occupation - SOM	EUR2017	0,000181	6,77E-6
☑	Land use: transformation - SOM	EUR2017	2,72E-6	5,35E-6
☑	Land use: occup. - flows biodiv., agric	EUR2017	4,72E-6	4,33E-6
☑	Water resource depletion	EUR2017	-0,000385	-0,000711

Figure 7.34. MMG impact assessment (monetary values) of the proposed bamboo joint and a traditional fish mouth joint.

7.3.2.3 *Comparison of a bamboo column versus a wooden, concrete or steel column*

The final step in the calculations was to identify whether bamboo obtains better LCA results than other conventional building materials. Figure 7.35 shows the results from the assessment of the **wooden column** (Parana Pine), including the steel parts required to attach it to other construction elements. Identical to the bamboo columns, a large part of the total environmental impact, with exception of land occupation, is addressed to the steel components. The wooden column is calculated with two steel plates of 11cm x 11cm. For the majority of the indicators, the steel plates have a lower impact than the wood itself, except for the indicators depletion of resources, human toxicity and ecotoxicity. This is most likely because even though from managed plantations, Parana Pine is still a tropical wood and is also treated against bio-attacks. Furthermore, the steel plates are in volume-ratio far smaller. Again, in relation to the volumes, it is not the bio-based material that causes a large impact, but the steel parts used to connect these materials to other construction components. Especially the fact that stainless steel, just as in case of the bamboo columns, has to withstand weathering elements which has a considerably large effect. The environmental impact could be reduced drastically when using less impactful types of steel or a less impactful product e.g. varnish or paint) can offer protection to weathering.

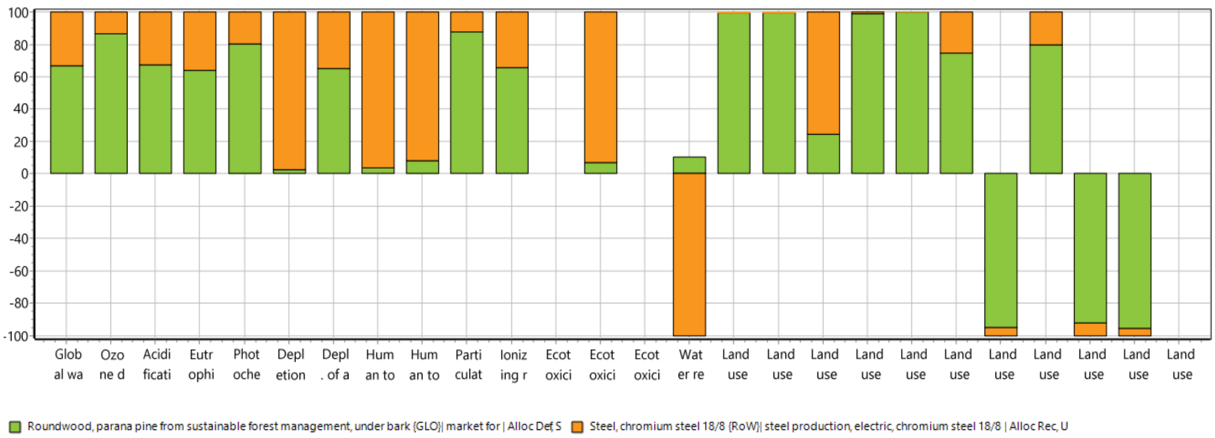

Figure 7.35. Environmental impact of a wooden column using the MMG-method.

Se	Effectcategorie	Eenheid	Totaal	wood column	Roundwood, parana pine	Steel, chromium steel 18/8 {RoW}|
	Totaal	EUR2017	5,37	x	2,56	2,81
	Global warming	EUR2017	0,598	x	0,398	0,2
	Ozone depletion	EUR2017	7,13E-5	x	6,17E-5	9,56E-6
	Acidification for soil and water	EUR2017	0,0336	x	0,0227	0,0109
	Eutrophication	EUR2017	0,267	x	0,222	0,0447
	Photochemical ozone creation	EUR2017	0,0033	x	0,00265	0,000659
	Depletion of abiotic resources-ele	EUR2017	0,000185	x	4,52E-6	0,000181
	Depl. of abiotic resources-fossil fu	EUR2017	x	x	x	x
	Human toxicity - cancer effects	EUR2017	1,74	x	0,0349	1,7
	Human toxicity - non-cancer effe	EUR2017	0,6	x	0,0289	0,571
	Particulate matter	EUR2017	2,04	x	1,79	0,251
	Ionizing radiation -human health	EUR2017	0,000543	x	0,000428	0,000115
	Ecotoxicity - terrestrial	EUR2017	x	x	x	x
	Ecotoxicity - freshwater	EUR2017	0,00115	x	6,19E-5	0,00109
	Ecotoxicity - marine	EUR2017	x	x	x	x
	Water resource depletion	EUR2017	-0,000787	x	9E-5	-0,000877
	Land use: occupation - SOM	EUR2017	0,000718	x	0,000716	2,44E-6
	Land use: occupation - biodiversit	EUR2017	x	x	x	x
	Land use: occup. - flows biodiv., u	EUR2017	0,0301	x	0,00731	0,0228
	Land use: occup. - flows biodiv., a	EUR2017	0,000143	x	0,000141	1,57E-6
	Land use: occup. - flows biodiv., f	EUR2017	0,0562	x	0,0562	6,73E-5
	Land use: transformation - SOM	EUR2017	3,24E-5	x	2,42E-5	8,21E-6
	Land use: transform. - biodiversity	EUR2017	x	x	x	x
	Land use: transf. - flows biodiv., u	EUR2017	x	x	x	x
	Land use: transf. - flows biodiv., a	EUR2017	x	x	x	x
	Land use: transf. - flows biod., for	EUR2017	x	x	x	x

Figure 7.36. MMG impact assessment (monetary values) of a wooden column including the steel connections.

Looking at the monetarized environmental impact (Figure 7.36), it can be observed that a total cost of 5,37 € is obtained for the considered wooden column which is significantly higher than both of the proposed bamboo columns. The main issue with wood, certainly in Brazil, is the lack of control and hence certainty whether the wood actually comes from a sustainably maintained FSC plantation. The greatest disadvantage of harvesting hardwood from rain forests is not the carbon sequestration debit, but the negative effect on biodiversity (van der Lugt & Vogtländer, 2015). One could also calculate the impact of other wood species, yet similar findings on the steel for the connector pieces would be obtained. This fact obliterates the difference between the wood types. In general, when regarding the impact of building solutions with bio-based materials, one can preliminary conclude that improvements need to be found in reducing the impact of the materials that are added to these bio-based materials. Clearly, the amount of steel to connect the wooden column to another constructive part is essential in the total impact of the proposed wooden column, if for example in a sensitivity analysis the amount of steel would be reduced by 2/3th (0.3 kg instead of 0.942kg), the impact of the wooden column would only be 3.46 € (2.56€ for the Parana pine and 0.894€ for the chromium steel parts 18/8). This however would give a wrong impression, for just like with bamboo columns there is needed a certain amount of connector pieces with proper weathering protection which needs to be included in the calculation in order to give a correct assumption. Assuming that no connector pieces would be needed for the wooden column implies that this is the same for bamboo.

The impact assessment results for the **concrete column** are illustrated in Figure 7.37 and 7.38. There are two main components in a concrete column namely reinforced steel and concrete. The orange part of the graph represents the total impact of the concrete and the green of reinforced steel. Despite the small amount in volume compared to the volume of concrete, for most indicators outside of GWP and Ozone depletion, reinforcing steel is the key driver of the environmental impact of the concrete column. Nearly all indicators illustrate that the impact of steel is higher than the actual concrete (orange) which corresponds the findings for the concrete infill of the bamboo columns. The environmental cost of a concrete column is 4.2 €. Considering the environmental cost of the wooden column above this is indeed a remarkable finding, for it is lower than the wooden column with the connector pieces attached. It is however important to consider that the total environmental cost is composed of all indicators combined. If one of the most urgent and crucial indicator GWP would be singled out, another result is obtained, in which the concrete column has far more impact than the wooden or even steel column as will be seen further on.

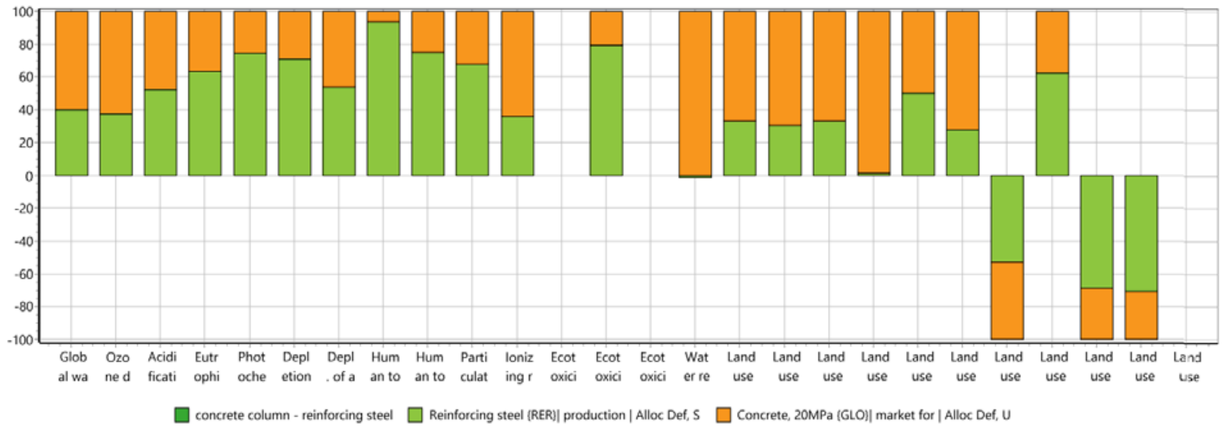

Figure 7.37. Environmental impact of a concrete column including the steel reinforcement.

Se	Effectcategorie	Eenheid	Totaal	concrete column -	Reinforcing steel {RER}|	Concrete, 20MPa {GLO}|
	Totaal	EUR2017	4,2	x	2,73	1,47
	Global warming	EUR2017	1,36	x	0,544	0,818
	Ozone depletion	EUR2017	7,82E-5	x	2,91E-5	4,91E-5
	Acidification for soil and water	EUR2017	0,0395	x	0,0206	0,0189
	Eutrophication	EUR2017	0,286	x	0,139	0,146
	Photochemical ozone creation	EUR2017	0,0053	x	0,00396	0,00134
	Depletion of abiotic resources-ele	EUR2017	0,000115	x	8,15E-5	3,38E-5
	Depl. of abiotic resources-fossil fu	EUR2017	x	x	x	x
	Human toxicity - cancer effects	EUR2017	1,17	x	1,12	0,0577
	Human toxicity - non-cancer effe	EUR2017	0,641	x	0,483	0,159
	Particulate matter	EUR2017	0,563	x	0,38	0,182
	Ionizing radiation -human health	EUR2017	0,000693	x	0,000225	0,000467
	Ecotoxicity - terrestrial	EUR2017	x	x	x	x
	Ecotoxicity - freshwater	EUR2017	0,00111	x	0,000803	0,000304
	Ecotoxicity - marine	EUR2017	x	x	x	x
	Water resource depletion	EUR2017	0,00173	x	-2,44E-5	0,00176
	Land use: occupation - SOM	EUR2017	1,08E-5	x	3,58E-6	7,23E-6
	Land use: occupation - biodiversit	EUR2017	x	x	x	x
	Land use: occup. - flows biodiv., u	EUR2017	0,123	x	0,0408	0,0826
	Land use: occup. - flows biodiv., a	EUR2017	0,000364	x	5,19E-6	0,000359
	Land use: occup. - flows biodiv., f	EUR2017	0,000118	x	5,92E-5	5,84E-5
	Land use: transformation - SOM	EUR2017	5,81E-5	x	1,63E-5	4,18E-5
	Land use: transform. - biodiversity	EUR2017	x	x	x	x
	Land use: transf. - flows biodiv., u	EUR2017	x	x	x	x
	Land use: transf. - flows biodiv., a	EUR2017	x	x	x	x
	Land use: transf. - flows biod., for	EUR2017	x	x	x	x

Figure 7.38. MMG impact assessment (monetary values) of a concrete column including the steel reinforcement.

A **steel column** consists of one single material, i.e. steel; hence the environmental impact is not presented graphically. Virgin steel has a larger GWP impact than steel with a recycled component (1.27€ vs 0.99€), and therefore it is chosen to only discuss the column that has a recycled content for comparison. It should however be noted that recycled steel scores worse than virgin steel on 'human toxicity' cancer effects – which gives a distorted overall eco-cost when comparing virgin and recycled steel. In Figure 7.39, a total environmental cost of 6.64€ for a steel column was calculated, assuming a column that has a high amount of recycled steel as discussed in the chapter on the life cycle inventory. The recycled steel is assumed melted electric in a steel mill, for which the following record was used " Steel, low-alloyed {RoW}| steel production, electric, low-alloyed | Alloc Rec, U". As 100% recycled steel does not yet exist, it was chosen to calculate a sensitivity of 63% 'virgin' steel and 37% recycled steel. The environmental load mainly comes from no carcinogenic substances, terrestrial ecotoxicity and global warming. But also its environmental load mainly comes from Human toxicity (cancer and not-cancer), as well as global warming. But also factors such as nonrenewable energy, aquatic ecotoxicity and finite resources play a great role. It is for this reason that the steel industry is recycling already 70% of the steel. The energy consumption is 15 to 15% less compared to the production of virgin steel. However, there is not enough secondary steel material (scrap) available to meet the worldwide demand (van der Lugt, 2017). In the case that the steel column would be provided in 100% recycled steel, the environmental cost would reduce drastically clearly, but up to this day the virgin content of steel is larger than the recycled percentage.

Se	Effectcategorie	Eenheid	Totaal	steel column recycled	Steel, low-alloyed	Steel, unalloyed {RoW}| steel
	Totaal	EUR2017	6,64	x	4,35	2,29
☑	Global warming	EUR2017	0,995	x	0,197	0,798
☑	Ozone depletion	EUR2017	5,22E-5	x	1,2E-5	4,01E-5
☑	Acidification for soil and water	EUR2017	0,0384	x	0,00925	0,0291
☑	Eutrophication	EUR2017	0,185	x	0,0472	0,137
☑	Photochemical ozone creation	EUR2017	0,00807	x	0,000678	0,0074
☑	Depletion of abiotic resources-ele	EUR2017	2,82E-5	x	1,47E-5	1,36E-5
☑	Depl. of abiotic resources-fossil fu	EUR2017	x	x	x	x
☑	Human toxicity - cancer effects	EUR2017	2,7	x	2,19	0,507
☑	Human toxicity - non-cancer effe	EUR2017	1,93	x	1,7	0,232
☑	Particulate matter	EUR2017	0,713	x	0,187	0,526
☑	Ionizing radiation -human health	EUR2017	0,000361	x	0,000155	0,000205
☑	Ecotoxicity - terrestrial	EUR2017	x	x	x	x
☑	Ecotoxicity - freshwater	EUR2017	0,00179	x	0,00138	0,00041
☑	Ecotoxicity - marine	EUR2017	x	x	x	x
☑	Water resource depletion	EUR2017	-0,000563	x	-0,00092	0,000356
☑	Land use: occupation - SOM	EUR2017	6,21E-6	x	1,58E-6	4,63E-6
☑	Land use: occupation - biodiversit	EUR2017	x	x	x	x
☑	Land use: occup. - flows biodiv., u	EUR2017	0,0712	x	0,0161	0,0552
☑	Land use: occup. - flows biodiv., a	EUR2017	4,78E-6	x	1,48E-6	3,3E-6
☑	Land use: occup. - flows biodiv., f	EUR2017	0,000101	x	3,6E-5	6,46E-5
☑	Land use: transformation - SOM	EUR2017	2,95E-5	x	7,04E-6	2,24E-5
☑	Land use: transform. - biodiversity	EUR2017	x	x	x	x
☑	Land use: transf. - flows biodiv., u	EUR2017	x	x	x	x
☑	Land use: transf. - flows biodiv., a	EUR2017	x	x	x	x
☑	Land use: transf. - flows biod., for	EUR2017	x	x	x	x

Figure 7.39. MMG impact assessment (monetary values) of a recycled steel column.

Figure 7.40 presents the life cycle environmental cost of the different columns. It can be observed that the bamboo columns outstands in the lowest impact. Remarkably a concrete column comes closest to the bamboo columns, even before the assembled wooden column, if all of the environmental indicators are assumed. Recycled steel has the highest impact. When looking at the important indicator GWP, a totally different image however is begotten.

Se	Effectcategorie	Eenheid	Bamboo column of 12 cm, 3m	Bamboo column of 4 times 4 cm	concrete column -	steel column recycled	wood column
	Totaal	EUR2017	2,51	3,65	4,2	6,64	5,37
☑	Global warming	EUR2017	0,283	0,302	1,36	0,995	0,598
☑	Ozone depletion	EUR2017	2,64E-5	1,93E-5	7,82E-5	5,22E-5	7,13E-5
☑	Acidification for soil and water	EUR2017	0,0193	0,0182	0,0395	0,0384	0,0336
☑	Eutrophication	EUR2017	0,0995	0,0809	0,286	0,185	0,267
☑	Photochemical ozone creation	EUR2017	0,00126	0,00111	0,0053	0,00807	0,0033
☑	Depletion of abiotic resources-ele	EUR2017	0,000209	0,000259	0,000115	2,82E-5	0,000185
☑	Depl. of abiotic resources-fossil fu	EUR2017	x	x	x	x	x
☑	Human toxicity - cancer effects	EUR2017	1,2	2,1	1,17	2,7	1,74
☑	Human toxicity - non-cancer effe	EUR2017	0,487	0,742	0,641	1,93	0,6
☑	Particulate matter	EUR2017	0,383	0,365	0,563	0,713	2,04
☑	Ionizing radiation -human health	EUR2017	0,000237	0,000203	0,000693	0,000361	0,000543
☑	Ecotoxicity - terrestrial	EUR2017	x	x	x	x	x
☑	Ecotoxicity - freshwater	EUR2017	0,000854	0,00138	0,00111	0,00179	0,00115
☑	Ecotoxicity - marine	EUR2017	x	x	x	x	x
☑	Water resource depletion	EUR2017	-0,000381	-0,00098	0,00173	-0,000563	-0,000787
☑	Land use: occupation - SOM	EUR2017	3,87E-5	4,86E-6	1,08E-5	6,21E-6	0,000718
☑	Land use: occupation - biodiversit	EUR2017	x	x	x	x	x
☑	Land use: occup. - flows biodiv., u	EUR2017	0,0351	0,0365	0,123	0,0712	0,0301
☑	Land use: occup. - flows biodiv., a	EUR2017	1,02E-5	3,11E-6	0,000364	4,78E-6	0,000143
☑	Land use: occup. - flows biodiv., f	EUR2017	0,00283	0,000175	0,000118	0,000101	0,0562
☑	Land use: transformation - SOM	EUR2017	3,41E-6	8,59E-6	5,81E-5	2,95E-5	3,24E-5
☑	Land use: transform. - biodiversity	EUR2017	x	x	x	x	x
☑	Land use: transf. - flows biodiv., u	EUR2017	x	x	x	x	x
☑	Land use: transf. - flows biodiv., a	EUR2017	x	x	x	x	x
☑	Land use: transf. - flows biod., for	EUR2017	x	x	x	x	x

Figure 7.40. A comparison of the MMG impact assessment (monetary values) for the various columns in different materials.

Since GWP is an important an urgent indicator, this will be singled out for comparison. Figure 7.41 compares the impact on climate change (first indicator GWP) of the bamboo columns with the conventional construction materials. The first two bars in the graph represent the bamboo column variants, in which the first bar is the single pole bamboo column of 12cm (dark green) and the second bar is the column variant with four small diameter bamboo poles of 4cm.

The GWP-impact of the wooden column (final bar) is about two times higher than the bamboo columns. Considering a concrete column that carries the given load (the third row in orange), the GWP impact is more than 4,5 times higher than the assembled bamboo columns. Finally, a steel column with the same load-bearing capacities has a more than a four-fold impact in comparison to the bamboo columns when it is made of virgin steel, 3 times higher when it is made of recycled steel, meaning that the sensitivity analysis of recycled versus virgin steel shows that it can improve by ¼ in impact with regards to the bamboo columns when using recycled content when the global warming potential indicator is reviewed. It can be concluded that bamboo is the least impactful material, even including the steel elements for the connection, reviewed both on GWP (Fig 7.41) as all of the other indicators (Fig 7.42). It is remarkable however that the perceived logical order of impact (bamboo->wood->steel->concrete) is true regarding GWP, but as seen above considering all possible indicators, a concrete column with reinforcing steel surpasses wood to be the least impactful material after bamboo. When looking closely at the table in Fig 7.40, it can be noted that the main cause for this is particulate matter (fine dust) and carcinogenic effects, mainly due to the presence of the chromium steel 18/8 in the assembled bamboo and wood materials (which concrete does not possess – instead it contains a differently formulated reinforcing steel). It can therefore be stated that, for the overall indicator impact the crucial driver for both the bamboo and wooden assembled column is the stainless steel used as connector. In order to improve the performance of the bamboo columns even more, one could try to reduce the amount of steel in the joints and/or improve or even replace the application of the boric acid treatment method. The impact of transport and grout inside the joint connections is of less importance, provided that the grout is foreseen at the joint and transport is regionally. Overseas transport is beyond the scope of this study, however van der Lugt and Vogtländer (2015) studied that transportation of raw bamboo stems has a considerable impact on the LCA-results. In this context, processed bamboo obtains better results. Van der Lugt (2017) calculated that the carbon footprint of sea transport using a volume-based-eco-indicator at a low weight/volume ratio of is 1,45 kg Co_2 eq/kg stem instead of 0,19 CO_2 eq/kg.

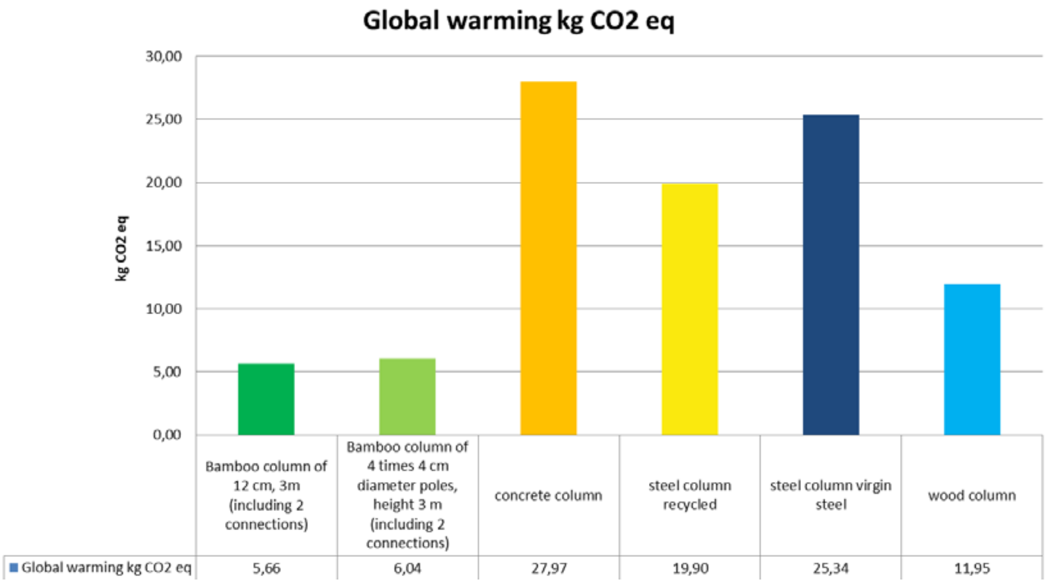

Figure 7.41. Comparison of the GWP-impact in kg CO_2 eq for the various columns in the different materials.

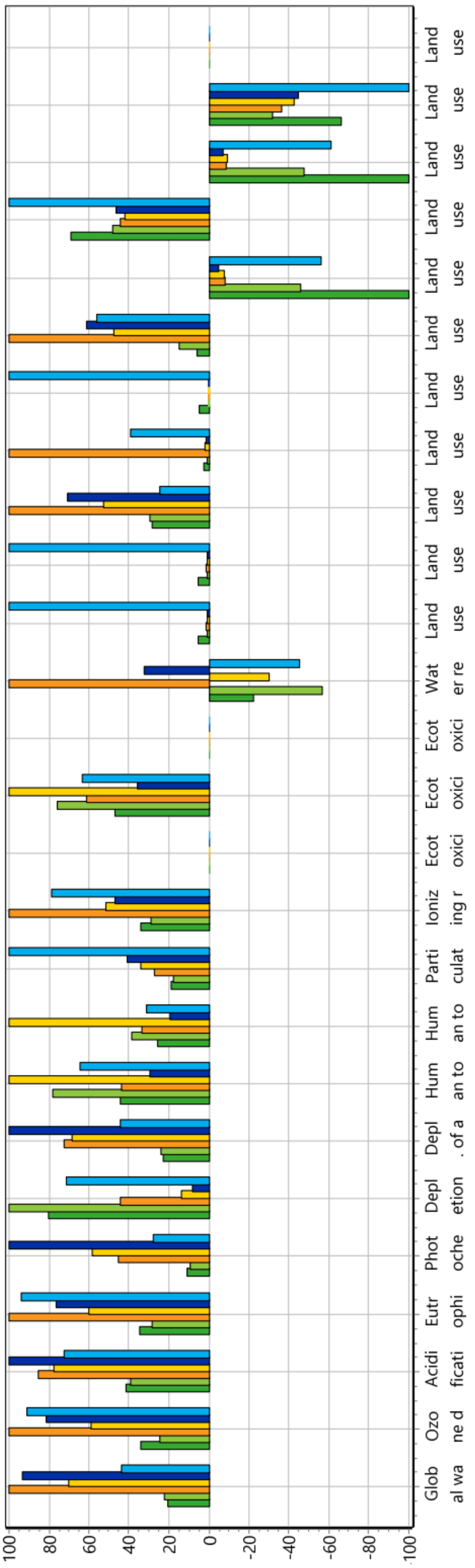

Figure 7.42. Overview of the environmental impact according the MMG-method for all the indicators defined for a load-bearing column. in which the first two are the two types bamboo columns, followed by the concrete column with reinforcing steel (orange), the steel column made of recycled steel (yellow), the steel column of virgin steel (dark blue) and the wooden column (light blue).

7.3.3 Carbon sequestration

The calculation of carbon sequestration is a disputable issue. When the biogenic CO_2 that was recorded by a bamboo stem during its growth phase is released again at the end-of-life of this bamboo stem (30 years for a 'tax-deductible' building) for example by disintegration in landfill, the net effect on global warming becomes more or less zero, regardless the fact that the CO_2 was taken out of the equation for 30 years. However, it is questionable whether the current urgent climate change problem will still be as urgent in 30 years' time, especially as technological progress could possibly lead to new solutions as ozone-depletion by CFK's was a problem a decade ago. The only certainty is that the carbon crisis poses urgent problems that need to be addressed now, for example by carbon sequestration in bamboo. When these bamboos were to be incinerated for electricity production at the end of their service life, this energy could replace energy from fossil fuels. According to van der Lugt & Vogtländer (2015) the end-of-life credit for electricity production from bamboo waste by combustion in a small electric power plant is in carbon footprint 0,782 kgCO_2 per kg or in eco-cost 0,147€ per kg of bamboo waste. Van der Lugt and Vogtländer make the assumption that 90% of the bamboo products will be incinerated for production of electricity and/or heat, whilst 10% (leftover) would end up in a landfill. This would result in a carbon footprint of 0,782 x 0,9 = 0,704 kg CO_2 per kg of bamboo product or in an eco-cost of 0,147 x 0,9 = 0,132 € eco-costs per kg.

When incinerated for energy at the end-of-life, the assembled bamboo columns would have successfully taken out carbon from the atmosphere, due to the carbon-credit effect of preventing the use of fossil fuels to generate energy (even without the actual sequestration in the plant). It is therefore essential to find ways to guarantee that the end-of life of a bamboo building is effectively done in an incineration plant for electricity generation or re-used in other applications (building, furniture or others).

As indicated by van der Lugt & Vogtländer (2015) is the global carbon sequestration with regards to bamboo proportional to the growth of the market for bamboo products because of the extra volume of bamboo in (new and existing) plantations as well as in durable products in the building and other industries. In order to get a correct idea of the amount of carbon that is durably sequestered by bamboo different steps have to be considered; 1- the ratio of carbon stored in forests to carbon stored in end-products 2- the land-use-change correction factor (because of the other type of biomass formerly present) 3- calculation of carbon extra stored in forests and plantations (because of the growth of bamboo production), 4- the amount of extra stored carbon in the building industry because of growth of the volume of bamboo in new plantations and finally 5- the calculation of the final result based on previous points. The calculation of the steps above can be found in the INBAR report nr. 35 (van der Lugt & Vogtländer, 2015) as well as in Booming Bamboo (2017) and will therefore not be repeated here. Yet, it has to be mentioned that van der Lugt and Vogtländer focus their study merely on processed bamboo (in boards, panels and other) and the calculation for unprocessed bamboo is unidentified.

The amount of biomass which can be produced by bamboo depends on the region and the species incinerated. Van der Lugt & Vogtländer (2015) established that for Phyllostachys Pubescens the total above- and below-ground biomass is 111 ton/ha dry matter. This holds a carbon content of 50%. In Booming Bamboo van der Lugt (2017) even calculated the amount of above- and below-ground biomass (dry matter) for the same species at 138 ton/ha. In a preliminary study by van der Lugt (2003) concerning the complete lifecycle (including retrieval of energy when incinerating the bamboo at the end of the service life), bamboo even turned out to have positive environmental costs. The amount of CO_2 sequestration of the single bamboo pole column (type 1) of the research is calculated based on the data of van der Lugt (2017), van der Lugt & Vogtländer (2015) and the wood-norm EN 16449 (2021). The bamboo column has a diameter of 12cm and weighs 4,25kg. Hence, 3,48kg of CO_2 was sequestered for this single pole. It is fair to say that the carbon sequestration was successful when the end-of life solution also was. If for example a construction would be composed of 100 FU (which is not unrealistic for a normal residential building), this would imply that a building can possibly sequester half a ton of CO_2. Referencing to a recent project by author for the entrance buildings of Planckendael, where three 25m high towers of will be built consisting of 10500 meters of bamboo with the same diameter as the FU, a stunning 17,5 ton of carbon would for example be sequestered (compared to a FU of 3m).

7.4 **Conclusion**

In this chapter, a life cycle analysis of bamboo columns was performed according the MMG method. Two illustrative bamboo columns were extracted from the case studies in Brazil as these were considered exemplary for a bamboo column and in regard to prefabrication and modularization. The following findings from the assessment could be found;

- For a dried, treated, transported yet non-assembled raw bamboo stem the **treatment** has the largest impact on nearly all the environmental indicators. The treatment method assumed for the LCA is the boucherie-method where pressure is applied to ‘push’ out the bamboo sap by forcing a cure, usually borax/boron, through the culm at the basal end. The pressure generated to push the solution through the culm, is the main energy consumer. One can possibly utilize another treatment technique where the energy consumption is less for example soaking the bamboo in a borax solution. Borax (Na2B4O7·10H2O) is currently the most frequently used cure for treatment of bamboo. It has an emission factor of 1,65 kg CO_2eq per kg product (Van der Lugt & Vogtländer, 2015). The possible treatment methods should be analyzed specifically on their life cycle impact for only than a conscientious choice of a certain treatment method can be made.

- A study by Van Durme et al. (2012) indicates that when long-distance sea transport was to be calculated, the factor **transport** would become the most impactful. This is quite logical because the bamboo stem itself has nearly no impact whatsoever, leaving only electricity, transport and treatment to be the impact factors. Van der Lugt et al. (2005) assessed a pedestrian bamboo bridge in the Netherlands on environmental, economic and practical aspects. This research concluded that even including sea transport to Europe, bamboo has a relatively small environmental load which was in several functions even 20 times more favorable compared to conventional building materials, i.e. concrete, steel and timber. In this research, the focus of the case studies is in Brazil and the bamboo sourced comes from a bamboo plantation in the region of São Paulo. Hence, the distance of the transport is limited and regional transport by means of a freight lorry already suffices. Possibly larger trucks (e.g. 28 tons instead of 5 tons) or more energy efficient trucks could induce a lower environmental impact. Although, the absence of sea transport already reduces significantly the environmental impact of bamboo. A study on industrial versus traditional bamboo construction by Escamilla et al. (2018) suggests that when bamboo is produced decentralized, it could even further reduce the volume of regional transportation. The same study also suggests that bamboo has the potential to balance the emissions caused by other (conventional) construction materials, making it a perfect addition even to other materials when a complete bamboo construction is not possible.

-Nearly no other structural construction material performs environmentally evenly well as bamboo. The **low impact of bamboo** can be attributed to the fact that a bamboo stem does not require any processing in order to be employed as a construction material. Bamboo used in its original form reduces the carbon cost considerably. Even wood has to be sawn to employable sizes and sanded by machines hence requiring an extra, energy consuming, step between the plantation and construction site. Van der Lugt & Vogtländer (2015) calculated that local use of unprocessed bamboo has a carbon footprint of 0,19kg CO_2eq/kg stem, which is the absolute lowest possible of all building materials.

- As **cost** is also an important factor in bamboo building, one should have a clear oversight of the cost balance. Van der Lugt & Vogtländer (2015) concluded that considering the purchasing cost, bamboo is by far the least expensive building material. However, because of the (perceived, not proven) shorter life span and the higher labour costs of bamboo, steel appears to be the most favorable material, due to its long life span. The problem with steel however is that the energy consuming and polluting production occurs now, regardless its long life cycle. Nevertheless, bamboo was proven to be competitive with the timber alternatives (van der Lugt & Vogtländer, 2015). Not only the building cost but also the eco-cost should be visualized when addressing the costs to clients. A visual tool to integrate LCA and LCC (lifecycle cost) in the early stage of a design has been developed by Miyamoto, Allacker & De Troyer (2019). This tool visualizes the eco-costs alongside the more direct economic factors such as building cost. This tool could even be integrated in the evaluation framework, the scope of this research. Furthermore, also the building technique used (traditional vs prefab) greatly determines the costs. Not only is the speed of construction a key factor, also the joint design and connection materials used play a decisive role. With regard to the **jointing methods**, it can be concluded that the steel variant is more beneficial when recycled steel is used or when the steel can be recycled or reused afterwards. Recycling is only possible when the opportunity to isolate the different building materials after the use phase is provided. A concrete infill at the joint can be done if necessary, but the roof weight and gravity already establish a similar effect. The use of hardwood joints is the most beneficial compared to the other materials on condition that the wood is sourced at a FSC managed plantation.

- Figure 7.41, one of the **key figures** in this chapter, presents an overview of the environmental impact of an assembled bamboo column compared to columns made of other construction materials based on equal loadbearing capacities. The results show that the GWP factor of an assembled wooden column (Parana Pine) has a twofold impact in relation to the bamboo solution, a steel column even four times as much and a concrete column 4,5 times higher than the assembled bamboo column from this study. Considering overall eco-cost a remarkable effect takes place in that the concrete column surpasses the wooden column. This is solely the effect of the use of stainless steel (whilst the concrete column has 'reinforcing steel' of a different composition) that makes both the assembled wooden as the assembled bamboo column score worse. In the stainless steel connector components lies the greatest potential for the improvement for both types of columns (wood and bamboo), as well as the treatment material for bamboo.

- In case bamboo would be addressed through the 'cascading'-principle, as described by van der Lugt & Harsta (2020), this impact reduction in comparison to other materials could even be semi-permanent. The cascading use principle gives priority to higher value applications that allow the reuse and recycling of products and raw materials. It also promotes energy use only when other options are starting to run out. Hence it prioritizes material use of biomass before energy use since burning implies the raw material being lost.

- As a final remark, it has to be noted that **proceeding insights** into the parameters of the LCA-assessment can alter the end results. Ramon & Allacker (2019) concluded that in current LCA-methods the influence of climate change is possibly underemphasized. Climate changes and climate regulations induce changes on the energy use and related GHG emissions. They recommend utilizing a holistic approach to avoid burden shifting when considering changes between different end-energy uses, energy mixes and technologies. Furthermore, the future time span should be divided per yearly time period encountering possible variations as technologies keep evolving.

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PART III

EVALUATION FRAMEWORK

CHAPTER 8 DEVELOPMENT OF THE EVALUATION FRAMEWORK

8.1 Introduction

Architectural design is a careful synthesis between function, form, technology and constraints such as time, money and regulations. The multifaceted nature of design has already been recognized since the late Antiquity, when Vitruvius (1999) described design in terms of firmitas, utilitas and venustas. Figure 8.1. translates these three main components visually, of which lifecycle is an enhancement to functionality (Gann et al., 2003).

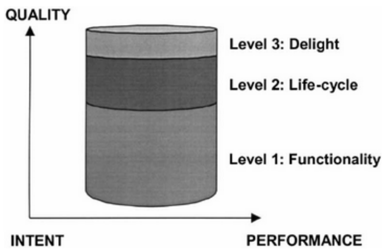

Figure 8.1. Three-layered cylindrical model. Retrieved from Design Quality Indicator as a tool for thinking by Gann, D.M., Salter, A.J., & Whyte, J.K. (2003), p. 325.

Although this model gives a good representation of the elements of importance in an evaluation framework; function, build quality and impact, it does not take the interaction of these aspects into account (Gann et al, 2003). Design quality is a complex phenomenon with interrelating aspects that can be judged from different perspectives, which makes it so difficult to find a systematic approach for its assessment (Van der Voordt & Van Wegen, 2005). The primary purpose of any qualitative evaluation is to enable reflection and help in the identification of future change and development. Evaluation can be defined as a process of observation and measurement judging quality and determining “value,” either by comparison to similar settings or to pre-set standards (Eilouti, 2020). This chapter aims to interpret and assign meaning to the design under assessment using a set of prescribed indicators, however does not present an overview of every contemporary architectural design quality assessment tool as this would lead away from the scope of this research. Yet, worth mentioning is the Design Quality Indicator (DQI). This tool was developed based on a “rational-adaptive approach” serving as a toolkit for improving the design of buildings. This model integrates both ‘hard’ physical and ‘soft’ perceptual criteria (Gann et al., 2003). Aside from general design criteria such as light, functionality, quality of spaces, etc. forming the basis of the DQI model, in this evaluation framework those criteria to help find the most optimum solutions for qualitative bamboo constructions predominate. Other tools were considered either too specific such as AEDET for hospitals or DEEP for military housing. LEED and BREEAM try to set the standards for certification of green buildings, while BQA aims to assess the performance of office buildings. Multi-criteria decision making models (MCDM) such as the Analytic Hierarchy Process (AHP) developed by Saaty (1990) are on the other hand methods to deal with complex problems (Harputlugil et al., 2011).

The main aim of this evaluation tool is to assist a bamboo architect in design decisions;

- Usable by both lesser and more experienced bamboo architects/designers
- Measure the design quality against the chosen intent for the building
- Allows participants to compare and adjust different design options
- Usable in the different phases of construction (pre-design, design, construction and in-use)
- Easy to use and clear interface

8.2 **Structure of the evaluation framework**

The evaluation framework is set-up as a multi-criteria assessment tool to optimise the building of bamboo constructions by assessing structural bamboo constructions based on their sustainability features, constructability, innovativeness and finally speed and cost of construction. A loadbearing bamboo structure can equally be an entire house, a structural framework or a single structural element in bamboo. Harputlugil et al. (2011) point out that as there is not a universal definition for architectural quality; the tools created for architectural design quality assessment should consider a flexible/adaptable system for criteria selection.

A building process can be divided in 5 different stages (Figure 8.2), indifferent of the function or size of the project. First, there is the pre-project phase that involves setting the project goals, financing, feasibility and pre-design. In the second phase, the conceptual design is developed that is gradually detailed during the building design phase. Thirdly, tenders for construction are called for and the contractor is decided. In the fourth phase, the construction process can be initiated. Finally, after the completion of the construction, in the fifth phase, the construction is handed over to the client whereafter there is still required yearly maintenance. It is best when the framework is already employed during the early design processes. This can be either in the pre-design phase, where besides the client´s vision for the project, also the scope, features and functionality of the building are determined or in the conceptual design phase where a more detailed, yet still preliminary design is drafted. However, this does not mean that in the other phases (tendering, construction or in-use phase) no valuable adjustments can be made after the evaluation with the proposed framework. In fact, although measuring quality of design at the different project stages is useful to set priorities and to see how the construction is performing. The actual result will only be known after the building is several years in use. During the occupancy stage, measurement and feedback such as post-occupancy evaluation (POE) can be carried out to determine the level of design quality (Suratkon et al, 2016). Returning to the design and procurement process, Dickson (2004) mentions that it can be seen as a series of decisions that lead progressively towards the built reality. Considering that a design process is the sum of decisions made by each stakeholder, a set of multiple criteria is required to come to a holistic framework. Designers are required to single out between quantifiable and non-quantifiable criteria. The objectives can be conflicting (e.g. economic vs ecologic) and therefore the solution is highly dependent on the preferences of the decision-maker and compromises must be made (Pohekar and Ramachandran, 2004). To cope with the complexity of assessment of architectural design quality, decomposing the quality hierarchically in criteria and sub-criteria might be a helpful approach (Harputlugil, 2011).

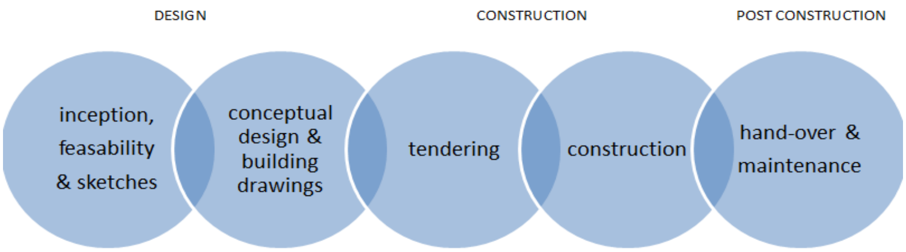

Figure 8.2. Building phases in an architectural project.

The difficulty of an evaluation tool lies in the question of who is going to assess the quality and how the consistency and objectivity of the evaluation can be obtained? Furthermore, not every criterion is equally important and what kind of a weighing system could be assigned? Each design and building process has its special characteristics and cannot be standardized easily. A quality evaluation is subjective since quality is appreciated differently by every individual (Allacker, 2010).

8.2.1 Evaluation framework indicators

The evaluation framework runs parallel with Vitruvius´ principles in order to propose a durable, innovative and low-cost bamboo building (assessed on stability, performance and design quality). The following indicators can be deduced from the literature research.

8.2.1.1 Component 1: stability

The section on stability first addresses the suitable species and their corresponding mechanical properties. Subsequently, the standards and codes for bamboo are listed, after which the possible structural systems and jointing systems are mapped, followed by bending and the fire resistance characteristics of bamboo (Figure 8.3).

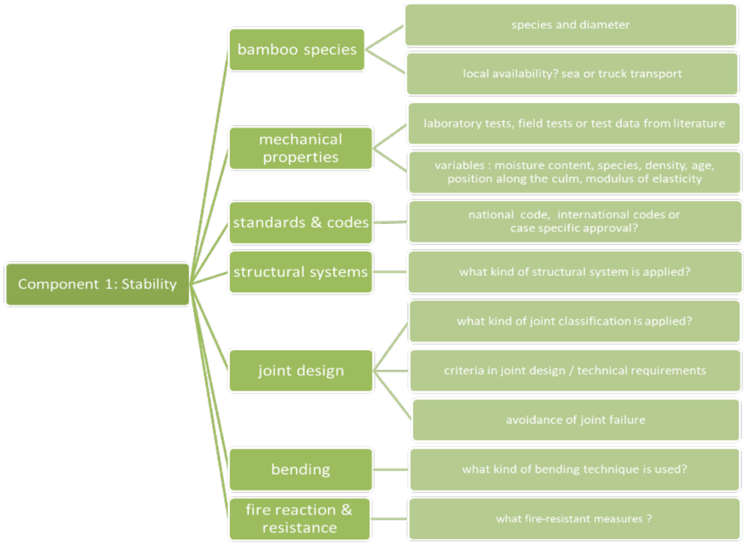

Figure 8.3. The evaluation framework indicators of the first component stability.

8.2.1.2 Component 2: Performance of a bamboo structure

The second component addresses the performance of a bamboo construction by means of the three pillars; people, planet, profit. The environmental performance discusses the environmental benefits, challenges and the opportunities of bamboo for circular building. Economic performance addresses the economic benefits and deficits. Finally the pillar social performance considers the indicators social cohesion, vernacular architecture and resilience to disaster (Figure 8.4.).

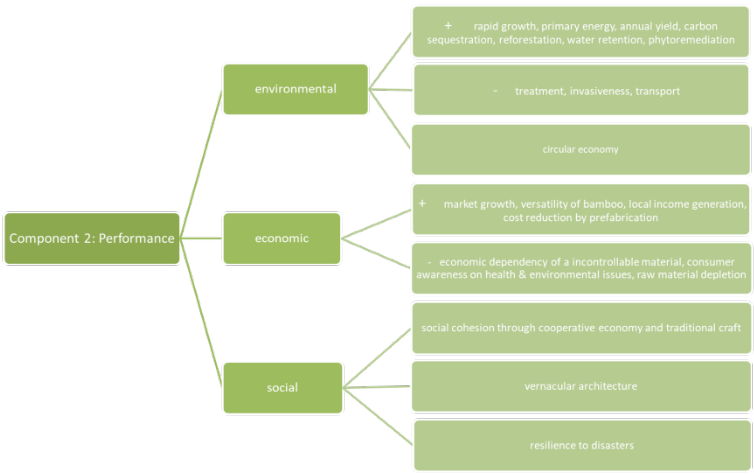

Figure 8.4. The evaluation framework indicators of the second component performance.

8.2.1.3 Component 3: Aesthetic quality of design

The final component targets those indicators in terms of the aesthetic quality seen in Figure 8.5. (proportionality, balance, order, coherence, form,…).

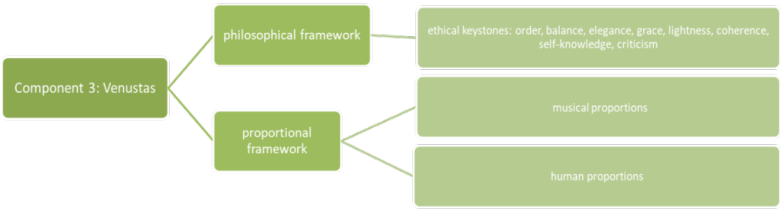

Figure 8.5. The evaluation framework indicators of the third component

8.2.2 Conceptual framework

According to the methodology used to develop the DQI Model by Gann et al. (2003), there can be distinguished equivalent factors in this evaluation framework; conceptual framework, data gathering tool and a weighing mechanism. The conceptual framework sets out the range of criteria that impact the quality of a bamboo design. The three components are deduced from the previous sections and form the basis for the conceptual framework demonstrated in Figure 8.6. In order to achieve a better quality and/or a higher performance, these components have to be in balance and at the same time fulfill as much as possible the requirements.

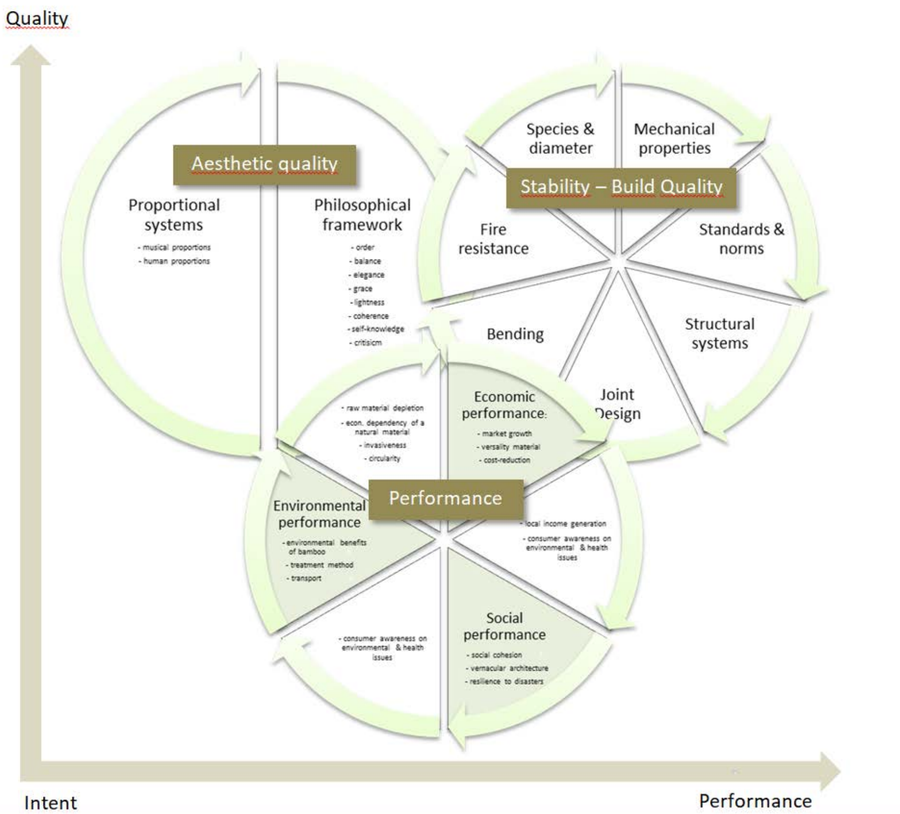

Figure 8.6. Conceptual framework

8.2.3 Requirements versus recommendations

In bamboo architecture, there is a great amount of design liberty. Although this can be considered as a considerable advantage, certain main requirements should be included as indispensable conditions. Each and every bamboo construction should fulfil the following basic conditions, regardless the specific intent, design or context;

- The treatment method offers a sufficient protection and the treatment cure applied is not a highly toxic chemical.
- The sourced bamboo has been dried until the moisture content is reduced to 12-20%.
- National or international codes are respected.
- As a technical design requirement the proposed construction needs to be protected from water, both capillary as direct (rain)water, and from direct sun.
- The application of non-toxic adhesives in the case that bamboo is further processed.

The structure of the evaluation framework is subdivided into two sections. Only when the above-mentioned prerequisites are met, the subsequent questionnaire can be completed. The second part of the framework is the questionnaire which consists of recommendations. The answers will depend on the concept, the context and/or the intention of the design.

8.2.4 Data gathering & weighing mechanism

The conceptual framework is the starting point for the development of a list of relevant questions for the data gathering. With the intention to start off with a broad spectrum of potential questions where after this list was edited and a limited selection was made. The main and sub criteria upon which the data gathering survey is built, parallels with Vitruvius´s three main principles to assess architectural quality and anew according the literature study, the case studies and the LCA discussed in the first two parts of this dissertation.

In the DQI model, the respondent is asked to indicate what are to him/her the most important features of the building prior to the evaluation. For example, if the respondent mentions the feature function, his responses considering the aspect function will be magnified (Gann et al., 2003). Following suit of the DQI assessing tool, it is opted to primarily request users to indicate the aspects of importance to their particular project; environmental, social, economic, circularity, aesthetics. Before the intent of the designer can be measured against the design quality, the evaluation framework should include the intent of the user in the beginning of the evaluation framework as well. This is done by accordingly (un)checking these options at the outset of the questionnaire. Giving an aspect the score of ‘0’, the entire column considering it, will become deactivated. On the other hand, when attributing a ‘1’ the column is activated. In the spreadsheet, this will automatically multiply the scores of this column e.g. environmental by one or zero. As such, it is possible to either review one, some or all of the above-mentioned aspects.

The questionnaire functions in a similar manner. The user has to respond a set of questions on stability, performance and aesthetic design quality. When the user responds a particular question in the query with “yes”, an underlying number (1) is activated versus the number zero (0) in case the answer is “no”. The outcomes hereof serve as a multiplication factor to the attainable score per question. Subsequently, a certain weight is given to each criterion as these cannot all be counted as equally important. This score is begotten by cross-referencing the criteria with the above-mentioned aspects; environment, social, economic, circularity and aesthetics. The weighing factor is determined by the extent these criteria meet the key aspects of this dissertation being sustainable, innovative and low-cost. Characteristics such as speed of construction, maintenance, ease of jointing, low environmental impact or a high reusability greatly affect the sustainability, cost and circularity of a construction (Gunawardena et al., 2012) which consequently results in better scores. Then again, the fact that besides tangible also intangible criteria are involved in the framework, Harputlugil et al. (2011) emphasize that intangible criteria cannot be objectively evaluated in a numerical way. Therefore, the criteria that are susceptible to subjectiviness or irrelevant in relation to the above-mentioned aspects, a score ‘0’ is given. For example, a question on the type of treatment method used for the bamboo poles is irrelevant to the aspect aesthetics and is given a ´0`.

The line of questioning shows the outcome via a variety of green in the final column. These shades of green range from no colour to dark green to present the user the result. Dark green means a positive result on the constructive, environmental, economic, social and aesthetical aspects. More specifically on those aspects that were activated from the start on and not those that were deactivated. Light green indicates that some of the aspects are subject to improvement and colorless either means that the outcome is irrelevant in relation to the aspect or none of the recommendations for a sustainable and innovative bamboo design have been met. In case one does not attain a satisfactory quantity of dark green results, it does not necessarily imply that the proposed bamboo design is useless. As said before, each project is case-specific and the intent of each project differs. In conjuction with the above, the use of negative outcomes is averted. Only the prerequisites (conditione sine qua non) addressed in section 8.2.3. are absolute, whilst the criteria in the questionnaire are recommendatory when aiming for a better design quality. The visual results will help the user to identify which criteria have a less than satisfactory result and determine whether this aspect is of importance to the design context or not. As long as the first mentioned ‘conditio sine qua non’ design principles are followed, it can be assumed that any bamboo project already has its merits. The evaluation framework has to be regarded as a tool to uncover where certain improvements to the bamboo design can be made and help designers to reflect on certain design decisions.

There are two versions of the evaluation framework; the extended and a moderate version (a quick scan). Figure 8.6. is an extract from the Excel spreadsheet of the extended framework featuring the numerical weighing system. However, it is the intention that respondents are provided the quickscan version wherein the weighing system is hided and only the output in the different shades of green comes up. This is preferred as a result of the higher user friendliness and to prevent alterations or confusion with the apparent weighing system. In accordance with the DQI model by Gann et al. (2003) this framework establishes a rough guideline of 20 minutes to be completed. The aim is to ensure that the respondents can move quickly through the questions without being overwhelmed by technical specifications. However, when a designer prefers to prioritize on those aspects that are of relevance to the design context, e.g. environmental, economic, social,.. or analyse how the color scheme and its supposed weight is begotten, the extended version is recommended. The extended version differs from the quickscan on the fact that the numerical scores behind the conclusions are visualised, and subscores on different fields can be reviewed independently. Both versions are provided in one Excel file where the first spreadsheet demonstrates the quick-scan and the second the extended version.

As part of the development process, the case study of the community center was tested on the functionality and user convenience to test and refine the instrument. The results of this pilot study are discussed in section 8.5.

EVALUATION FRAMEWORK FOR LOAD-BEARING BAMBOO STRUCTURES

INTRODUCTION

The evaluation framework determines the score of a sustainable, innovative, low-cost load-bearing bamboo structure (not entire the house).
The scores are displayed via the intensity of the colour green; the darker, the more impact (because the project scores better on more aspects)
The scores can be reviewed as a total or per subscore below each aspect (environmental, social, economic, circularity, aesthetic).
In order to see where the project can be improved, the 'zero-scores' can be filled in as '1' , showing the intensity of green and thereby its relevance to the project.

INSTRUCTIONS

The module has to be used as following;
° Only when all the statements in the 'conditione sine qua non' apply to the project, the questionnaire of the module can be completed.
° Each statement of the questionnaire has to be answered whether it applies to the project under evaluation (enter 1) or not (enter 0).
° This framework targets the Brazilian context (hot and humid tropical conditions), the module must be adapted when another context is to be considered.
° The digital excel-tabel (on request) can used interactively

Aspects to be reviewed by the designer	environmental	social	economic	circularity	aesthetic
Check boxes for each aspect with "1" or "0" if it is desired to review them or not.	1	1	1	1	1

EVALUATION FRAMEWORK

CONDITIONE SINE QUA NON

Treatment method
The sourced bamboo poles have received a proper treatment against natural decay.
The sourced bamboo poles have not been treated by means of the highly toxic chemicals NaPCP, ACA, CCA,...
The sourced bamboo poles have been dried until the moisture content is reduced to 12-20% (generally 3 months).

Application of toxic adhesives
When bamboo is used laminated, no highly toxic levels of formaldehyde or other toxins are used.

International codes
The national codes (when in China, India, Ecuador, Peru, Colombia, Brazil) have been checked and applied to the project.
The international ISO-22156 and ISO-22157 codes have been consulted and taken into account for the project.

Technical design requirements
Protection of the bamboo from radiation and water (both upward water as well as precipitation).

QUESTIONNAIRE

COMPONENT 1: STABILITY

main categories	statements	environmental	social	economic	circularity	aesthetic		score	applies	result
1.1. Species										
Bamboo species										
	Guadua A.., Phyllostachys P. or Dendrocalamus G. or A. or another known species suitable for construction is employed.	2	0	1	1	0		4	1	4
	Species obtained from plantations close to project site are used (even if they are small diameter bamboos).	2	2	2	2	0		8	1	8
1.2. Mechanical Properties										
Test data										0
	General data from literature on the used species has been used.	1	0	0	1	0		2	1	2
	Specific test data on the lot of bamboo is used instead of general data on the species.	2	1	-1	1	0		3	1	3
	A field test (e.g. by means of the test-kit developed by K. Harries) is used to determine strength.	2	2	-1	1	0		4	1	4
Mechanical properties										
	Bamboo species with larger wall sizes are selected.	2	0	-1	1	0		2	1	2
	The density of the bamboo poles is between 0,5-0,9 g/cm.	2	0	-1	2	0		3	1	3
	The moisture content of the dried bamboo poles is between 12-20%.	1	0	-1	1	0		1	1	1
	The age of the bamboo poles is between 3 to 5 years.	2	0	-1	1	0		2	1	2
	Position along the culm (base, middle, top) is checked and only base and middle parts are applied as these have a larger wall size.	1	0	-1	0	0		0	1	0
	The project employs the bamboo in tension (best property) or in compressive strength.	2	0	-1	2	1		4	1	4

The project avoids the use of its limit values.	1	0	-1	1	-1	0	1	0
The stability of the construction is calculated by an authorized engineer.	2	1	-1	2	0	4	1	4
1.3. Standards and Building Codes for Bamboo								
International codes								
The ISO code has been consulted, not only the technical specifications but also the specifications on plantations, treatment,...	2	1	0	2	0	5	1	5
Mechanical laboratory tests have been performed according ISO-22156 and -22157 on the applied bamboo lot to determine its values.	2	0	0	2	0	4	1	4
Laboratory tests have provided data on the strength values, diameter, age, position along culm, density, moisture content and MOE.	2	0	-1	2	0	3	1	3
National codes								
The national code has been consulted, not only the technical specifications but also the specifications on plantations, treatment,...	2	1	0	2	0	5	1	5
In absence of a national code, relevant codes from other countries such as the NSR-10 from Colombia have been consulted.	2	0	0	1	0	3	1	3
Case specific approval is begotten from the government in case national codes are lacking.	2	0	-1	1	0	2	1	2
1.4. Structural Systems								
Type of structural system								
The project can be defined as organically woven, freeform architecture (as described in 3.4.1).	1	1	-1	-2	2	1	1	1
The project can be defined as curvilinear architecture (as described in 3.4.2).	1	1	-2	-1	2	1	1	1
The project can be defined as truss architecture (as described in 3.4.3).	2	1	-1	1	2	5	1	5
The project can be defined as a geometric structure; space frame, grid shell, diagrid, dome, etc. as described in 3.4.4).	2	1	-1	2	2	6	1	6
The project can be defined as orthogonal bamboo architecture (as described in 3.4.5)	2	1	2	2	2	9	1	9
1.5. Joint Design								
Technical requirements								
The joints are foreseen close to a node resulting in higher resistance to shear forces.	1	0	-1	2	0	2	1	2
Moment forces in joints are avoided as much as possible, e.g. by the use of hinges.	1	1	-1	2	1	4	1	4
In case of large moment forces in the joints, tension band are used at the end of the bamboo stem.	-1	1	-1	2	-1	0	1	0
Steel parts such as hex nuts, wire rods and washers are provided in galvanized steel and protected with a varnish layer .	-1	2	-1	2	1	3	1	3
The joints are designed as such that the need for grout in the connections is reduced as much as possible	1	0	-1	2	0	2	1	2
When using grout in the connections, the cement-sand proportion is 1 to 2 (or 3) and a measured amount of water is added.	0	0	-1	0	0	-1	1	-1
The amount and diameter of the drilled holes is kept to a minimum (3- 4cm in diameter) according to the codes.	1	1	-1	1	2	4	1	4
Joint classification								
Most of the joints are part of group 1 - transferring compression through contact to the whole section.	2	1	-2	1	1	3	1	3
Most of the joints are part of group 2 - transferring force through friction on the inner surface or compression to the diaphragm.	2	2	2	2	1	9	1	9
Most of the joints are part of group 3 - transferring force through friction on the outer surface.	1	2	-1	1	1	4	1	4
Most of the joints are part of group 4 - transferring force through bearing stress and shear to the wall from a perpendicular element.	1	1	-1	2	2	5	1	5
Most of the joints are part of group 5 - Transferring force perpendicular to the fibers.	-1	2	2	1	1	5	1	5
Most of the joints are part of group 6 - Transferring radial compression to the centre of the pole.	-1	1	-1	1	1	1	1	1
Criteria for joint design								
Penetration in the bamboo poles by nails, screws or bolts is reduced as much as possible	2	0	2	2	2	8	1	8
The intrinsic qualities of bamboo are favoured in the joint design (tensile & compressive) and the weaker avoided (shear & bending).	2	1	-1	2	1	5	1	5
Ease of production of the joints in terms of required equipment and handicraft skills.	2	2	2	2	0	8	1	8
The joint is prefabricated and adaptable, simplifying a modular set-up of the intended project.	2	2	2	2	1	9	1	9
The provided joint is stable, both in relation to time as strength.	2	2	2	2	1	9	1	9
The dimensions and the joint itself can be adapted according to a modular (prefabricated) system.	2	2	2	2	1	9	1	9
The strength of the joint is laboratory tested and its behaviour can therefore be predicted.	1	1	-1	2	0	3	1	3
The provided joint is cost-efficient in relation to the entire construction cost (speed of construction vs cost per piece).	1	1	2	2	1	7	1	7
The applied joint consists of materials that can easily be found in local construction stores, welding or carpentry shops.	1	2	2	2	0	7	1	7
The aesthetic of the joint is carefully studied and designed.	1	1	-1	2	2	5	1	5
Avoidance of joint failure								
Possible situations of elevated stresses and bending in structural elements are monitored in time and maintenance is planned.	1	1	-1	2	0	3	1	3
Cracks and splits in structural bamboo elements are monitored and immediately remediated (e.g. mix of glue and sawdust).	1	1	-1	2	1	4	1	4
Severe cracks are monitored and initially remedied by tension bends and finally replaced when needed.	1	1	-1	2	-1	2	1	2
The limit state diagram (as described in 3.5.4.) is used to determine the potential risk of crack propagation	2	0	-1	1	0	2	1	2
1.6. Bending								
Bending of bamboo poles								
The project does not consist of structural bended elements	2	1	-1	1	1	4	1	4

statements	environmental	social	economic	circularity	aesthetic		score	applies	result
The project applies the immersion technique by bending freshly cut bamboo in lukewarm water.	1	0	-1	1	1		2	1	2
The project applies the combustion technique by bending freshly cut bamboo with use of a blowtorch according correct procedures.	-1	0	-1	0	1		-1	1	-1
The project applies no slashing technique (bending by making many tiny cuts in the bamboo).	1	0	-1	1	1		2	1	2
The project applies the bundling technique by bundling multiple small diameter bamboos together.	1	1	-1	0	1		2	1	2
The project applies bamboo´s natural curvature and makes a curves divided over several segments.	1	1	-1	0	1		2	1	2
1.7. Fire reaction and fire resistance									
Fire reaction and fire resistance									
Literature on fire reaction and fire resistance is studied in detail in regard to the project.	1	1	-1	2	0		3	1	3
The bamboo used for the project was tested in a laboratory setting to determine its fire reaction.	2	2	-1	1	0		4	1	4
Escape routes are projected and discussed with the local fire department.	1	2	-1	1	0		3	1	3
A fire retardant chemical is added to the bamboo during the treatment process.	-1	1	2	1	0		3	1	3
A fire resistant coating is applied on the bamboo after the construction process.	-1	1	2	1	0		3	1	3

main categories / statements	environmental	social	economic	circularity	aesthetic		score	applies	result
COMPONENT 2: PERFORMANCE									
2.1. Environmental Performance									
A: Ecological Benefits									
Rapid growth & renewability									
The sourced bamboo is grown in tropical conditions (rapid growth, large height & thickness).	1	1	-1	1	0		2	1	2
The sourced bamboo is grown on the hillsides (strength > erosion control, less rapid growth yet generally more qualitative).	1	1	-1	0	0		1	1	1
Regular harvest (> yield, CO_2 sequestration, material quality, land scarcity).	2	2	2	2	0		8	1	8
Less yield in harvest (thick canopy, no loss of species, more undergrowth).	2	1	-1	0	-1		1	1	1
Interplanting/agroforestry (> biodiversity, < monoculture, profit, logistic).	2	1	-1	1	0		3	1	3
Carbon sequestration									
The bamboo comes from an unmanaged plantation or bamboo forest.	1	1	-1	1	0		2	1	2
The bamboo comes from a managed plantation where is regularly harvested (avoiding stored carbon to be released into the air again).	2	1	-1	1	0		3	1	3
The bamboo comes from a managed agroforestry site with a variety of high yielding species.	2	1	-1	1	0		3	1	3
The bamboo comes from a community based plantation.	2	2	2	2	0		8	1	8
The bamboo is used in a long-term construction resulting in durable sequestration.	1	1	-1	2	1		4	1	4
Bamboo will be used for electricity production or in another recycling process at the end-of-life in the assessed project.	2	1	-1	2	0		4	1	4
The local government financially stimulates low-carbon applications in tenders.	2	1	-1	2	0		4	1	4
Reforestation and restoration of degraded land							0		
The sourced bamboo comes from a wasteland, poor farmland or other degraded areas (lower quality).	2	1	-1	2	-1		3	1	3
The sourced bamboo comes from a borders, riverbanks or areas in risk of desertification.	2	2	-1	1	0		4	1	4
Only the mature bamboo is cut (age between 3-5 years) with a maximum of 20-25% of the entire bamboo bush.	1	0	-1	1	0		1	1	1
Water retention									
The sourced bamboo is planted to reduce erosion thereby allowing new plant growth.	2	1	-1	1	0		3	1	3
Phytoremediation									
The sourced bamboo comes from areas that are being cleansed by it (and toxins sequestered in it).	2	1	-1	2	0		4	1	4
B: Ecological Challenges									
Treatment method									
The sourced bamboo has received a treatment against natural decay.	2	1	2	2	0		7	1	7
° by means of a traditional technique; clump curing, leaching, smoking.	-1	1	-1	1	0		0	1	0
° by a chemical treatment; soaking, boucherie, autoclave,...).	2	1	-1	2	0		4	1	4
Treatment with the low-toxic chemical boric acid (also named boron, borax) or zinc chloride.	1	1	-1	1	0		2	1	2
Treatment with the medium toxic chemicals CCB, creosotes, TCP or LOSP.	1	1	-1	1	0		2	1	2
Treatment with the highly toxic chemicals CCA, ACA, NaPcP.	2	-1	-1	1	0		1	1	1
Transport									
Bamboo is sourced in vicinity of the project (<100km) - short distance truck transport	2	2	2	2	0		8	1	8
Bamboo is sourced in the same (tropical) country or continent (> 100km) - long distance truck transport, no sea transport	2	1	-1	1	0		3	1	3
Bamboo is sourced in another continent and requires sea-transport and the project is situated closer to locations for wood provision	1	1	-1	2	0		3	1	3
Bamboo is sourced in another continent and requires sea-transport yet the project is no closer to location for wood provision.	1	0	-1	1	0		1	1	1
Invasiveness									
The bamboo species used have a pachymorph (clumping) rhizome system.	2	1	-1	1	0		3	1	3
The bamboo species used have a leptomorph (running) rhizome system.	1	1	-1	1	0		2	1	2

C: Circular Economy								
Aspects of circularity								
The project includes the possibility of later re-use, repair, refurbishment, remanufacturing or recycling.	2	2	-1	2	1	6	1	6
After the project (end-of-life phase), the bamboo will be decomposed without any toxins in nature as a natural nutrient.	1	1	-1	2	0	3	1	3
The bamboo poles can be dismounted and replaced as a result of an adaptable jointing method.	2	2	2	2	1	9	1	9
Bamboo elements can be extracted from the rest of the construction without steel, concrete, glue or other inseparable binders.	1	1	-1	2	0	3	1	3
Repair and maintenance are calculated within the project (in cost, timing, design).	2	1	-1	2	1	5	1	5
Bamboo construction is offered as a 'service' rather than object (including a contract for maintenance and repairs).	1	1	-1	2	0	3	1	3
The amount of bamboo needed for the stability is calculated without overdimensioning.	1	1	2	2	1	7	1	7
2.2. Economic Performance								
A: Economic Benefits								
Market growth								
The project foresees in upscaling of the suggested solution (mass production) to alleviate the housing deficit.	2	2	-1	2	1	6	1	6
The project foresees in an international application outside of the producing country (> export).	-1	2	-1	2	0	2	1	2
Multi-functionality of bamboo								
The project foresees in the utilization of the entire bamboo plant, even the non-constructive rest parts for charcoal, food or biomass.	1	1	-1	2	0	3	1	3
The project foresees in compressed beams and columns instead of 'round' raw bamboo poles.	1	1	-1	1	0	2	1	2
The project foresees in bamboo finishing of walls, floors, ceilings etc. with bamboo composites, panels or flooring.	2	1	-1	2	1	5	1	5
Local income generation								
The project is located in the tropical south and generates local income.	2	2	2	2	0	8	1	8
The project allows for local value addition by means of collateral products from left-overs (e.g. bamboo lamps, interior decoration,..).	2	1	-1	2	0	4	1	4
The project allows for value addition by means of innovative jointing or engineered processing in higher income countries.	1	1	2	2	1	7	1	7
Structural elements are preassembled by the local harvesting communities.	1	2	2	2	0	7	1	7
Lab testing and/or codification is done in the country of origin.	2	2	2	2	0	8	1	8
Cost reduction through prefabrication								
The structural bamboo design allows for prefabrication in a replicable and modular way.	2	2	2	2	1	9	1	9
A temporary structure/shelter is built near the project site to enable a dry and secure prefabrication or preassembly.	2	2	2	2	0	8	1	8
Material waste is reduced by optimisation of sizes (reducing the amount of cut-offs).	2	1	2	2	0	7	1	7
The structural bamboo design does not depend on artisanal connections or techniques.	1	-1	2	2	-1	3	1	3
Decontextualisation is avoided through design and adjustment liberty allowing for adaptations to a specific context.	2	1	-1	2	1	5	1	5
B: Economic Deficits								
Economic dependency of a natural, incontrollable material								
The rare occurrence of flowering is considered by the interplantation and mixed use of different bamboo species.	1	1	-1	2	0	3	1	3
The production chain (plantation), treatment and drying processes and logistics chain is controlled by independent organizations.	1	1	-1	2	0	3	1	3
Health and environmental issues								
The project does not apply toxic adhesives.	2	2	2	2	0	8	1	8
It is checked whether the adhesives applied in the engineering processes respect the allowable levels of toxins.	1	1	-1	1	0	2	1	2
The laminated bamboo used in the project has a solvent free, low-formaldehyde low-toxin basis.	2	1	-2	2	0	3	1	3
Raw material depletion								
The logistic chain of production is ensured, even in case of a high demand for bamboo.	1	1	-1	2	0	3	1	3
2.3. Social Performance								
Social cohesion through cooperative economy and traditional craft								
The project design utilizes local craft or local traditions.	1	2	-1	1	1	4	1	4
The project improves traditional or local construction techniques (e.g. improvement of the wattle and daub technique).	2	2	-1	1	1	5	1	5
Social cohesion and sense of pride is enhanced by technology-transfer but with local decision-making.	2	2	-1	2	1	6	1	6
Local and/or cooperative entrepreneurship is supported and even promoted.	2	2	2	2	0	8	1	8
Unskilled workmen from the local community is trained and schooled in bamboo building techniques (e.g. TOTEM by INBAR).	2	2	-1	1	0	4	1	4
Regional scaling-out of the project is foreseen for regional income-generation.	1	2	-1	2	0	4	1	4
Vernacular architecture								
The project provides in a critical regionalism that acknowledges the local traditional architecture.	1	2	0	1	2	6	1	6
Prefabrication in the project leaves ample flexibility to add or subtract culturally determined elements.	1	2	-1	2	2	6	1	6
Build according to bioclimatic principles.	2	2	-1	2	1	6	1	6
Abstract regionalism (culturally determined use of voids, courtyards, mass, ventilation, etc..) is applied.	2	2	-1	1	1	5	1	5

main categories	statements	environmental	social	economic	circularity	aesthetic		score	applies	result
Resilience to disaster										
	In areas with risk for earthquakes attention is given to disaster-proof structural elements such as articulated joints for earthquakes.	1	2	0	2	1		6	1	6
	The project involves prefab emergency shelter or another type of intervention in the prevention or solution to natural disasters.	2	2	-1	2	0		5	1	5
COMPONENT 3: AESTHETIC QUALITY OF DESIGN (Venustas)										
3.1. Aesthetic Design Quality										
General aesthetic properties										
	Consious design decisions were taken in terms of aethetics that do not lead to a higher building cost.	1	-1	2	1	-1		2	1	2
	The aesthetical aspects of the project do not imply a lack of protection against the weather conditions.	1	1	-1	2	2		5	1	5
	Attention has been given to the aesthetical design quality honouring order, subtility, balance, elegance, coherence, grace & lightness.	2	2	-1	1	2		6	1	6
Proportional systems										
	A proportional system (musical, golden, modulor, van der Laan,...) is used as the basis of the design as described in section 5.3.	1	2	2	2	2		9	1	9
	The design has been checked with the PhiMatrix software whether it coheres with the golden proportions.	1	2	2	2	2		9	1	9
	The used proportional system leads to a facilitation of prefabrication and modularity.	1	2	2	2	2		9	1	9
	Standardized dimensions based on proportional systems are addressed to the prefabricated columns and joints	1	1	2	2	2		8	1	8
	TOTAL	174	159	81	195	58		174	76	**349**

e 8.7. Extended version of the evaluation framework.

8.3 **Application of the evaluation framework (quickscan) to the community center**

The results of the quickscan applied to the community center are shown in Figure 8.8 below. For reasons of clarity, the column marked in yellow still shows the answers 0 or 1, showing where “true” and “false” were used the case of the community center. In the final version of the quickscan, the respondent will not be able to see these numbers to avoid disorientation. The designer only needs to complete “true” or “false” in the quickscan, which automatically links to the hidden weighing system of the extended framework for the calculation of the result. The quickscan on the community center was carried out in order to refine and to out all of the bugs in the draft version. As a result, several questions were removed or rephrased after completion. It was also noticed that some questions referred to the same matter and also in these cases several adjustments were made.

The aim of the evaluation framework set out in section 8.1. was to serve both the experienced as well as inexperienced bamboo architects and that the questionnaire could be completed in a limited period of time. The time needed and the complexity of the questionnaire was carefully monitored whilst applying it to the community center case. The time required for completion is between the 15 and 20 minutes. In this quickscan, all of the main criteria; environmental, social, economic, circular and aesthetics were used to assess the community center. The assumptions and priorities that went into the creation of this framework were made more explicit, and the final aim to compare and adjust different bamboo designs was further refined. Although a wider sample of evaluated bamboo constructions would be needed before a relevant comparison between different bamboo projects can be made.

Zooming in on the actual results of the community center, it could be noticed that especially the environmental and social aspects have positive outcomes. The social aspects perform well in this case most likely because this is a community project with the goal to increase the social cohesion and to generate local income by means of cooperative working methods. For commercial or temporary constructions, the output would be less positive. Overall, bamboo will achieve good results on the environmental criteria due to the fact that the ecological benefits of bamboo are so particularly outspoken. In the case of the community center, sufficiently aged Dendrocalamus poles were cut for the columns by means of an axe at an agroforestry site at 40km distance. The difference in output in comparison to the Phyllostachys poles used for the roof rafters acquired at a managed plantation at 250km distance is substantial. The most ideal situation would be to attain bamboo from a well-managed plantation that ensures the removal of aged bamboos, undertakes necessary measures against the invasiveness of bamboo, combines the production of other bamboo species and numerates its workers well. Even better would be when the plantation is located nearby, preferably on a hillside and in addition on soil that is eroded, polluted or abandoned without other possibilities of reforestation. It has to be noted that this combination of ideal circumstances is unattainable and should not be aspired. Especially the criteria regarding phytoremediation are exceedingly ambitious.

Despite the overall good performance, there is still room for improvement, more specifically on the stability criteria. With the objective to save costs, a type of steel of less quality was used in the community center, which corroded in a short period of time. Another unanticipated aspect open to improvement appeared to be the fish mouth jointing technique. Although this technique was initially perceived as the best method to joint bamboos, it is time-consuming, requires artisanal production and skilled craftsmen which leads to a higher cost. There is also a greater risk of splitting and failure when not properly executed. Furthermore, a greater amount of steel is required to make the joint. In the subsequent cases, the author tried to develop jointing methods where the previous deficits would be considerably less.

None of the joints in the center was provided with a tension band, only after the splitting or cracking problems had already occurred. The application of tension bands from the onset would have possibly prevented these problems. Tension bands increase the overall security level, especially at bamboo ends and joints as moment forces can lead to raptures.

Finally, no fire testing or safety prevention was done in this project, and mechanical testing at the university was done without the knowledge of the relevant iso-code, for this was not available yet to designer and laboratory researcher. Bamboos were tested however at the University of Rio in order to ensure inherent quality, calculations with these results were however not yet performed, also by lack of knowledge of the designer/author at that time. However, in this particular case with an abundance of escape routes and proximity to the outdoor, it would have been illogical to use for example protective paint for fire safety and even ecologically undesirable. Since the building was only groundfloor with abundant quick escape routes, the lack of of precise calculation was also tolerable for it was based on relevant experience from contacted professionals.

EVALUATION FRAMEWORK - QUICK SCAN VERSION OF THE COMUNITY CASE STUDY

QUESTIONNAIRE

The case study has been checked on all of the 4 criteria; environmental, social, economic, circularity and aesthetic

COMPONENT 1: STABILITY

main categories	statements	applies	result
1.1. Species			
Bamboo species			
	Guadua A.., Phyllostachys P. or Dendrocalamus G. or A. or another known species suitable for construction is employed.	1	
	Species obtained from plantations close to project site are used (even if they are small diameter bamboos).	1	
1.2. Mechanical Properties			
Test data			
	General data from literature on the used species has been used.	1	
	Specific test data on the lot of bamboo is used instead of general data on the species.	1	
	A field test (e.g. by means of the test-kit developed by K. Harries) is used to determine strength.	0	
Mechanical properties			
	Bamboo species with larger wall sizes are selected.	1	
	The density of the bamboo poles is between 0,5-0,9 g/cm.	1	
	The moisture content of the dried bamboo poles is between 12-20%.	1	
	The age of the bamboo poles is between 3 to 5 years.	1	
	Position along the culm (base, middle, top) is checked and only base and middle parts are applied as these have a larger wall size.	1	
	The project employs the bamboo in tension (best property) or in compressive strength.	1	
	The project avoids the use of its limit values.	1	
	The stability of the construction is calculated by an authorized engineer.	0	
1.3. Standards and Building Codes for Bamboo			
International codes			
	The ISO code has been consulted, not only the technical specifications but also the specifications on plantations, treatment,...	1	
	Mechanical laboratory tests have been performed according ISO-22156 and -22157 on the applied bamboo lot to determine its values.	0	
	Laboratory tests have provided data on the strength values, diameter, age, position along culm, density, moisture content and MOE.	1	
National codes			
	The national code has been consulted, not only the technical specifications but also the specifications on plantations, treatment,...	0	
	In absence of a national code, relevant codes from other countries such as the NSR-10 from Colombia have been consulted.	1	
	Case specific approval is begotten from the government in case national codes are lacking.	0	
1.4. Structural Systems			
Type of structural system			
	The project can be defined as organically woven, freeform architecture (as described in 3.4.1).	0	
	The project can be defined as curvilinear architecture (as described in 3.4.2).	0	
	The project can be defined as truss architecture (as described in 3.4.3).	1	
	The project can be defined as a geometric structure; space frame, grid shell, diagrid, dome, etc. as described in 3.4.4).	0	
	The project can be defined as orthogonal bamboo architecture (as described in 3.4.5)	1	
1.5. Joint Design			
Technical requirements			
	The joints are foreseen close to a node resulting in higher resistance to shear forces.	1	
	Moment forces in joints are avoided as much as possible, e.g. by the use of hinges.	0	
	In case of large moment forces in the joints, tension band are used at the end of the bamboo stem.	0	
	Steel parts such as hex nuts, wire rods and washers are provided in galvanized steel and protected with a varnish layer .	1	
	The joints are designed as such that the need for grout in the connections is reduced as much as possible	0	
	When using grout in the connections, the cement-sand proportion is 1 to 2 (or 3) and a measured amount of water is added.	1	
	The amount and diameter of the drilled holes is kept to a minimum (3- 4cm in diameter) according to the codes.	1	
Joint classification			
	Most of the joints are part of group 1 - transferring compression through contact to the whole section.	1	
	Most of the joints are part of group 2 - transferring force through friction on the inner surface or compression to the diaphragm.	1	
	Most of the joints are part of group 3 - transferring force through friction on the outer surface.	0	
	Most of the joints are part of group 4 - transferring force through bearing stress and shear to the wall from a perpendicular element.	0	
	Most of the joints are part of group 5 - Transferring force perpendicular to the fibers.	0	
	Most of the joints are part of group 6 - Transferring radial compression to the centre of the pole.	0	
Criteria for joint design			
	Penetration in the bamboo poles by nails, screws or bolts is reduced as much as possible	1	
	The intrinsic qualities of bamboo are favoured in the joint design (tensile & compressive) and the weaker avoided (shear & bending).	1	
	Ease of production of the joints in terms of required equipment and handicraft skills.	1	
	The joint is prefabricated and adaptable, simplifying a modular set-up of the intended project.	0	
	The provided joint is stable, both in relation to time as strength.	1	
	The dimensions and the joint itself can be adapted according to a modular (prefabricated) system.	0	
	The strength of the joint is laboratory tested and its behaviour can therefore be predicted.	0	
	The provided joint is cost-efficient in relation to the entire construction cost (speed of construction vs cost per piece).	0	
	The applied joint consists of materials that can easily be found in local construction stores, welding or carpentry shops.	1	
	The aesthetic of the joint is carefully studied and designed.	0	
Avoidance of joint failure			
	Possible situations of elevated stresses and bending in structural elements are monitored in time and maintenance is planned.	1	
	Cracks and splits in structural bamboo elements are monitored and immediately remediated (e.g. mix of glue and sawdust).	1	
	Severe cracks are monitored and initially remedied by tension bends and finally replaced when needed.	1	
	The limit state diagram (as described in 3.5.4.) is used to determine the potential risk of crack propagation	0	
1.6. Bending			
Bending of bamboo poles			
	The project does not consist of structural bended elements	1	
	The project applies the immersion technique by bending freshly cut bamboo in lukewarm water.	0	
	The project applies the combustion technique by bending freshly cut bamboo with use of a blowtorch according correct procedures.	0	

main categories / statements	applies
The project applies no slashing technique (bending by making many tiny cuts in the bamboo).	1
The project applies the bundling technique by bundling multiple small diameter bamboos together.	1
The project applies bamboo´s natural curvature and makes a curves divided over several segments.	0
1.7. Fire reaction and fire resistance	
Fire reaction and fire resistance	
Literature on fire reaction and fire resistance is studied in detail in regard to the project.	0
The bamboo used for the project was tested in a laboratory setting to determine its fire reaction.	0
Escape routes are projected and discussed with the local fire department.	0
A fire retardant chemical is added to the bamboo during the treatment process.	0
A fire resistant coating is applied on the bamboo after the construction process.	0

COMPONENT 2: PERFORMANCE

main categories	statements	applies
2.1. Environmental Performance		
A: Ecological Benefits		
Rapid growth & renewability		
	The sourced bamboo is grown in tropical conditions (rapid growth, large height & thickness).	1
	The sourced bamboo is grown on the hillsides (strength > erosion control, less rapid growth yet generally more qualitative).	1
	Regular harvest (> yield, CO_2 sequestration, material quality, land scarcity).	1
	Less yield in harvest (thick canopy, no loss of species, more undergrowth).	0
	Interplanting/agroforestry (> biodiversity, < monoculture, profit, logistic).	0
Carbon sequestration		
	The bamboo comes from an unmanaged plantation or bamboo forest.	1
	The bamboo comes from a managed plantation where is regularly harvested (avoiding stored carbon to be released into the air again).	1
	The bamboo comes from a managed agroforestry site with a variety of high yielding species.	0
	The bamboo comes from a community based plantation.	1
	The bamboo is used in a long-term construction resulting in durable sequestration.	1
	Bamboo will be used for electricity production or in another recycling process at the end-of-life in the assessed project.	0
	The local government financially stimulates low-carbon applications in tenders.	0
Reforestation and restoration of degraded land		
	The sourced bamboo comes from a wasteland, poor farmland or other degraded areas (lower quality).	0
	The sourced bamboo comes from a borders, riverbanks or areas in risk of desertification.	0
	Only the mature bamboo is cut (age between 3-5 years) with a maximum of 20-25% of the entire bamboo bush.	1
Water retention		
	The sourced bamboo is planted to reduce erosion thereby allowing new plant growth.	1
Phytoremediation		
	The sourced bamboo comes from areas that are being cleansed by it (and toxins sequestered in it).	0
B: Ecological Challenges		
Treatment method		
	The sourced bamboo has received a treatment against natural decay.	1
	° by means of a traditional technique; clump curing, leaching, smoking.	0
	° by a chemical treatment; soaking, boucherie, autoclave,...).	1
	Treatment with the low-toxic chemical boric acid (also named boron, borax) or zinc chloride.	1
	Treatment with the medium toxic chemicals CCB, creosotes, TCP or LOSP.	0
	Treatment with the highly toxic chemicals CCA, ACA, NaPcP.	0
Transport		
	Bamboo is sourced in vicinity of the project (<100km) - short distance truck transport	1
	Bamboo is sourced in the same (tropical) country or continent (> 100km) - long distance truck transport, no sea transport	0
	Bamboo is sourced in another continent and requires sea-transport and the project is situated closer to locations for wood provision	0
	Bamboo is sourced in another continent and requires sea-transport yet the project is no closer to location for wood provision.	0
Invasiveness		
	The bamboo species used have a pachymorph (clumping) rhizome system.	1
	The bamboo species used have a leptomorph (running) rhizome system.	1
C: Circular Economy		
Aspects of circularity		
	The project includes the possibility of later re-use, repair, refurbishment, remanufacturing or recycling.	0
	After the project (end-of-life phase), the bamboo will be decomposed without any toxins in nature as a natural nutrient.	1
	The bamboo poles can be dismounted and replaced as a result of an adaptable jointing method.	1
	Bamboo elements can be extracted from the rest of the construction without steel, concrete, glue or other inseparable binders.	0
	Repair and maintenance are calculated within the project (in cost, timing, design).	1
	Bamboo construction is offered as a 'service' rather than object (including a contract for maintenance and repairs).	1
	The amount of bamboo needed for the stability is calculated without overdimensioning.	0
2.2. Economic Performance		
A: Economic Benefits		
Market growth		
	The project foresees in upscaling of the suggested solution (mass production) to alleviate the housing deficit.	1
	The project foresees in an international application outside of the producing country (> export).	0
Multi-functionality of bamboo		
	The project foresees in the utilization of the entire bamboo plant, even the non-constructive rest parts for charcoal, food or biomass.	1
	The project foresees in compressed beams and columns instead of 'round' raw bamboo poles.	0
	The project foresees in bamboo finishing of walls, floors, ceilings etc. with bamboo composites, panels or flooring.	0
Local income generation		
	The project is located in the tropical south and generates local income.	1
	The project allows for local value addition by means of collateral products from left-overs (e.g. bamboo lamps, interior decoration,..).	1
	The project allows for value addition by means of innovative jointing or engineered processing in higher income countries.	1
	Structural elements are preassembled by the local harvesting communities.	1
	Lab testing and/or codification is done in the country of origin.	1
Cost reduction through prefabrication		
	The structural bamboo design allows for prefabrication in a replicable and modular way.	1
	A temporary structure/shelter is built near the project site to enable a dry and secure prefabrication or preassembly.	1
	Material waste is reduced by optimisation of sizes (reducing the amount of cut-offs).	1
	The structural bamboo design does not depend on artisanal connections or techniques.	0

	applies
Decontextualisation is avoided through design and adjustment liberty allowing for adaptations to a specific context.	1
B: Economic Deficits	
Economic dependency of a natural, incontrollable material	
The rare occurrence of flowering is considered by the interplantation and mixed use of different bamboo species.	0
The production chain (plantation), treatment and drying processes and logistics chain is controlled by independent organizations.	0
Health and environmental issues	
The project does not apply toxic adhesives.	1
It is checked whether the adhesives applied in the engineering processes respect the allowable levels of toxins.	0
The laminated bamboo used in the project has a solvent free, low-formaldehyde low-toxin basis.	0
Raw material depletion	
The logistic chain of production is ensured, even in case of a high demand for bamboo.	1
2.3. Social Performance	
Social cohesion through cooperative economy and traditional craft	
The project design utilizes local craft or local traditions.	1
The project improves traditional or local construction techniques (e.g. improvement of the wattle and daub technique).	1
Social cohesion and sense of pride is enhanced by technology-transfer but with local decision-making.	1
Local and/or cooperative entrepreneurship is supported and even promoted.	1
Unskilled workmen from the local community are trained and schooled in bamboo building techniques (e.g. TOTEM by INBAR).	1
Regional scaling-out of the project is foreseen for regional income-generation.	1
Vernacular architecture	
The project provides in a critical regionalism that acknowledges the local traditional architecture.	1
Prefabrication in the project leaves ample flexibility to add or subtract culturally determined elements.	1
Build according to bioclimatic principles.	1
Abstract regionalism (culturally determined use of voids, courtyards, mass, ventilation, etc..) is applied.	1
Resilience to disaster	
In areas with risk for earthquakes attention is given to disaster-proof structural elements such as articulated joints for earthquakes.	0
The project involves prefab emergency shelter or another type of intervention in the prevention or solution to natural disasters.	1
COMPONENT 3: AESTHETIC QUALITY OF DESIGN (Venustas)	
main categories / statements	**applies**
3.1. Aesthetic Design Quality	
General aesthetic properties	
Consious design decisions were taken in terms of aethetics that do not lead to a higher building cost.	1
The aesthetical aspects of the project do not imply a lack of protection against the weather conditions.	1
Attention has been given to the aesthetical design quality honouring order, subtility, balance, elegance, coherence, grace & lightness.	1
Proportional systems	
A proportional system (musical, golden, modulor, van der Laan,...) is used as the basis of the design as described in section 5.3.	0
The design has been checked with the PhiMatrix software whether it coheres with the golden proportions.	0
The used proportional system leads to a facilitation of prefabrication and modularity.	1
Standardized dimensions based on proportional systems are addressed to the prefabricated columns and joints	0
TOTAL	

Figure 8.8. Quickscan of the community center.

8.4 Conclusion

The translation of the conceptual framework into a workable excel spreadsheet tool allows for a detailed analysis of the quality of a bamboo design. Furthermore, it enables optimisation of a design. Therefore it proves to be useful both for a detailed analysis as a rough screening or simple checklist at the start of the design process. When completing the excel spreadsheet, the output of a "true" or "false" answer automatically appears in a customized color scheme. Without the use of a numerical scoring system, the impact of the input is visualised in the intensity of the color green. With this information in mind, the designer can adapt the project or design by making small modifications with a positive impact in the assessment form. It has to be clearly noted that it is impossible to obtain a dark green colour (the most positive impact possible) on each question and it is not the intention of this tool to strive for this. Projects will always obtain better results on one aspect than on other. Criteria are also sometimes contradicting. It is up to the designer and the stakeholders to define the goals of the project and set priorities. Once these are set, the framework can also be used to assess these aspects that are of importance for that specific project. Moreover, the framework can support defining the goals and priorities during the project definition. When for example, the social aspect of a project is more relevant to the stakeholders than the economic aspect; the user can scan in the evaluation framework for those relevant criteria and focus hereon. It is highly recommended to employ the evaluation framework in the beginning of the design process when the most important decisions are taken. It is in this phase that the design is the most receptive to alterations and can still be easily improved if necessary.

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CONCLUSIONS & DISCUSSION

CHAPTER 9 CONCLUSIONS AND DISCUSSION

It is observed that worldwide an increasing number of bamboo constructions are being built. As a consequence, bamboo is becoming more widely known as a building material. Whereas in the past mainly those with low incomes employed bamboo out of necessity for a cheap housing material, a slow shift is occurring to the middle and upper class. Nonetheless, it is a common misunderstanding that building with bamboo would automatically be cheap. It is a time-consuming material to build with if the proper techniques are not used and in terms of safety, durability and construction techniques multiple measures have to be met. The Colombian architect Simon Velez has phrased it popularly that a bamboo building requires "*proper boots and a hat*"` (Minke, 2012). Although this indeed sums up the most important protective issue, it by no means includes all the requirements. This dissertation focused on finding and translating what exactly are these bamboo construction requirements, going beyond the existing building norms & standards. The criteria established by Vitruvius in the classic age to assess architectural design quality also form the basis of this evaluation framework; Firmitas, Utilitas & Venustas (respectively in chapter 3, 4 and 5). Important strengths, but also challenges in building with bamboo have been identified. It has been demonstrated that in order to achieve a durable yet low-cost and innovative loadbearing bamboo structure, prefabrication and modularity are indispensable construction principles. The prefabrication of modular elements enables an accelerated construction speed and certain ease of construction. In an orthogonal structural system, bamboo is used at its best and prefabrication of modular elements is a straightforward process. Curvilinear or organic structures, when reviewing them in the light of the structures intended in this research, are not recommended because actively bending bamboo culms weakens the quality of the culm and this deficit needs to be intercepted by adding more bamboo. When striving for an innovative, sustainable and low cost construction, actively bending bamboo with unnatural small curve-diameters cannot be justified.

Some of the formalistic/organic architecturally "designed" and temporary bamboo constructions have led to the incorrect perception that in bamboo architecture anything is possible, although these constructions are not designed according the requirements and will presumably deteriorate soon. In case of the temporary construction this is not problematic, yet the image of the construction remains and is anchored in people´s sub consciousness that this is how can be built with bamboo. However, from experience in reviewed case studies it can be said that the consequence of a small design decision can have large implications (both negative and positive). It is for this reason that in chapter 2 provides an overview of the most influential bamboo architects of this time and their techniques and chapter 6 discusses the case studies from the author in Brazil. Through experimental architecture, some innovative ways of implementing bamboo have been tested and tried. The main findings have been summarised in this concluding chapter.

The LCA analysis demonstrated that bamboo has a very high potential in terms of sustainable building as a direct result of its low environmental impact. Bamboo requires little to no engineered processes, has the ability to uptake high amounts of carbon, it grows and matures in four years, has a high annual yield, a rooting system that counters erosion and clear-cut is not an issue as only mature bamboos are cut. Nevertheless, some factors do have a negative impact on bamboo´s environmental impact of which the treatment solution and - method are the most prominent, before transport and electricity use. The best way to durably stock carbon is the application of bamboo for the longest possible time span, despite that this implies a proper chemical treatment against insects. It is advisable to search for more environmental friendly treatment solutions. Furthermore, circular jointing methods are a prerequisite. Every joint needs to permit adaptability, maintenance and a correct end-of-life use (reuse, recycling, energy production). It should be possible to dismount the different connecting materials (steel, wood,..) to provide each material a corresponding end-of-life.

9.1 Summary of main findings and evaluation framework

Part I of the dissertation presented a literature study on bamboo as a construction material based on the below-mentioned key aspects. These three main subdivisions are loosely based on Vitruvius' key aspects of architecture; Firmitas, Utilitas and Venustas. By describing bamboo by means of these key aspects, a holistic evaluation framework for constructing with bamboo is provided. The answers to the research questions listed in chapter 1 are summarised in this section.

A. **Stability**: state of the art on bamboo, national and international codes, mechanical properties, structural systems, joint design, bending and fire reaction,
B. **Performance** of a bamboo in construction: social, economic and environmental performance,
C. **Quality of design**: the role of a qualitative design in the acceptance of a material.

A. Which criteria should be met in order to attain a qualitative, solid and durable bamboo building?

Research Question: How can the stability of a bamboo construction be ensured?

Bamboo grows in a variety of species however only three of them are prominently used in the construction industry: Phyllostachys Pubescens (Moso), Dendrocalamus Giganteus/Asper & Guadua Angustifolia Kunth. It is a fundamental prerequisite to build with woody (not herbaceous) species that are appropriate to build with. Bamboo´s material properties are mainly determined by the factors species, diameter, and density of the fibers, moisture content and age. These factors are greatly influenced by the climatologic circumstances and the location where the bamboo is grown. As a result, there is not only a high variability between the different bamboo species, but also between the same species and even the different positions along the culm (top or bottom). It can be concluded from the multifold of studies on the mechanical properties of bamboo that there is no unambiguous answer. In literature, average and recommended values are available. Bamboo has an overall good performance on its mechanical properties, yet is weak in taking strain caused perpendicular to the fibers (Sánchez et al. 2019; Janssen, 2000). Generally, a safety factor of 1,5 should be applied for limit state design based on the Colombian NSR G12 or the ISO22156 code (Kaminski et al., 2016). In section 3.3. an overview is given of the existing standards & norms in the countries applicable. The ISO standards 22156 and 22157 along with several national codes and standards provide testing methods on the determination of the physical and mechanical bamboo properties and provide design values for the structural design with bamboo. These should be consulted before even starting to design with bamboo.

Research Question: Which key factors have an impact on the durability of a bamboo structure? How can the service life be enhanced?

The natural durability or service life of most bamboo species is relatively low and varies between species, climate and usage. The service life of untreated bamboo is 1-3 years if it is in contact with the atmosphere and/or soil, 4-6 years if it is covered and 10-15 years if it is covered and used in a not very humid climate. Treatment can prolong the service life of bamboo over 30 years (Janssen, 1995), without a proven limit to the life expectancy when protected physically. Hence, preservation is a key element in the durability of a bamboo structure. Bamboo should be treated soon after being cut and before drying. As the susceptibility of bamboo to pest attacks is highly influenced by the sugar level present in the bamboo sap at the time of harvest, it is primordial to respect the preferred time for harvest. Culms younger than 3 or older than 5 years may not be cut. The first are highly susceptible to attacks by insects, fungi and decay, while the latter have become impermeable to a treatment solution. It is also desirable to cut during wintertime and early in the morning as the bamboo sap content inside the culm will be at its lowest.

Treatment methods that remove the nourishment of the insects are the most difficult to implement, however the most effective. Cheap and traditionally applied methods are amongst others smoking, leaching, heating and immersion. Chemical treatments such as the boucherie method or the vacuum tank include the usage of chemical coatings or the impregnation of liquids, e.g. boron-based solutions. Preservatives that act on the face of the culm require that either each diaphragm is perforated or a small hole is drilled in each segment before the solution can reach the softer inside. The penetration of the tissue by chemicals is more difficult than in building timber because the vessels of bamboo are orientated axially and they cover only 10% of the cross-section of the culm. External paintings are not considered as a good option as the high silica content causes low absorption rates and the paint has to be reapplied regularly (Dunkelberg, 1985; Janssen, 1995). Once felled and treated, bamboo must be dried. Seasoned bamboos appear to be stronger and more resistant to the attack of pests. Bamboo dries best in the shade under air dry conditions to avoid surface cracking and splitting due to excessive shrinkage (López, 2003). To increase the natural durability of bamboo, it is essential to take into account following design principles:

- Protect the structure from rain by providing a watertight roof and a large roof overhang,
- Avoid direct contact with the soil. Humid underground can cause purification/resistance loss,
- Protect the structure against direct sun irradiation,
- Ensure adequate drainage,
- Provide adequate ventilation.

Research question: What kind of structural systems can be distinguished in bamboo construction and what is the consequence in terms of durability and sustainability?

In the literature on bamboo, a classification system that discusses or groups potential structural systems in bamboo is non-existent. In this dissertation, the author introduces a classification in five structural systems according to their level of recti linearity, ranging from organic to orthogonal.

° **Organically woven structures** involve freeform shaped constructions that are either arbitrary or geometrically woven. These structures are difficult to calculate, even more so because this structural system is conceived in an intuitive manner where its final form is shaped on site without the aid of a pre-calculated model, often provided in strips of bamboo (split cane) or small bendable bamboos. A consequence is that providing a protective roof covering for the bamboo is arduous and therefore this structural system is predominantly used for temporary constructions.

° **Curvilinear architecture** means consisting of curved lines. It is an antonym to rectilinear. Curvilinear forms are mainly designed through form-finding and can also be referred to as organic architecture where natural forms are adapted to generate irregular geometries. These are form-active structures, meaning that the loads are taken by the form or shape of the structure. Such structures can withstand well axial, tension or compression forces but not bending moments (Nurdiah, 2016). Curvilinear structures often require the bamboo poles to be bent thereby weakening the bamboo.

° **Truss architecture** is structurally the most firm and logic system for it transfers forces in the most efficient manner. Geometrical triangulation systems are also found in timber and steel structures. When no bending is required in a structure, the bamboos rarely split and demonstrate a better performance in resisting forces (Widyowijatnoko, 2012). The durability of the bamboo is higher because the trusses are protected by a roof and lifted high from the ground.

° Geometric structures are based on mathematical calculation and principles such as spaceframes, grid shells and geodesic domes. Beneficial to this structural system is its capacity to foresee large free spans with a relatively light own weight. Normally, this structural system is provided in steel or aluminum components industrially manufactured at millimeter precision. However, tubular steel or aluminum elements can easily become replaced by hollow bamboo canes and offers many ecological benefits at the same time.

° Orthogonal architecture might seem the least obvious one, but this term refers to bamboos that are merely employed in a horizontal (beams) or vertical (columns) manner or a combination of both.

Because of its rectilinear appearance, it is associated with modern architecture. In order to ensure the durability columns need to be lifted from the ground and beams need to construct as such that they receive minimal strain perpendicular to the fibers. Modularity and prefabrication can easily be become with this type of architecture.

Research question: How can joints/connections be designed to ensure fast construction at a low cost and low environmental impact?

Several difficulties arise when bamboo culms need to be joined (RWTH Aachen University, 2002):

- **Round profile**: roundness leads to difficult geometric structures at the knot,
- **Fibers**: all fibers are longitudinal orientated. Bamboo is therefore unsuitable for loads in the cross direction (low shear strength) and tends to split easily in the direction of the fibers,
- **Hollow**: there is no material to tighten the bamboo in the middle of the culm,
- **Natural material**: bamboo varies in diameter, wall thickness, length of internodes and quality. The latter depends of the specie and the environmental conditions. Additionally, bamboo tapers, making diameters at the bottom differ from those at the top.
- **Nodes**: the round tube is not entirely hollow but divided through nodes,
- **Surface**: the surface of the cane is slippery and hard.

Considering the jointing of whole bamboo members, it is best to make a distinction between low-tech and high-tech solutions. Low-tech refers to a low level of technology, often developed many decades ago at a low-cost and using a straightforward technique that can be assembled by unskilled workers. High-tech joints on the other hand involve a specialized and complex technique of the joint itself which implies a higher cost and the need for skilled workers (RWTH Aachen University, 2002). The most commonly used connection method in traditional bamboo architecture is a fish mouth joint, despite the fact that this joint is relatively labor-intensive and also requires certain skills. On the contrary, modern bamboo architecture constitutes predominantly of bolted joints fixated with grout. It can be noted that the more efficient a connection is, the greater the benefit of the material qualities. Arce-Villalobos (1993), Jayanetti & Follet (1998), Janssen (2000), Widyowijatnoko (2012) and many others have provided ample descriptions of possible joint connections and even determined a classification based on the methods how a connection is made. The classification of Widyowijatnoko is the most comprehensive and elaborates on the classification set out by Janssen, although it departs from a different emphasis on the way forces are transferred; compression along the fibers or perpendicular to the fibers and the position of the joint/connector (inside or outside the poles). In se, joint connections with bamboo are elongations, orthogonal connections, angles (<90°) or 3D joints.

When considering the purest manner of load transferal from one bamboo to another or another structural element, a connection with contact over the entire section of the wall is the best possible way, even more so in compression. However, this is not always the easiest solution, the most aesthetically pleasing nor the cheapest jointing method. Providing a connector piece inside the cavity or attached to the outside of the culm are the fastest methods and moreover the easiest to prefabricate. Drilling into a bamboo cane should be applied with care as this can entail splitting or cracking and therefore predrilling is suggested. Glues, wires and rope connections offer an alternative, but have disadvantages regarding user-friendliness, reversibility and/or environmental degradation. The material used for the connector pieces is of importance for the environmental impact. Wood or pressed bamboo as connector pieces have a much lower impact than for example steel or concrete. The durability of the connection refers to the capacity to withstand wear and tear or decay. It implies its resistance against degradation under environmental conditions (corrosion, decay through moisture or UV, etc.) and the grade of destruction of the cane due to the intervention of the connection. In this regard, it is important that a joint allows for repair and maintenance. The construction should allow replacing damaged elements or poles in an easy way. A reversible connection is the most adaptable connection as it can be fully dismantled without destroying the bamboo poles. Size variability of bamboo remains challenging in joint design: the tolerance for the natural irregular dimensions (tapering, variating diameters, different distances between the node, etc.) of bamboo has to be taken into account. The higher the tolerance, the easier it is to combine different bamboo canes. Besides labor hours, also the local availability of materials and whether expensive tools or skilled labor is required, determines the cost.

The second aspect **Performance** addresses the key factors related to the functioning of bamboo as a construction material and the requirements in order to obtain a sustainable bamboo structure. The strengths, weaknesses and challenges are discussed by means of three pillars; "planet, people and profit" or environment, economic and social. These pillars are often interrelated and cannot be regarded as autonomous factors. One aspect may impact another e.g. when an individual or community experiences better economic circumstances, the social benefits will improve accordingly.

B. **Which key factors have an impact on the performance of bamboo as a construction material and need to be fulfilled in order to obtain a sustainable bamboo construction.**

Research question: Which factors play a role in terms of environmental performance of bamboo?

Bamboo´s main advantage is its low impact on the environment. In general, a shift is occurring from a linear production scenario to a circular one in order to diminish the consumption of primary resources. Bamboo is considered to offer a great potential to replace or reduce the use of conventional materials. The subsequent paragraph summarizes the environmental strengths of bamboo as well as the environmental aspects that can possibly have an adverse effect.

° **Rapid Growth:** because bamboo belongs to the grass species, it reaches up to full height in a couple of months and becomes mature in 3 to 5 years' time. In comparison, most trees need to grow 15-20 years to get up to full length. Its rapid growth makes bamboo an excellent reforestation plant.

° **Primary Energy:** bamboo requires a very low amount of energy for its production. Only 300 MJ/m³ of energy is required to produce 1m³ bamboo as to 600 MJ/m³ for timber, 35.500 MJ/m³ for virgin steel and 4600 MJ/m³ for cement (Manandhar et al., 2019; Hammond & Jones, 2008).

° **High annual yield:** compared to other bio-based materials, the annual yield of bamboo is high. Guadua and Dendrocalamus have an average annual yield of 9m³ per ha and in ideal circumstances, annual yields over 20m³ have been reported. In comparison, the average annual yield for European oak and Scots pine is 3m³ per ha and for meranti and Chinese fir 4m³ per ha (van der Lugt, 2017).

° **Carbon sequestration:** bamboo has a carbon storage between 30 to 121Mg per ha and a carbon sequestration rate between 6 to 13Mg per ha per year. In other words, bamboo sequesters 3, 5 to 7 times more carbon than a (generic) tree. Carbon storage is higher in a managed plantation where mature bamboos are harvested thereby creating space for new ones. In terms of carbon footprint, not only the carbon sequestration of the plant itself has to be taken into account, but also the carbon emission during every step in the production chain such as harvesting, treating, processing and shipping. When bamboo is used in its natural form, only the treatment method and sea transport are impactful factors in terms of greenhouse gas emissions (Manandhar et al, 2019, van der Lugt, 2012).

° Reforestation and restoration of degraded land: bamboo is considered as one of the most appropriate plants to be grown in areas with erosion problems. Its extensive root and rhizome system in addition to the multitude of bamboo poles and shoots help to secure the soil, improve soil quality and restore the water table while its dense foliage offers protection against beating rains. Bamboo is also suitable to be planted in areas where farming is no longer feasible such as degraded land areas or eroded slopes (van der Lugt, 2017).

° Water retention: in accordance with the reforestation qualities, bamboo retains water well as the leafy mulch accumulated beneath the bamboo plant conserves moisture and assists the earth to absorb and retain moisture more effectively. Additionally, the dense canopy of leaves intercepts a considerable amount of rainfall, decreasing the direct soil erosion (Minke, 2012; Janssen, 2000).

° **Phytoremediatio**n: during growth phase bamboo has the capacity to uptake toxins and heavy metals, even more than poplar and willow, and both renowned for their benefit in this field. A contributing factor is the end of life of the bamboo because when incinerated or decomposed, bamboo will release the toxins that were captured yet when sequestered the toxins remain inside the stem and are no hazard for the user (Joos, 2011; Potter, 2009).

° **Treatment:** especially the chosen treatment method has a great impact on the carbon footprint. Yet, as has been referred to already, without a proper treatment the life span of bamboo decreases significantly. Therefore treatment can be considered as a non-avoidable condition if bamboo is to be used long-term. Regarding the toxics that are suitable as a preservative, it can be concluded that boron (borax) appears to be the safest, the most cost-effective and accordingly the most practiced. The methods used to enter these preservatives can variate from low-scale (soaking, steeping & lime-washing) to high-end techniques (boucherie method, vacuum tank). In general, low-tech techniques have a lower cost and a low environmental impact, but also a lower durability (Janssen, 2000).

° **Invasiveness**: when acquiring bamboo from a plantation, one must analyze its origin. Just as bamboo´s capacity for cleaning polluting areas can be beneficial to its environmental performance, bamboo sourced from areas where it has invaded intact bio systems while becoming the main species has a negative impact. Invasive species is one of the main causes of biodiversity loss. Running types of bamboo are found to be more aggressive than clumping types but also the thick canopy of bamboo does not allow for much undergrowth (van der Lugt, 2017; Pagad, 2016).

° **Transport:** transport is not the highest negative impact factor when reviewed in a regional context. In case the bamboo plantation and construction sites are proximate to each other, local transport by truck suffices and the impact of transport remains relatively small. It can be concluded that when a bamboo stem is applied in the country of harvest, the environmental impact of transport is limited, however in case sea transport is required, the hollowness of the stem (which makes the volume high in comparison to its weight), the impact significantly rises and even becomes a more important negative factor than treatment.

Research question: Which factors play a role when in terms of economic performance of bamboo?

° **Market growth:** in 2018 the international bamboo and rattan trade reached USD 3,25 billion and the domestic commodities in China USD 46 billion. These numbers show that China is an absolute leader in both the production as in the export of bamboo products while Europe and the USA are the largest importers. A 5% growth is expected based on growing investments in the development of infrastructure, increasing use of sustainable building resources, timber prices that are rising and a higher consumer awareness regarding the applications and benefits of bamboo are expected to drive the market growth over the forecasted period (INBAR, 2021; van der Lugt, 2017).

* **Versatility of the material:** the applications of bamboo are numerous, diverse and new products continue to be developed each day, mainly processed ones. The largest share of bamboo products belongs to engineered products such as plywood, flooring and pulp & paper. Also the health benefits of bamboo shoots create many applications for medicinal purposes. Only a minor share pertains to raw bamboo members.

° **Local income generation:** bamboo primarily grows in (sub) tropical countries. Hence an increase in the production of bamboo products directly generates more income for the inhabitants of these regions. By adding value at the plantation site, an even higher income could be generated e.g. product development, laboratory testing or codification. Jobs could range from low-skilled agricultural jobs to higher skilled jobs required for the production of value-added products.

° **Cost reduction through prefabrication:** a serial and industrialized process minimizes the cost of production and reduces the amount of waste. Moreover, the man-hours required to assemble a project can be diminished. However, the magnitude of the savings can vary significantly depending on the degree of prefabrication and the component in question. This is also ecological because energy efficient criteria can be met using low impact materials and the material waste created during the construction can be reduced maximally (Leoncini et al., 2017). The University of Melbourne calculated that by the optimization of sizes, the material loss by cut-offs could be reduced up to 52%. Hence, the mere fact that production is being done in a quality controlled factory environment makes for a safer, faster and cheaper product (Gunawardena et al., 2014).

° **Economic dependency of a natural, uncontrollable material**: bamboo has a peculiarity that when it flowers, it shortly thereafter dies. For bamboo plantations of that particular flowering species such occurrence is devastating. Fortunately, this only occurs with intervals of 60 to 120 years yet scientists have not yet discovered the reason for this mass flowering. To that end, diversification of bamboo species in each plantation is essential. Furthermore, bamboo remains in a smaller or greater degree susceptible to degradation by bio attacks and weathering conditions.

° **Consumer awareness on health and environmental issues**: besides the toxic chemicals used for the treatment of bamboo, also the application of toxic additives in engineered bamboo products can lead to environmental and health implications. In the past, the consumer was often unaware of product related risks; however this is changing rapidly (Manandhar et al, 2019). When the strict regulations during usage and disposal are minimized or neglected and consumer goods is found to be unsafe, this can have severe economic implications such as restrictive measures, including bans, from the consumer market such as the example of the ´ecologic` coffee cups from bamboo shows. Because the cups leach melamine and formaldehyde, the product was taken off the market.

° **Raw material depletion:** a higher demand for bamboo can lead to a depletion of the raw material and eventually even cause deforestation. Care has to be taken that an increase of the bamboo economy does not lead to over-harvesting or premature harvesting as was already noted in the northeastern Yunnan province in China where a decline in bamboo forest was reported after extensive logging thereby ravaging new shoots in order to meet the increased demand (Manandhar et al, 2019; Wenyuan et al. 2006). As the economic equilibrium between demand and supply has to be maintained, the production capacity needs to be increased by investing in new, sustainably managed plantations before a shift towards bamboo in the construction industry is feasible.

Research question: Which factors play a role in terms of social performance of bamboo?

The social pillar is arguably the most difficult to measure for it discusses the improvement of social structures in terms of education, expression of culture, standard of living and equalization of rights. To determine the level of social performance, one first needs to establish the social performance indicators to measure the performance. Social benefits in relation to bamboo involve amongst others the development of scale-businesses in either local communities or individual families (that grow bamboo around the house), augmentation of the social cohesion (reviving traditional craftsmanship & working together in cooperatives) and bamboo´s resilience to disaster.

° Social cohesion: traditional bamboo construction techniques were generally handed down from generation to generation thereby becoming part of the socio-cultural structure. Lately, however, these techniques have gotten into oblivion under the pressure of fast and modern construction materials. Yet, bamboo has great opportunities to strengthen the self-reliance of local communities, even more so when it is presented in an educational frame and the introduced techniques rely on the traditional skills and pride in local craftsmanship. INBAR has delivered already outstanding work in this field by distributing bamboo research for free and by setting up social developing and technical programs worldwide. Exemplary are the ´Technology Transfer Models` called TOTEMS which are practical information resources to aid local representatives in teaching certain skills at community level, thereby assisting in their (economic and social) development. Considering only basic masonry tools and skills are necessary, little capital/financial input is required to start a bamboo business. This low entry threshold makes the bamboo construction industry quite accessible.

° **Vernacular architecture:** principally refers to construction techniques that have been handed down over many generations, influenced by the traditions of the respective culture and based on trial-and-error in order to get to the most adapted housing for a particular climate (Zhai & Previtali, 2010). In vernacular bamboo architecture, the characteristics that are specific to bamboo have been optimized and even possess connection methods that cannot be applied to other materials. Designers should be careful not to simply discard or on the other hand simply copy these vernacular ideas, but find a balance in between. Neither modern improvements nor traditional construction phenomena should just be neglected. The cultural difficulty lies exactly on the dichotomy between globalization and vernacular, where the first is characterized by efficiency, mass production and prefabrication, and the vernacular by local climate, geography and cultural traditions. When a correct balance is attained, social progress can occur.

° **Resilience to disaster:** a disaster often forces the affected people or communities to leave behind their agricultural activities and move to urban centers where they have little to no chance of competing in the local economy due to their lower education level. Bamboo´s resilience to disaster is multi-faceted. First of all, houses built in bamboo, especially in earthquake stricken areas, are less liable to collapse as bamboo does not lose its structural integrity immediately and the affected bamboo members can easily be repaired afterwards. Earthquake forces are a result of mass and the imparted acceleration thereon, the lightweight nature (high strength-to-weight ratio) and the ability to absorb energy at connections, makes for resilient buildings. Bamboo has a better resilience than timber which has a higher density (Janssen, 2000; Kaminski et al, 2019). Secondly, bamboo serves well for the reconstruction of destroyed houses. Bamboo can substitute the damaged members or simply provide support for damaged house parts. Thirdly, bamboo can help to counter erosion as a result of its extended root system, especially in areas that have been affected by flooding or other water-related disasters such as tsunamis. Erosion control can be done by planting shoots in the pluvial deposits which are the result of the sedimentation of a flooding, but with an adequate amount of subsoil for bamboo to grow on (Manandhar et al., 2019). Fourthly, even in case of forest fires, where the ecosystem with its plants, trees and animals is irretrievably lost, bamboo has the potential to relieve the pressure from deforestation by replacing the vegetation and biomass at a faster rate than trees are able to do. Finally, bamboo can even provide a solution when soils are polluted for example after a mining disaster where a toxic mudflow leaves mine tailings. Bamboo can take up toxic residues by the process of phytoremediation.

Research question: How to build bamboo structures with an efficient resource (and energy) use and how can bamboo structures be designed that they ensure adaptability and circularity?

As a response to the increasing material scarcity, a transition of the traditional linear production scenario towards a circular and renewable model is fundamental (van der Lugt, 2012). Technical materials such as fossil fuels, plastics and metals are finite materials and cannot be recreated easily. In a circular economy, these materials are only used instead of being consumed. Because of their finiteness a long-life cycle is advocated by means of re-use, refurbishment, repair, remanufacturing and recycling as opposed to a linear process that requires a constant new resource input whilst creating waste, pollution and emissions at the beginning and the end. However, bio-based construction materials such as wood, bamboo, hemp can be incorporated into the ecosystem and re-generated through biological processes. In the bio-cycle it is important to let the ecosystem do its work as well as possible. Consumption may take place during this cycle (fertilization, food, water) as long as the streams are not contaminated with toxic substances and ecosystems are not overloaded. Bio-based raw materials can then be regenerated (Ellenmacarthurfoundation.org, 2019). In other words, it is essential to avoid the pollution of the raw bamboo culm whether it is by adding environmentally irresponsible nutrients, by treating it with heavily toxic chemicals, by jointing it with inseparable non-biological elements or by processing it with toxic adhesives. Only then, bamboo is able to return into the biological cycle as compost or biomass. This awareness also relates to how bamboo architecture should be designed, especially in the jointing methods but also in the structural system in terms of the protection against weathering and the ability of maintenance, repair or replacement. Regardless the fact that bamboo is part of the bio cycle, the objective is that its service life should be as long as possible. Although it might seem counterintuitive, when a bamboo has had a service span longer than the required time to grow back (preferably extended as much as possible through cascading into lower value-added applications), it is favored to burn it for green energy in a specialized biomass plant (Ellenmacarthurfoundation.org, 2019; van der Lugt, 2017).

The final element **Venustas** focuses on the aesthetical aspect of bamboo. Although bamboo as a construction material is gaining interest, it has not reached its full potential yet. Multiple factors plays a role herein such as the continuing perception of bamboo as a poor man´s material with a limited durability and a higher construction cost as a result of the unfamiliarity with the material, but also due to the lack of well-designed and replicable examples. Aside the technical aspects of bamboo, the aesthetical aspect also plays a significant role in the acceptance of the material. The perception of bamboo contradicts greatly between countries but also in education levels. In western countries, bamboo is associated to tropical countries and is often not even considered as a possibility, amplified by the fact that there is no a tradition in building with bamboo in Europe or North-America. On the other hand, in countries where bamboo naturally occurs, often higher educated people regard upon bamboo as an upscale material as they reference to luxurious bamboo villas, hotels or restaurants they have seen in books or online while lower educated people view bamboo as ephemeral and of poor quality as they reference to poorly executed houses in their close surroundings built by people that possess nor the means or the knowledge to treat the poles or to build according the correct design principles. Nevertheless, it can be noted that bamboo is facing a perception problem, which can possibly be remedied by aesthetics: acceptance through design. Qualitative and copyable examples can inspire others on the condition that the architecture is attainable and a balance in cost-efficiency is found. The duality of bamboo exists in the fact that it is either employed in high-end or low-end constructions. Bamboo needs to fill the gap in between and address the middle class with affordable, well-designed bamboo architecture equal to what Ikea has done in the furniture industry.

C. Research question: How can designers/architects achieve aesthetical, durable yet innovative bamboo architecture?

Research question: Which factors determine the aesthetical quality of a bamboo design?

Aesthetical quality cannot easily be determined in a set of rules as it is a subjective and changeable matter within era and context. According to De Botton (2008), it has become an unanswerable question because ‘how can anyone claim to know what is beautiful and what not’? This is also manifested in the actual meaning of the word described in the dictionary as a philosophy that explores the nature of art, beauty and taste with the creation and appreciation of beauty (Merriam-Webster.com, 2020). Notwithstanding, already since the earliest civilisations mankind has searched to achieve beauty in its buildings by setting out rules of thumb to follow. In Greek times, the concept of beauty was closely interlinked with ethical values such as moderation, harmony and symmetry. Proportionality was considered as a mathematical approach to achieve these ethical values and ultimately beauty. The measurements of the building could coincide with e.g. musical proportions (a fourth, a fifth, etc.) or the golden mean based on Fibonacci’s sequence. For the architects at that time those were the rules of thumb to determine which type of columns (width and height) was appropriate for their work, especially since the quarries provided only prefabricated elements in standard diameters and heights (Snijders & Gout, 2007; Livio, 2002). Aesthetical assumptions were codified and popularized in pattern books for ‘ordinary builders´. Originality was far less of an issue for the architect or client. After the classic period, the application of proportionality in architecture slumbered on and was merely used in religious and monumental buildings. The use of proportional systems only resurged again in post-war modernism where there was a momentous lack of housing and an urgent need for fast construction methods, yet the architects of that time still looked for ways

to ensure aesthetic quality. The combined aspect of applicability on large scale and inherent aesthetical qualities in proportionality was noted by modernists' architects such as Le Corbusier, Mies Van Der Rohe and Dom Hans van der Laan (Mattei, 2014). In recent years however, architects have turned again against the very idea of these ´rules`, declaring them as naive and absurd. Architects are called upon to be original and to invent new styles (Ruskin, 1989). Criticism, predominantly by mathematicians, on proportionality, mainly dispute that the application by architects during the classic ages cannot be established as there are no writings hereof and when studying the designs or buildings of e.g. Palladio, the correctness of the proportional system deviates from the actual measurements. It has to be noted that this is a design tool and actual measurements can deviate for many reasons such as the terrain of the building site, inaccuracies in the actual execution, etc. Proportionality is rather a starting point in the beginning of the design process. After sketching the first drafts, it might be an interesting exercise to examine whether the lay-out is subject to improvement according to the theory of proportionality. Whereas in the past 'ideal' proportions had to be calculated or drawn (e.g. with a pair of compasses), in modern times this can be done with the aid of computerized software that allows the user to place 'golden' forms such as a rectangle, circle, square, etc. over any computer drawing (AutoCAD or vector works).
By opposing and correlating also psychological studies on proportionality, it was examined if there is any truth behind the appeal of proportions to the human eye. Pros and cons were found, however no absolute truth could be found in such. Research often contradicts itself depending on the conviction of the researcher.

Research question: To what extent can proportionality and prefabrication be valuable strategies in terms of durability and cost-reduction?
In order to address a wider market for bamboo, it is imperative that there exist qualitative examples but the building cost remains similar to conventional materials. This objective can only be obtained when the design departs from prefabrication and modularity. Only on that condition construction time and inherently the building cost can be reduced. Differentiating bamboo lengths in combination with different bamboo diameters could lead to proportionality comparable to the column height and interspace systems of Van Der Laan, Alberti and Palladio. Exemplary to this idea are the columns in the community centre in Camburi that are composed of four bamboo culms of 6m height and a diameter of 20cm or the columns in the art gallery in Catuçaba consisting of four bamboo culms of 2,4m height and a diameter of 6cm. These heights and widths reflect approximately the golden proportion. As was the case in ancient Greece or Rome, prefabricated building-elements that already posses inherent proportional systems could democratically achieve visually appealing elements in a cost-efficient manner; only the producers of the prefabricated bamboo elements needs to take care per element proportional rules of thumb are followed so that these, by the standardized dimensions given, determine width and height in buildings as well without the designer, builder or user needing to think about such.

In **part II** of the dissertation, nine case studies designed and built by the author in Brazil are discussed. These case studies provide insight in the reality of building with bamboo and demonstrate the actual flaws and strengths of bamboo. To elaborate further on the aspect of sustainability, a durability analysis is performed on one of the cases, the community centre, fifteen years after being built. The discussion of these cases helps to understand and discover causal links and pathways. As such, it is a tool to refine the theory from the literature study.

D. Research question: What learnings can be drawn from the cases?

Research question: Which successes or mistakes were noted that (dis)accord with literature?

The reviews of best practices are rare in bamboo architecture, although these can provide other designers much relevant insights in terms of flaws and successes in the built reality. The case studies discussed in chapter 6 affirm the significance of the correct protection of the bamboo culms from weather conditions corresponding with the information found in literature. Especially in the first two case studies, it was apparent that an inadequate design can lead to a rapid decay of the construction. There was no roof provided for the bridge and the roof of the handicraft shop with almost no roof crossing and too little inclination caused water to stagnate on the reed roof, thereby significantly reducing its service life. In each case, another issue predominated. In the handicraft shop the upward soil caused deterioration of the eucalyptus columns. In the community centre, a lack of ventilation in the storage rooms had fungi proliferation and a darkening of colour as result. In the veranda and the guesthouse the bamboo appeared not to be properly treated and was attacked by insects. In other words, the lack of a proper treatment and the exposure to radiation and precipitation can be detrimental to bamboo, but also upward soil, humidity and ventilation are fundamental factors to consider. Not retrieved from the literature study, yet revealed in the durability analysis on the community centre, is that horizontally provided bamboo members are more susceptible to decay than vertically positioned ones, presumably due to the fact that water and humidity remain longer on a horizontal member.

One should be careful to not let design issues or formalism govern the chosen solutions for it will most likely lead to a reduced durability of the construction, especially in climates with pronounced weather conditions. The challenge lies in finding a correct balance between protection, ventilation and an appealing design. In general, designing with bamboo can be reduced to three main design decisions; 1) the bamboo species and diameter to work with 2) the structural system 3) the jointing method.

1) Initially, the author worked predominantly with large diameter bamboos, but in search for a lighter architecture and greater workability, the author transferred to the application of small diameter bamboos. In the LCA it was calculated that a single large diameter bamboo column performs better than 4 small diameter bamboo columns. Therefore the author would suggest combining different diameters according the design.

2) In the case studies different structural systems were applied, but soon it was noticed that a straightforward truss or orthogonal system provide the best protection to the culms. Geometric, organic and curvilinear structures were not applied in the case studies, notwithstanding bending of bamboo members was applied in the art gallery and the bamboo canopy. Bending is a time- and energy-consuming process, it weakens the stem and it is delicate to attain similar curvatures. The author applied bended members in addition to the chosen structural system, rather as an aesthetical aspect and not as much as a structural one, e.g. the arches of the art gallery refer to a monastery.

3) A joint can be designed in multiple ways and although the main principles come down to only a few categories, the options are numerous. Moreover, as the materials to apply in the joint connection are variable. In the first cases, jointing methods from known architects such as Simon Vélez, Hidalgo-López and Marcelo Villegas were practised. Over time, there was sought to provide for a jointing method that allows maintenance, but also repair and even replacement of the bamboo members. Because this was impossible in the primary constructions, the durability of these constructions was constrained. In addition, a joint is in preference simple to execute, economical and provided in readily available materials. The author developed a joint where a standard wire rod length is inserted into the concrete foundation and on the other side a bamboo culm is positioned, lifted 10-15cm by means of a hex nut and a large diameter washer. In the following cases, the same technique was employed. This continuous search to improve the jointing methods, led to a transition from the application of steel to hardwood connector pieces such as the ´violin` and ´bird` joint, respectively discussed in section 6.8 and 6.9. The combination of a hardwood piece and one of more wire rods inserted in different angles right through enables any possible connection and with the aid of a simple hex nut the bamboo can be secured in the desired position. The weight of the roof furthermore maintains the bamboo into position. Only if necessary, grout is inserted in the

compartment where the jointing occurs. When grout is used, the replacement of bamboo members is more complicated but not impossible.

Finally, the construction time has an impact as well. The bamboo structure of the community centre was built in the middle of the summer and the bamboo culms suffered considerably from the alternating heat and rains. It is recommended as long as there is not a roof, a temporary protection or canvas protects the building site.

Research question: Which aspects proved to be beneficial to the sustainability, innovativeness and the cost?

Preconditional for a durable construction is an effective treatment against insect attacks, fungi and decay. Also a protective layer in varnish and regular maintenance are imperative aspects. Cracks, regardless how small, need to be closed off. In case of a structural problem, the bamboo in question needs to be repaired or replaced immediately before affecting the entire construction. Whatever problem arises, it needs to be tackled and solved in order to enlarge the durability of the construction.

Although it might seem contradictionary, innovation does not necessarily imply a higher cost. It can even reduce costs when one seeks solutions with an open and creative mind set. Replacing steel by wood is perhaps not as innovative, yet the way in which the wood is applied is straightforward and reproducible. It is advisable in future research or practical applications to search for even more sustainable materials in the connection of joints, e.g. compressed bamboo fibers, hard recycled plastics,… Provided a particular design would lead to a higher building cost, it can generate an aversion to bamboo. Bamboo has to remain economically competitive compared to other conventional building materials, especially in destitute communities where cost is a decisive factor.

Part II of the dissertation also involves an LCA analysis of two different types of bamboo columns extracted from the case studies. Both columns are analysed on their environmental impact following the MMG method and are afterwards also compared to the conventional materials; wood, steel and concrete.

E) What conclusions can be made from the Life Cycle Analysis?

Research question: What are the main drivers in the life cycle environmental impact of a bamboo column (two types) and what are the points of attention to limit the environmental impact?

One of the main reasons to use bamboo in architecture is its considerably high capacity of carbon sequestration, as well as the low environmental impact it has when compared to standardized building materials such as concrete, steel and others on more than one impact factor. In this thesis, a Life Cycle Analysis was performed (using SimaPro-Software) in order to assess this impact.

When applying bamboo in the manner which is advocated in this thesis, treated with borax, using external screw-unscrew steel or wooden joints, with concrete infill, however, the perception might exist that all of these ecological benefits might have become obsolete. It is therefore important to correctly assess the data behind environmental impacts of not only bamboo, but also its process, transport and added materials to become an actual structural member. How much impact is added by each feature, and can other options be found if the impact proves too high? The borax-treatment for example, however effective and low-toxic it is, does have a considerable environmental impact when its entire process to become a treatment agent is reviewed, and this therefore also affects the treated bamboo. Future research could address the environmental impact of borax to further diminish the impact of bamboo in construction. When the impact of grout is reviewed on the total impact of a bamboo building element (in the studied case a column), it is found that the volume needed to make a joint (filling two or more internodes) is negligible or at least low in percentage of the total impact. This requires however to only fill the internodes where joints are applied, when the grout/cement would be added to the entire stem the impact there-of would rise substantially above the other impact factors. Opposite to what intuitively might be perceived, transport also does not play a large part in the total impact of the bamboo building element (column), provided that it remains regionally in a radius of no more than 300km around the plantation. Other studies have pointed out that sea-transport or inter-regional transport might become the largest impact factor in the total of impact factors of a bamboo building element, but this was beyond the scope of this study for the area of focus was on the tropic region of Brazil. This might however be highly interesting to investigate in a follow-up study. Finally steel, necessary to make joints in bamboo proves to have one of the largest impact-factors when one regards the bamboo column, or any other bamboo joint for that matter. Even artisanal made joints such as the fish mouth joint contain steel wire rods to anchor one bamboo to another, in fact more than the suggested joints in this thesis (that appear to hold more steel simply because the steel is visible). One could argue that it is possible as well to joint bamboo with ropes or lashings, but for long term-construction friction or vandalism might make these joints dangerous. For the LCA study in this thesis, long term effects or emissions were excluded (also because it was chosen that the impact should not be transferred to later stages when the environmental problem is acute), but the use of recycled steel, or the recycling of the joint itself should however put a question mark towards the long-term impact of this element with the structural bamboo-column. It possibly falls below the impact-level of other parts of the process or constitution of a bamboo column, but as stated before this long-term effect was beyond the scope of this study.

When assessed within the bamboo as a composed building material itself, the steel and borax are a significant part of its impact, when however compared to other building materials; the assembled bamboo column performs substantially better with regards to environmental impact.

In this thesis, a bamboo column from the case study of the guesthouse was assessed in load-bearing capacity, and not in the real load of the roof that was carried in the example of the case study. It was studied how much load the column from example could theoretically take (load bearing capacity), also with regards to its height. This height proved to be the determining factor rather than the compressive force that bamboo can take, because buckling would occur first before its limit of compression would be reached. The begotten amount of applicable load/force was then studied for columns in steel, concrete and wood (Parana Pine). In the specific case of a bamboo column and the set boundaries (distance-transport, manner of fabrication…), it was found that this structural element was considerably less environmental impactful than any of its competitors. Even with the impact of borax or steel joints competitors do not even come close when GWP is regarded as impact, so one might wonder how imperative it is to find another preservative and jointing material in order to diminish the impact even more. It should be noted however that, when the overall eco-cost of all indicators are combined (not only GWP), the results are closer then when only GWP is considered. This is mainly due to the carcinogenic content and particulate matter (fine dust) that the stainless steel produces. The main improvement regarding all environmental indicators for the assembled bamboo (but also wooden) column can therefore be found in this connecting material.

Research question: How does the environmental impact of a bamboo column perform compared to conventional materials?

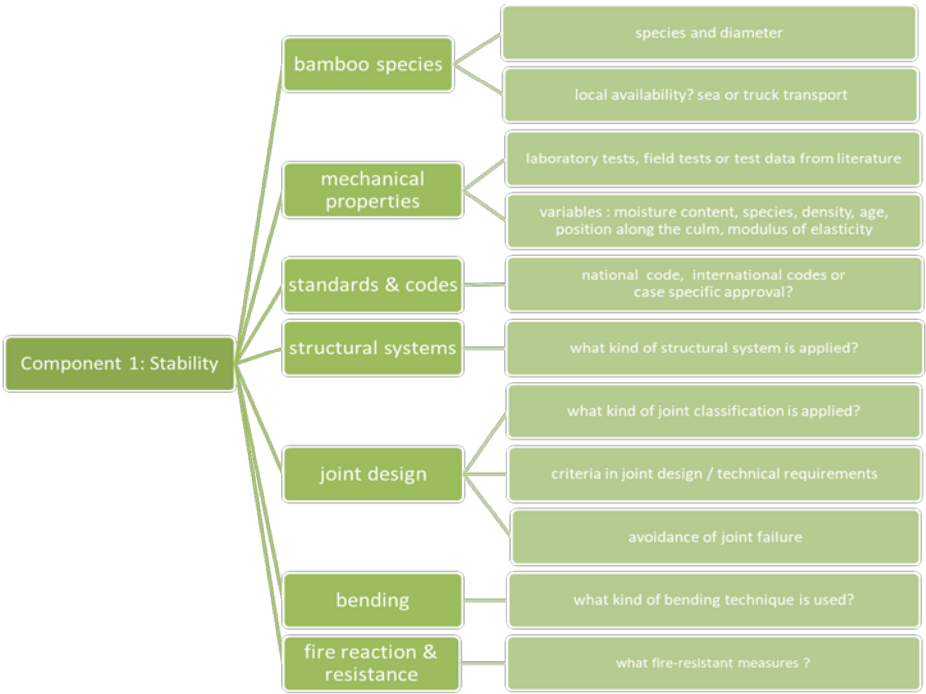
When regarding the environmental impact of a bamboo column trough an LCA-point of view, it is clear that even completely assembled, in tropical regions bamboo constructive elements as specified in the LCA chapter of this thesis has the lowest possible environmental impact compared to a wooden column (with similar assembly as the bamboo column in order to attach it to other constructional elements), a steel column (with a large number of recycled content), and a concrete column.

After discussing and analysing the above-mentioned aspects, crucial elements for a "low-cost, sustainable, prefabricated, modular bamboo building" are selected. These results are converted into an evaluation framework in **Part III** of the dissertation. It is not the aim to claim what a good bamboo design should look like and present designers a subsequent scoring system. The framework is conceived as a set of guidelines that lists important aspects to attain a qualitative and durable bamboo building.

F. How can the evaluation framework contribute to more qualitative bamboo architecture?

Research question: Which evaluation indicators can be defined to determine a holistic framework?

The aim of this dissertation and the evaluation framework in particular is to provide architects a framework within which they can design bamboo constructions. By means of a set of guidelines architects can evaluate the lay-out for a load-bearing bamboo structure. Even an experienced bamboo architect or builder might get new insights reading this dissertation, principally from the sections on structural systems, joint design and the life cycle assessment of two different bamboo prototype columns. However, the main target audience for the evaluation framework are the inexperienced architects/designers that seek to evaluate the fundaments of their bamboo design from the start on. The idea behind the evaluation framework is to have a visually weighed check-list in which certain aspects are 'conditio sine qua non' and others are optional but advisable. If only these basic rule-of-thumbs are regarded, one can already build structures that are beneficial on many aspects of impact, unequalled by most other building materials.



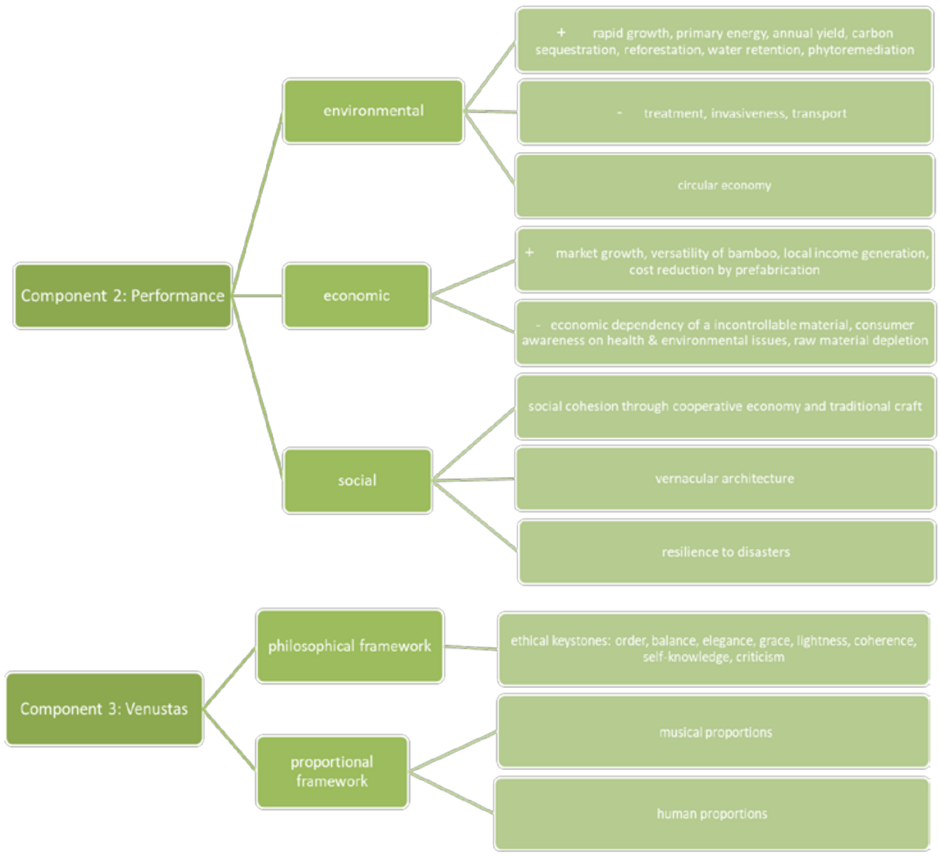


Figure 9.1. Evaluation framework indicators

Research question: How can these criteria be translated into a framework that enables the evaluation of bamboo designs?

The quality of a bamboo design does not depend on a single criterion, but a wide range of criteria and each design is conditioned by the human and natural resources, cost and time. These proxies along with the design intent provide a means for evaluating the quality of a bamboo design (Gann et al., 2003). A design process is a series of decisions, not only by the designer but by every stakeholder, which collectively and progressively leads towards the built reality (Dickson, 2004). The objectives of the stakeholders are usually conflicting and therefore the solution highly depends on the preferences of the decision-makers, and often compromises must be made (Pohekar & Ramachandran, 2004). To cope with the complexity of the evaluation of the quality of a design, Harputlugil et al. (2011) propose a hierarchic decomposition of design quality in criteria and sub-criteria. The DQI model served as an inspiration in the process hereof, although given the distinctive character of the subject of this research, the same criteria cannot simply be adhered. The (sub) criteria for the evaluation framework correspond with the threefold components described by Vitruvius (1999) customized to bamboo in specific. Also the literature study is lined up accordingly.

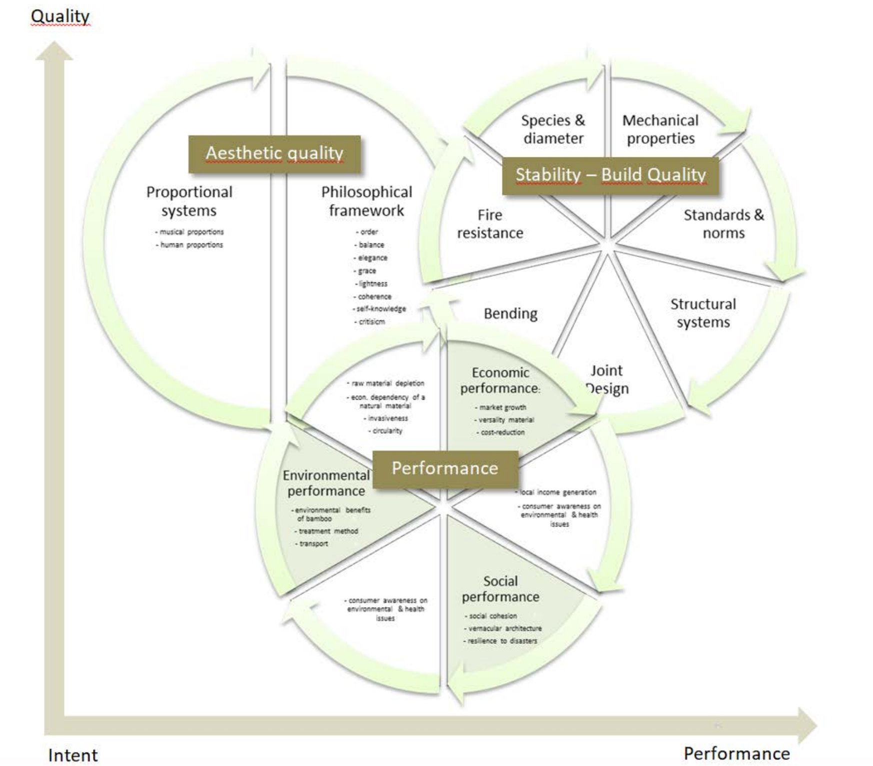


Figure 9.2. Conceptual framework

First, several conditions need to be fulfilled when working with bamboo, no matter the context, intent or design principles. In the second part of the framework, the user has to answer a questionnaire with ´true’ or ´false`. A certain weight is given to each criterion as these cannot all be counted as equally important. The weighting factor is determined to which extent these meet the key aspects of sustainability, cost reduction and innovativeness. However, it was opted not to have a numerical outcome and only show the results in different shades of green, ranging from no colour to dark green. Dark green means a positive result on the constructive, environmental, economic, social and aesthetical aspects. Light green means that only some aspects are subject to improvement and no colour means that none of the proposed suggestions for a sustainable and innovative bamboo design have been met. As such, the user can identify at once which criterion obtain a lesser result and can evaluate whether this is an aspect that is of importance to the design context or not. The option to review a project solely through one or more sub-aspects (environmental, social, economic, circularity, aesthetic) is given as well.

9.2 **Limitations of the study**

The research focusses on load-bearing elements in bamboo and does not discuss the complete building envelope. Although even the walls, floors, furniture, etc. can all be provided in bamboo, this research limits itself to the load-bearing skeleton. The scope of the research would become too wide if every building element in bamboo would have to be researched. This focus is also the most logic and coherent because in the past decade the author has been concentrating on the application of raw bamboo in load-bearing structures, primarily in truss and orthogonal structural systems. This personal preference is however no judgement to other categories of applications of bamboo in a construction, merely a continuation to the mastered practices and knowledge. This focal point on low-cost, innovative and sustainable bamboo prototypes might preclude deviating structural systems. It is for this reason that the evaluation framework does not provide a scoring system, only indicators via a color scheme, indicating the aptitude towards the focus of the thesis on sustainable, innovative and prefabricated bamboo construction systems. It also have to be noted that the evaluation framework does not guarantee good bamboo architecture; it merely assists an architect or designer in the design process when one needs to determine the species and diameter, the structural system and jointing method to use as well as to review other issues on stability, durability, sustainability and innovation. It is impossible to provide a contingency framework that includes every possible parameter.

Another possible critique to this research is most likely directed to chapter 5 on the aesthetic quality of design (Venustas). The author is aware that this is a delicate topic, nevertheless it was deemed sufficiently important as the general perception of bamboo is most likely what keeps bamboo from being accepted by a wider public. The proportional system is a perfect tool to achieve modular and adaptable buildings that allow for prefabrication as the dimensions are similar and can be produced in advance. Elaborating on the proportional systems might seem limitative when it comes to aesthetics, however it was aspired to explain the universality hereof in an as objective manner as possible by appointing as much evidence as counter-evidence. Kant already points out in 1785 that there cannot be made a scientific judgment on beauty, only a critical review on past theories and writings.

9.3 **Recommendations for future research**

An important shortcoming in bamboo architecture is the unpredictable cost to get a building permit. As no international approved certification is admitted worldwide, local governments can ad hoc request for laboratory testing and other types of proof of quality, especially in case of larger and/or public buildings. This was for example the case for the Zeri Pavilion designed for the Expo 2000 in Hannover where the German government required such detailed information and testing that the Zeri Initiative finally decided the built a replica (scale 1:1) in Colombia to perform real-life testing (Minke, 2012), but is still true up to this day for example in the fire testing, mechanical testing, wind-tunnel testing and such in the project of the entrance buildings to the Zoo of Planckendael by author. More study and effort needs to be put into the gathering, comparing and translation of available academic data into a comprehensive international standard. Very little academic research has been done so far in terms of fire resistance of bamboo, despite the fact that this is an essential aspect in the certification process and permit approval. Also the constructional part within a standard is very limited and should be more detailed.

Research on how a quality and certified label could be set up for the selling market of raw bamboo poles also seems fundamental. A key pillar in this matter is the treatment method, for the quality hereof directly impacts the durability of the bamboo poles. A quality control should be performed on the bamboo lots before these can be sold. Bamboo´s mechanical properties and natural variation contribute to the difficulty in obtaining accurate quantitative data and as a consequence bamboo is sometimes unreliable. Variation in the cross-section can substantially impact the bending and axial stiffness of the culm (Arce-Villalobos, 1993). Buckling can occur in bamboo culms because of its slenderness and curvature. Yet, these issues are avoidable through a quality control. Both standardization and certification require a set of quantitative performance measures that need to be met before a certificate can be handed out. Research needs to expose what these measures should exactly encompass. The logistical chain of prefabrication can also be studied further on, for example by studying and devising new machinery and logistical processes that reduce the time to provide prefabricated elements, that e.g. do not depend on the time it takes to dry the cement in joints on both sides of a bamboo building element before a next one can be made.

In this dissertation, the case studies executed by the author in Brazil have been analysed and discussed and one of these cases has been analysed on its durability 15 years after being build. It is recommendable to go deeper into the discussion of built examples and analyse real life bamboo buildings worldwide. Interesting conclusions might arise in regard to the different climate zones, weather conditions, building techniques, treatment methods… Much can be learned from the practice, nevertheless this information is at no time bundled and remains information that is only shared sporadic and on small scale. This practical information, however, should be shared with everyone that chooses to build with bamboo. Also, it would be very interesting to know how the well-known examples such as the Green School by John Hardy or the buildings by Vo Trong Nghia have withstood time. What are their successes and what could be improved? What improvements have been done over the years to prolong the durability of the construction? Perhaps a post-construction evaluation model to assess the quality of bamboo constructions in-use phase can be developed. Also, the life expectancy of bamboo buildings can be researched in more detail; in literature and conferences worldwide random numbers of years life expectancy are being claimed, but none resting on fundamental or relevant research, even more so taking into account 'recent' treatment techniques and design recommendations that prolong the life expectancy of a building. Bamboo buildings that reach the projected age that some proclaim to be the maximum age a bamboo building can exist, have for example never been treated with the chemical solutions deemed necessary nowadays and can therefore not provide answers towards life expectancy.

Although, there already exists a classification and suggestions are provided in terms of the different jointing systems, more detailed studies on this matter are advisable. The applied jointing system is a crucial and defining aspect in the design. Because a bamboo is round and hollow it is challenging to connect it to other straight-lined materials. Possible solutions to do this are numerous, yet it remains imperative to continue to seek for easy to produce and low-cost jointing systems. One possibility that should be looked into in detail is the 3D printing of connector pieces, conceivably with bamboo fibres. The LCA study in section 7 has illustrated that the replacement of the steel connector pieces into a more sustainable material would involve a beneficial environmental impact. A further analysis into the development of standardized columns and beams, or entire structural systems for that matter, is equally important. This can benefit the construction process and even the construction speed. It can be studied whether there is a possibility that plantation owners add value to the bamboo poles by selling prefabricated and standardized bamboo columns with connector pieces attached to it. Perhaps this initiates a new market.

Finally more research needs to be done in environmentally friendly treatment methods. The performed treatment has a great impact on the LCA compared to (regional) transport and grouted infill, that have a significantly smaller influence or impact in comparison to the treatment chemicals. It is not only the toxicity of the materials that are used; also the amount of energy required during the treatment process plays a significant role. Nevertheless, when low-tech treatment techniques are applied, the duration of the treatment itself takes several days because it involves a natural diffusion process. Is it possible to combine high and low-tech methods that require little energy input? It is recommended that effective yet non-toxic preservatives are researched in order to even further diminish the low impact that composed bamboo building elements have in relation to other building materials.

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