

Mind, Tool & Matter

SYNERGIES IN DIGITAL FABRICATION AND BAMBOO CRAFTSMANSHIP

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Title: Mind, Tool & Matter – Synergies in Digital Fabrication and Bamboo Craftsmanship
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Degree Awarded by Oxford Brookes University
Submitted in partial fulfilment of the requirements of the award of Doctor of Philosophy

March 2021

ACKNOWLEDGEMENTS

To my parents Manuel & Eugene Assis Rosa who have always supported me with their unconditional love. Thank you for the freedom and encouragement.

I am in gratitude to Marcel Vellinga who has been a fantastic supervisor and friend.

To the support, encouragement and guidance from Georgia Butina Watson, Matt Gaskin, Ray Ogden and Jane Anderson at Oxford Brookes University.

To the excellence of the examiners Laura Novo de Azevedo, Jose Pedro Sousa and Jonas Hauptman who gave their positive critical review and support for the research and encouragement to take this project further.

To James Palmer and Chris Fulton who have been instrumental in helping me shape this project. For all their support and friendship I am very grateful.

Thank you to David Trujillo, Hector Archila and Roger Martinez who guided me through the world of Bamboo in Colombia.

To Asta and my children, Amelia and Leonardo, who supported me with their love and gave me the time to be able to carry out this project.

To Oxford Brookes University for financially supporting this degree.

To all my friends who have supported me and have been just as enthusiastic as I have for doing this PhD. Thank you, Richard Paice, David Martins, Samuel Matias, Daniel Rowland,
Tony, Alain & Paulo Assis Rosa, Mario Jorge, Lindsey Round Turner, Chris Bath, Justin Chapman, Reuben Turvey, Orit Sarfatti, Christina Godiksen, Salem Al Qudwa, Andrea Placidi, Francesco Proto, Karl Kjelstrup-Johnson,
Hossein Sadeghi, Marcelo Gunther, Joel Chappell, Debbie Martin, Sophie Raeder, Jonathan Perris, Scott Scanlan, Jacek Kazberuk, Lukasz Gregorczyk, Paul Houston, Roman Skok and Marc Rower.



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ABSTRACT

Bamboo is widely used as a construction material in many places across the tropics, presenting a viable approach to locally-sourced, sustainable resource usage. Colombia has a well-established tradition in craftsmanship and design, preserved in a legacy of vernacular and contemporary architecture. This research project studies the limitations and potentials of large culms of bamboo (Guadua) for its use in mainstream architectural design and construction. The thesis aims to integrate digital design and fabrication technologies into existing workflows to aid and enhance craftsmanship and design. This research project proposes an innovative low-cost digital fabrication (CNC) machine which, through an integrated workflow, enhances the possibilities of innovative design, fabrication and application of bamboo buildings in mainstream contemporary construction. This proposed methodology of design to construction can support a wider use of bamboo through intermediate technologies, empowering communities with small to medium-sized industrial solutions, encouraging sustainable social and economic growth. Overall, it is argued that bamboo can contribute to the aims of a circular economy and to meeting the UN's sustainable development goals.

1.

INTRODUCTION

Bamboo has been used as a construction material for centuries by the peoples of Asia, Central Africa and South and Central America. As a native grass to these regions, people have traditionally used this readily available material for many applications from buildings, to furniture to hand objects. There are many examples of vernacular historic buildings within these contexts that have utilised the properties and characteristics of bamboo, adapting to the environmental context and expressing their local cultural styles, but could its usefulness in the future be so much more? This thesis puts forward the contention that bamboo can offer incredible solutions to many of the environmental, technical, social and cultural issues present in our built environment. In doing so, bamboo and its use as a construction material can both bridge the gap between past and present, tradition and innovation, scarcity and sufficiency, and encourage the new paradigm that is rapidly advancing architectural design: digital fabrication – be that complex and sophisticated or simple and economical.

The circular economy – much praised by economists (Kircherr, Reiki,Hekkert 2017; Geissdoerfer, Savaget, Bocken, 2017) – demands materials and processes that enable the world to be self-sufficient and self-supporting. With the growing requirement to create supply chains which are regenerative based on renewable energy and resources, bamboo is a material both readily available and affordable to even the poorest of nations, and yet versatile enough – particularly with the assistance of modern technology – to be usable as a mainstream material used in the most complex and ambitious buildings. The design proposals presented in chapter 8 have taken the principles of the Circular Economy as a basis for the development of these projects to support the vision set by this system and to demonstrate the potential of bamboo in this vision for sustainability.The advances in digital technologies and specifically digital fabrication machinery and software tools have created the opportunity for integration of design, analysis, manufacturing, and assembly in architecture, and the chance to reassess and potentially redefine the relationship between design and production (Kolarevic, 2004). As Oxman and Oxman (2010) emphasize fabrication is a revolution in making of architecture", which "has a profound influence upon the definition of the requisite knowledge base of the architect. Fabrication Laboratories in architecture schools have become the testbeds for development and assessment of new design and production knowledge (Gershenfeld, 2005; Celani, 2012; Valdes et al., 2013; Blikstein, 2013

This thesis focuses in particular on material as the key driver in the ecology of making, bringing together digital and non-digital fabrication as an exploratory mode of practice for material innovation. Mind, Tool and Matter interweaves three theoretical discourses to interrogate methods of design for the advancement of the applicability of bamboo. That is, the thesis will discuss the anthropological study of human processes of making and design (mind) in relation to contemporary tools of fabricating and manipulating matter for architecturally scaled applications (Adamson, 2007; Dormer, 1994; Carpo, 2011; Castle, 2010; Glynn, 2013; Gromazio, 2014; Hensel, 2004; Ingold, 2013; Kolarevic, 2004; Lawson, 2005; Leatherbarrow, 2008; Lloyd, 2006; Menges, 2006; Miller, 2005; Oxman, 2010; Pye, 1995; Sennet, 2008;

Image removed due to copyright restrictions

Image 1.1 (Minke, 2012, p. 86)

Marchand, 2010). These three discourses inform the conceptual framework of the study, which determines the design enquiry through analysis, making, drawing and reflecting. The synthesis of the theoretical review, the design analysis and the case studies aim to contribute to both the advancement of bamboo in the construction of architecturally scaled structures and our understanding of the role of digital and non-digital practices.

BAMBOO CAN OFFER INCREDIBLE SOLUTIONS TO MANY OF THE ENVIRONMENTAL, TECHNICAL, SOCIAL AND CULTURAL ISSUES PRESENT IN OUR BUILT ENVIRONMENT.

AIMS

The principle research question for this study is "**can digital fabrication methods, material properties and characteristics, coupled with human experience and skill, advance the applicability of bamboo culms for innovative architectural scaled applications"** The study aims to investigate innovative design and fabrication methodologies and socio-cultural practices for the applicability of bamboo (with a focus on Guadua) for architectural scaled applications in Colombia.

This thesis will contribute to current research on digital fabrication, focusing on the processes of making and architectural design in relation to bamboo. The study will be underpinned by an investigation of craftsmanship, which delineates a conceptual and practical framework for research in digital design and traditional practices. Through an interdisciplinary study combining anthropology and architecture, the resulting research framework will provide design and fabrication principles synthesised from material and cultural investigations with the bamboo species Guadua (Guadua angustifolia).

The research fieldwork was based in Colombia as this is a country which traditionally uses Guadua for the construction of houses and other architectural structures. There is a live inheritance of traditional knowledge in how to work with Guadua that is transmitted from one craftsman to another, carrying important layers to the engagement with this material at an architectural, spatial and cultural scale. Focusing on Colombia enables the study to specifically interact with the cultural, social and environmental contexts of this type of bamboo architecture.

The objectives of the research are:

1. To understand the context of bamboo in architectural design and construction and to identify limitations and potential for design and fabrication applications.

2. To develop a conceptual and methodological framework from the literature on anthropology of making, craftsmanship, computational design, digital fabrication and design theories, in order to identify gaps in existing knowledge.

3. To develop digital fabrication principles informed by bamboo and the conceptual framework and to carry out design prototypes and digital design work to determine new design principles for using bamboo in mainstream practices.

DIMENSIONS

There are two dimensions to which this thesis contributes. The first is technical and focuses on bamboo as a material for construction, identifying possibilities and constraints, looking at existing tools and modes of constructing with bamboo. The second dimension is more cultural and pertains to the mode of thinking of both the designer and the maker in the context of traditional bamboo craftsmanship inColombia and digital fabrication processes.

TOOL AND MATTER

The use of digital and technical advances, as well as a new understanding of the potential capabilities of bamboo, is taking the historical perception of bamboo and thrusting it into the future. The renowned bamboo architect Simon Velez and his contemporaries (Mauricio Cardenas, Jaime Pena, Rafael Pena, Jorg Stamm, Marcelo Villegas), with their in-depth understanding and manipulation of the inherent strengths and nature of the material, are transforming bamboo from a material of the past to a material of the future, and whilst it is not the remit of this project to mimic that same innovative zeal at local level, the design of the cutting tool at the centre of this thesis will represent the first step towards a use of bamboo with just as much imagination, innovation and vision.

The project seeks to provide the developing world of bamboo with principles that both the skilled and unskilled can put to positive use for the advancement of not only the use of bamboo in future construction work, but also the building of a solid, secure and sustainable methodology for using bamboo.

This study follows those of architectural research centres around the world (CITA/KADK, ETH Zurich, Bartlett School of Architecture, Architectural Association, Institut d'Arquitectura Avançada de Catalunya, RMIT in Melbourne, University of Sydney, Stuttgart/ITKE, Universität für Angewandte Kunst Vienna/IOA, and others) and leading industry partners (Foster + Partners, White Arkitekter, BIG, HENN, ROK, Cloud 9, Buro Happold, str. ucture, designtoproduction, Smith Innovation, Blumer-Lehmann, S-Form, Factum Arte Desarrollos Digitales, McNeel Europe and others), which focus on understanding materials not as static or inanimate but as engaged agents determined by specific qualities. Material performance and digital fabrication are regarded as some of the richest sources of innovation in architectural design research with direct relevance and impact in industry.

This research contributes to the field by investigating the specific relationships between the designer, fabrication technologies and material knowledge. Whilst construction applications are common, bamboo technology is characterised by bespoke small-scale routes to delivery with low levels of systemisation or automation, and compares unfavourably with established supply routes for other materials in developed economies, such as timber framing, light steel framing, fabricated steel frames and concrete.

This study investigated opportunities for the lateral translation, or technology transfer, of modern production technology as already established in parallel fields, to the specific context of bamboo. It established ‘road mapping’ options for technical development to facilitate more effective and wider usage of the material, and opportunities for innovation.



MIND

The research framework broadens out from the technical domain of fabrication to explore the meaning of 'craft' in current practices and in specific conditions and contexts. The research examines the particular social, cultural and environmental conditions of craft, design and fabrication in Colombia, where a specific genus of bamboo (Guadua) is widely used for construction. The case studies, the precedent analysis, and the discussion on processes of making and designing establish the framework for the design propositions.

Through the work of the anthropologists Tim Ingold (2013) and Trevor Marchand (2010) the thesis will discuss the processes of making and the human engagement in these processes. Ingold contributes to architectural discourses by distinguishing between hylomorphism (matter/form), in which form takes precedent in the process over material knowledge, and morphogenesis (form/creation), in which form develops through a symbiotic relationship between intrinsic material qualities. Through the works of Gilbert Simondon (1992), and Gilles Deleuze and Felix Guattari (2004), Ingold (2013) argues that when the maker has a form in mind, it is not this form that makes the work. It is the engagement with materials (Ingold, 2013).

The thesis is structured in 9 chapters, organised according to the research framework which addresses the areas of discussion to meet with the aims and objectives and to address the research question. A brief summary is as follows:

Chapter 2 – The Currency of Bamboo

This chapter gives a historical overview of the socio-cultural use of bamboo in various projects around the world demonstrating the nature of the applications to architecture. The chapter outlines the current field of research in bamboo, particularly with Guadua, the genus most commonly used in Colombia, identifying the limitations and opportunities of this material as well as leading examples of contemporary designs.

Chapter 3 – Digital Design and Craftsmanship

The discussion presented in this chapter provides an overview of digital design, computation and fabrication. The aim is to contextualise the current research in digital fabrication where material is the driver for digital methodologies with innovative outputs which challenge the norm of design and making practice.

Chapter 4 – Methodology

This chapter discusses the context of design research and action research, presenting the conceptual and methodological principles and how the objectives are addressed in this thesis.

Chapter 5 – Bamboo and Digital Fabrication

This chapter provides an overview of existing bamboo projects which have been designed with digital design and fabrication methods. This provides a synthesis of existing research and defines the context of this thesis' contribution.

Chapter 6 – Mind Tool and Matter in Practice

This chapter focuses on the processes behind craft, how the transmission of knowledge takes place and how this relates to design thinking, tools and material. Addressing these characteristics provides insight for the development of innovative systems in which digital fabrication can contribute to the advancement of bamboo design and fabrication.

Chapter 7 – Digital Thinking – Digital Fabrication with Bamboo

This chapter discussed the development of a digital tool as part of a system to integrate current methods of fabrication with digital solutions to overcome the limitations of bamboo. The chapter further discusses the holistic approach to design from material to constructed form, utilising the most effective way to achieve innovation and advancement in fabricating with bamboo for architecture.

Chapter 8 – Design Application

Following the digital fabrication parameters identified in the previous chapters, 4 design proposals demonstrate the applicability of the digital system presented for the advancement of bamboo for design and construction in contemporary practices.

Chapter 9 – Summary and Conclusions

Addressing the research question and identifying the conclusions to the research, this chapter provides an overview and highlights the contributions to knowledge presented in this thesis.





2.

CURRENCY OF BAMBOO

Bamboo continues to charm many across the world because of its aesthetic and environmental-friendly characteristics. In many regions around the world, bamboo has been used for generations as a structural and non-structural material in arts and crafts, furniture and buildings. The cultural and social significance of bamboo is still evident in many parts of the world today. However, in regions where bamboo is native, it is often regarded as a poor man's material – a perception that poses a challenge to those interested in reinstating or learning from its architectural qualities (Hidalgo-Lopez, 2003; Minke, 2012; Frey, 2013; Ufellen, 2014).

2.
CURRENCY OF BAMBOO

Despite the existence of more than 2400 bamboo species, only a few are suitable for applications in architecture due to significant differences in size and strength. The lack of standardisation, the variability of the material, and a shortage of skilled craftsmanship are the key issues facing engineers, architects and designers working with bamboo, preventing wider adoption. Nevertheless, research is being carried out around the world to enhance the applicability of the material, focusing on the grading and strength characterisation of the different species, their treatment, and overall quality control (Trujillo, 2016).

In 2014, an intensive research workshop was held in Colombia, entitled 'Promoting Bamboo as a Construction Material', organised through the British Council's Research Links initiative in conjunction with the University of Bath and the University of Los Andes in Bogotá. A total of 27 participants attended the workshop, including researchers from universities and institutions in the UK , such as ARUP, University of Bath, Coventry University, University College London, University of Liverpool, University of Sheffield, and Oxford Brookes University, and in Colombia, Universidad Nacional de Colombia (UNAL), Universidad Tecnologica de Pereira, Universidad del Valle (Cali), Universidad de los Andes, Sociedad Colombiana del Bambu, Apiros, V&V, AOM S.A.S, and Colguadua. Workshop attendees included biologists, geologists, architects, anthropologists, designers, engineers, artisans and craftsmen, collectively considering the specific obstacles to an enhanced and more efficient use of bamboo as a construction material, whilst bearing in mind the cultural, economic, political and practical constraints imposed by the realities of economy, the material itself, the extent of the knowledge and understanding of the people potentially using it, and the access – or lack thereof – to advanced technology.

Following a number of field visits to bamboo forests, bamboo preservation and treatment factories and various bamboo structures, followed by a series of workshops with the participants, the conclusions were as follows:

a Knowledge and correct use of the specific types of connections is critical for the success of using bamboo. Connections are often basic and inefficient. These can be improved with better knowledge and understanding of the material and of the preservation and manufacturing processes, and of how these can be utilised to increase strengths and minimise inherent weaknesses. Joints that were most in need of refinement were nail joints, bolted joints, fibre-reinforced polymer dowels, bonded rods, finger joints, strapping, glued/fused and traditional – dovetail and dowel. All such joint making could be improved by more precise cutting.

b Improved documentation of the geographical areas in which bamboo grows, the physical and mechanical properties of each type of bamboo being cultivated and how these relate to specific conditions – for example, extreme temperatures, seismic activity, flooding and drought –, are all necessary. This would serve to establish the most effective species for various areas of industrial and commercial exploitation.

c There is a need to establish best practice for the use of bamboo both in the round and as sheet material, together with the supplementary materials used alongside it for construction. For example, there are limitations with the use of concrete infill due to expansion and contraction when curing, hygroscopic movement and the type of mechanical fixings that can be used. Defining strengths and weaknesses could also be used as guidance on how to approach specific problems of construction and thus improve safety and application.

d A comprehensive grading system is needed to enable the material to enter into mainstream construction and, following on from this, for standardised prefabrication parameters which would enable off-site production and potentially streamline supply (thereby avoiding deficits in product availability), establish quality control guidelines and ensure the best material is used for the most appropriate job (Trujillo, 2016).

These findings led to the consideration of how I could advance the use of bamboo by fusing knowledge of digital fabrication technologies with traditional craftsmanship methods of making bamboo structures.

There are at least two ways of encouraging increased use of bamboo:

1. To review and encourage the use of bamboo parametrically, particularly using its morphology for its development as a material integral to new architectural structures. This would entail manipulating the possibilities afforded by computational design and digital fabrication, and building bigger, better and more technically sophisticated and complex structures to showcase the versatility of bamboo – where access to the appropriate technology, resources, expertise and capital is available.

2. To take a more pragmatic view by seeking to develop practical means and processes of digital fabrication that are already within the grasp of the people currently using bamboo where it is native. This could also allow for a more technological application as this becomes available, thus extending the use of bamboo in both basic construction, as well as allowing for the possibility that increased and more flexible use of it as a material at 'ground roots' level will also encourage its use in more ambitious construction projects.

The former strategy would undoubtably be a worthy project and in line with the current trend of pushing the boundaries of construction beyond the historical reliance on manual calculation, the architect's vision and the craftsmen's skill. However, communities where bamboo grows in abundance, generally do not have access to the precise cutting and engineering tools needed for designing complicated joints and structures around the morphology of the material.

Most countries in which bamboo can be found – and in great supply – are underdeveloped and are often lagging in integrating technology into daily activities. However, though limited in technological capacities, these countries possess a wealth of experience and knowledge of the application of bamboo and are rich in material resources. For people in places such as Columbia, China and India, bamboo presents a significant solution to housing shortages and economic and social challenges, by offering job creation and progress towards greater autonomy. Thus, although commonly regarded as the poor man's building material, bamboo offers an accessible solution. The research workshops demonstrated that beyond an exemplar of the possibilities of bamboo as a more widely-used construction material, there is a need for practical solutions. These solutions need to make bamboo workable for communities and also lend themselves to continued advancement by adapting and growing in parallel to increased progress and by contributing to global sustainability goals.

SOLUTIONS NEED TO MAKE BAMBOO WORKABLE FOR COMMUNITIES AND ALSO LEND THEMSELVES TO CONTINUED ADVANCEMENT BY ADAPTING AND GROWING IN PARALLEL TO INCREASED PROGRESS AND BY CONTRIBUTING TO GLOBAL SUSTAINABILITY

THE SOCIO-CULTURAL HISTORY OF BAMBOO

Historically, bamboo was used 'in the round' to construct (Hidalgo-Lopez, 2003), in columnar form, using the bamboo culm as a strut to build with and from – a method still commonly used. For example, the nipa house, or bahay kubo, is a stilt house built by indigenous cultures of the Philippines. Nipa houses were the native homes of the people of the Philippines long before the Spaniards arrived. They were designed to endure the extremes of the country's climate and environment and were subsequently developed into the Bahay na bato, a noble version of the original stilt house that fused Chinese and Spanish influences and eventually became the prototype of the colonial Filipino home, with open elevations and good ventilation (Hidalgo-Lopez, 2003; Cabalfin, 2020).

Image removed due to copyright restrictions

Image 2.1 by Philippinen Basilan Seezigeuner (1999)



Image 2.2 of a bamboo house in the old Sector of the city of El Cerrito Cerrito by Diego Carreio Murillo (2006)

Bamboo has long been central to traditions and vernacular architecture in the countries in which it is abundant. Bamboo was widely used for everyday objects by the ancient Mayan and Inca civilisations, as well as in Southeast Asia and Latin America, and its use in building systems in the form of riven culm and strips is evident as early as 1300 BCE in Ecuador (Hidalgo-Lopez, 2003). An early example of a plastered cane wall system – bahareque style (a construction method using clay or mud, reinforced with sticks or canes) – is regarded as one of the oldest bamboo structures found in South America (Hidalgo-Lopez, 2003, p51). It is composed of clay and bamboo slats, bound together using the wattle and daub technique.

Wattle and daub is a building technique common to many peoples across the world. With bamboo in such abundant supply in the Americas, it inevitably developed into the base material used for 'quincha' in Peru, a traditional system employing wood, bamboo, mud straw and grass (Hidalgo-Lopez, 2003). Moreover, bahareque and adobe walls became the preferred form of construction by the Spanish when colonising the country (Castillo, 1996).

Images 2.3 & 2.4 from Giant American Bamboo in the Vernacular Architecture of Colombia and Ecuador (James J. Parsons, 1991)

Image removed due to copyright restrictions

Guadua siding photograph by Jorge Moran Ubidia (Parsons, James J., 1991, p. 143)

Image removed due to copyright restrictions

Ecuadorian village street with stilt Guadua houses

Image 2.5 Estudio de factibilidad para la construcción de viviendas de interés social con el sistema constructivo de bambú en el municipio El Tuma-La Dalia, departamento de Matagalpa (2014).

Image removed due to copyright restrictions

Ultimately, the predominant use of bamboo and other locally available materials, together with vernacular construction methods, shaped the colonial style of the Spanish Americas. The development that Colombia experienced after independence from the Spanish in the eighteenth century, known as 'colonización antioqueña', marked the formation of a new identity and resulted in significant period of change in the country's history (Parsons, 1991). Similarly, a new architectural identity developed that was associated with bamboo and timber (Robledo-C., 1996), originating in coffee-growing regions of Armenia and Pereira in which these materials were widely available (Hidalgo-Lopez, 2003). A typical farmhouse from this period was thus based around a bahareque of bamboo or metal and later became the standardised format for most of the nineteenth- and twentieth-century colonial buildings still to be found in Spanish America and beyond (Hidalgo-Lopez, 2003).

Buildings in this style were usually two-storey with a bahareque structure, using bamboo as the basic frame material. At the end of the nineteenth and the beginning of the twentieth century, other materials, such as steel and cement, were introduced and the traditional bahareque was covered by metallic sheeting and/or cement instead. The bamboo thus became used for internal, rather than external, architecture, but nevertheless remained an integral part of the structure.

Image 2.6 bahareque embutido (2015)



Image removed due to copyright restrictions

Image 2.7 Four storey Guadua building in Manizales with bahareque encementado on the top floor (Santos, 2015, p. 52; and Hidalgo-Lopez, 2003)

Throughout the twentieth century, carpenters, practitioners, architects and engineers in Colombia mastered building and connection techniques that are still in use today. In the 1980s, architects such as Simón Vélez took inspiration from bahareque systems and, in particular, from the 'colonización Antioqueña' style. Vélez started a trial-and-error experimentation with the use of round culms of Guadua for large structures. Cantilever roofs of up to six meters were designed and successfully built using traditional collar and tie systems, as well as bridges that span 40 metres. Vélez also introduced the use of cement mortar-filled internodes in bolted connections, which allowed for more rigidity in the overall structure of Guadua (Santos, 2015).



Image 2.9 Characteristic dwelling built with bamboo culms and with bahareque encementado in the coffee region in Colombia

Image 2.8 Bamboo structures using Guadua
a) Cantilevered roof of stable by Simón Vélez.
b) Forty-meter span pedestrian bridge in Pereira, Colombia by Jorg Stamm .

a)



b)



Guadua has been integral to every aspect of life for the indigenous people of the Cauca Valley coffee regions. The material was used to build columns for houses, to make weaponry, utensils, furniture, and for the construction of aqueducts, bridges, fencing and river vessels. Guadua poles exhibited the trophy heads of the dead taken in battle and Guadua tubes played a role in funerary practices (Patino, 1995) As Guadua was so multi-functional, the Spaniards quickly adopted it upon colonising the Americas and used it for various purposes, including housing, until the decline of the Quimbaya (the pre-Columbian culture of Colombia). The area was thereafter abandoned for almost three centuries, eventually being reoccupied by the Antioquenos (the indigenous peoples of Antioquenio) at the end of the nineteenth century, when farms and homes were constructed using the baharaque design, and bamboo (Hidalgo-Lopez, 2003).

As construction methods progressed, cement and brick gradually gained in popularity until bamboo construction was largely abandoned, apart from its use in poorer and more rural areas. When the Colombian economy stagnated in the 1990s, urban centres in the 'coffee region' were most adversely affected, unemployment was rife, income levels declined and, with it, building standards. Following the earthquake in 1999, many more sources of employment were lost and, as a result, many local people moved away. The shantytowns that sprang up around Guayaquil, Manta, Esmereldas, Pereira, Manizales, Armenia and Cali, as well as other smaller settlement areas, reinforced bamboo's place as a material used purely to create temporary shelter until materials such as brick and cement could be used to construct more durable buildings (Parsons, 1991). As Parsons writes, '…as urban structures and housing design have become increasingly heterogeneous, guadua has been seen more and more as the poorman's lumber, the commonplace building material that campesinos [people who work the fields] live with.' (Parsons, 1991, p133).

Post 1990s, city dwellers had come to regard bamboo as something associated with poverty and lower class. Therefore, an increasing dislike of bamboo replaced its historical perception as the go-to material, sustaining generation after generation, inherent in the design of vernacular housing and as much part of the economy as coffee.

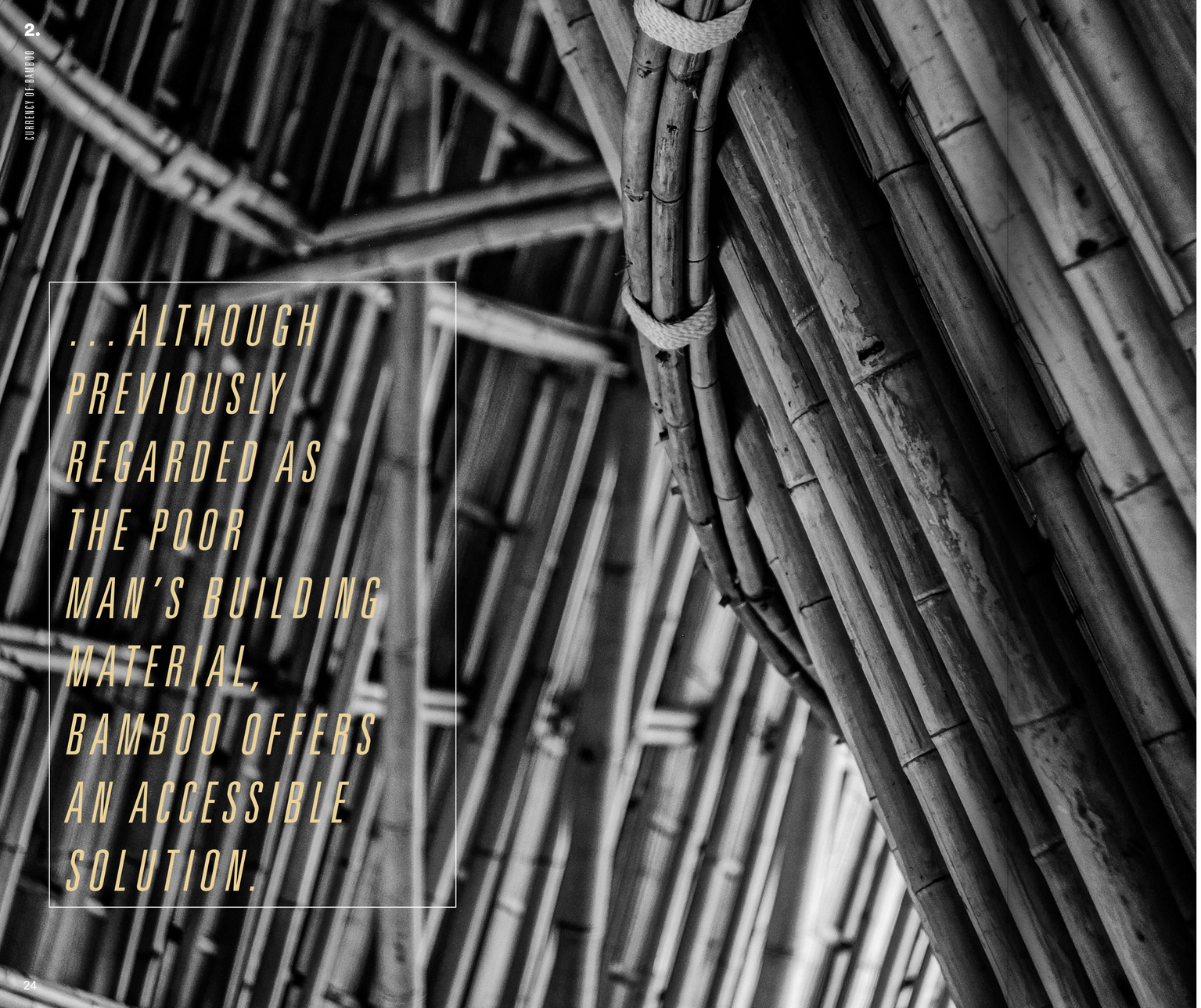
Bamboo became the material used only by the poor. The Spanish had already progressed to timber, and subsequently metal and concrete, abandoning the use of bamboo – thus dubbed 'green gold', 'poor man's timber', 'friend of the people' and 'cradle to coffin timber' (Northeast Window - October 5, 2017 blog page 'Bamboo: "Poor man's timber" to "green gold"') and even referred to by Simón Vélez as 'the poor man's wood' (The City Paper Bogota, 'The man who went bamboo') for the indigenous and lowlier social classes.

In Colombia, the long-standing structural style based around the Antioquenos bahareque design continues into the twenty-first century with structures such as the Residential Ensemble in Carmen de Apicala, Tolima, Colombia (Minke, 2012, p. 92), where Guadua angustifolia bamboo is used in form, structure, balconies, floor slabs and roofs.

Image removed due to copyright restrictions

Image 2.10 Bahareque, the system of flattening bamboo culms to apply as wall surfaces. These are then plastered to make the internal or external walls.(Minke, 2012, p92)

Symbolism of shape and design has always mattered and has remained an important element of construction. Buildings are inextricably linked to the physical and thus the philosophical becomes intrinsic through construction. Buildings need to reflect the central meaning of the lives of the people inhabiting them, and in doing so, are imbued with culture, history, tradition and belief in a way that transcends the physical.



...ALTHOUGH PREVIOUSLY REGARDED AS THE POOR MAN'S BUILDING MATERIAL, BAMBOO OFFERS AN ACCESSIBLE SOLUTION.

Bamboo grows in vast quantities in Colombia, China, India, Nigeria, and Brazil, amongst other countries. The most comprehensive survey of bamboo source locations is contained in the latest Forest Resource Assessment report (FAO, 2010b), compiled by the Food and Agriculture Organization of the United Nations (FAO) (Santos, 2015). Bamboo is not a tree but in fact a giant grass and can develop to its full adult height, diameter and external wall thickness in as short as six months, after which it continues to mature for up to a further ten years before being subject to decay (Santos, 2015).

Traditionally, construction with bamboo in Colombia has been conducted using round culms of the bamboo species Guadua. It has been proven to be seismically resistant and stable during earthquakes and is widely promoted as an environmentally-friendly building system (Santos, 2015). Its physical properties vary depending on the climate, humidity, topology, soil, altitude above sea level, age and the part of the stem being used. For example, density increases with height but, in contrast, decreases with age (Santos, 2015) and growth conditions materially affect the overall anatomy or the basic composition of the tissue in the stem (Weinstock, 2006). Tangential tension capacity is one of bamboo's most significant weaknesses – the elasticity modulus in the tangential direction is about one-eighth that of the corresponding longitudinal direction (Arce-Vilalobos, 1993), thus it is weakest when cross-cut.

Nodes are the weakest points of all, with an elasticity modulus 40% that of the internode section (Arce-Vilalobos, 1993). Thus, it is better to use culms with long internodes. The more nodes the culm has, the less effective it is for carrying loads and the more subject it is to deformation. Size, density, tensile strength and mode of use therefore also determine how specific bamboo can be used.

The preservation process, which involves the infiltration of boron-based chemicals through the conducting vessels at the end of the bamboo culm needs to occur within 24 hours of cutting, as the culm naturally closes within 24 hours of harvesting (Janssen, 2000). Processing plants should therefore ideally be geographically close to plantations and forests to enable the successful implementation of the preservation process, though this is not always possible if plantations are located in remote regions.

Curing, seasoning, preservation processes – such as smoking, whitewashing with Ca(OH)2 to form calcium carbonate or a combined preservative and fire-retardant process utilising a cocktail of different chemicals dissolved in water – drying, sectioning, flattening and selection processes all determine the final use of the individual culm (Jayanetti & Follett, 1998; Liese, 2003; Montaya, 2005; MinAmbiente, 2010; Santos, 2015). Cutting and subsequent treatment of bamboo also affect its strength and flexibility. These factors collectively create variability in building systems using bamboo. Generally, contemporary systems include:

- Bamboo in the round in panels
- The addition of mud walls
- Use of steel joints
- Concrete infill and bases

Many of these systems can be seen in the techniques used to construct the structures mentioned above – The Residential Ensemble in Carmen de Apicala, The Indian Pavilion, EXPO 2010, Shanghai, the buildings that formed the Biennale in Baoxi, China, to name but a few. However, where technology is scarce and craftsmen often still work with their hands and their hand tools, each construction method brings its own set of specific challenges. No matter how creative the design is, the method of completion will still determine the reality of its creation. The Zeri Pavilion, which was built for Expo Hannover 2000 (discussed in more detail below), was built with a group of 47 designers and craftsmen using both modern and traditional equipment. Even though it embodies a combination of the old and the new, often only the 'old' is available. There are numerous jointing systems that can be used but where joints must be cut manually with hand tools, accuracy is contingent on the skill of the craftsman, particularly as bamboo canes rarely grow straight or predictably. This creates numerous challenges with forming neat and effective joints. Strips, laths and belts can be used for traditional connection techniques, laminates require steel and alternate fixings, but a well-made joint is inevitably stronger and more durable. Fish mouth joints can be created using a hole saw and can be finessed with a rotating roller of sandpaper. Other cuts can be formed with machetes, knives or specially designed tools but these are all time-consuming and not cost-efficient when building to scale. Whilst the rise of new technology in the developed world enables the creation of the inspirational structures described in this chapter, there remains the need for a small-scale tool that is easy to transport, use and manufacture, which could revolutionise the use of bamboo in areas in which the old ways still prevail.

The vernacular use of bamboo in Colombia has also established a traditional knowledge base of craftsmanship that contributes to innovative construction systems, particularly in relation to earthquake resistance and joint connections (Sharma, 2010), making it an ideal material to use in seismically active areas. As such, bamboo structures are now appearing around the world, utilising many kinds of supplementary and complementary materials. In Indonesia, a guesthouse building is based around an oval structure defined by ridges and beams of bamboo, covered with Alang Alang (Imperata cylindrica) (a tough resilient grass also used in thatched roofs) – a relatively simple form of bamboo construction (Minke, 2012).

In Colombia, however, La Casa del pueblo Library in Inza, Cauca, is based around porticos anchored with metal rods, covered with lightweight concrete but also with a straw roof. It exemplifies the design developed by Simón Vélez, in which the joint between column, beam and truss can transmit movement forces – ideal for an area vulnerable to regular seismic movement.

Image removed due to copyright restrictions

Image 2.11 (Minke, 2012, p. 86)

From the 1980s onwards, with projects initiated by Simón Vélez and his contemporaries, ranging from social housing, prefabricated homes costing less than a typical annual salary, to communal structures and buildings regarded as iconoclastic, the emergence of a new paradigm was encouraged. The paradigm had nothing to do with parametric design or technological advance but with vision – one in which the once 'poor man's timber' began to come back into its own. Once dwindling communities in Colombia that had comprised an ever-aging population of the unemployed and unemployable were once again repopulated, with work stemming from the use of bamboo for construction. The efficacy of such projects can be evidenced by projects such as the social housing prototypes created by Bamboo Think Tank (2015).

Traditionally, round guadua was used for the frame structure and riven/treated guadua panels or boarding was used for walls, floors and ceilings. In the 1980s, Simón Vélez started a revolution by taking inspiration from the bahareque and 'colonizacion antioquena' style to build various large sculptural structures with cantilevers and large spans. Substantial contemporary use of bamboo in construction can now be seen, in particular, in Colombia, which has inspired the use of bamboo for its structural and architectural aesthetic value (Vegesack & Kries, 2000). Measures to integrate the old and the new in terms of architectural vision and native materials continue to develop into the archetypal design structures fabricated with bamboo that we see today, some of which are illustrated below.

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Image 2.12 (Minke, 2012, p. 104)

Image removed due to copyright restrictions

Image 2.13 Connection joint with bolted connections and mortar (Escamilla, 2019)



Image 2.14 Cantilevered roof of Iglesia sin Religion by Simón Vélez

Image 2.15 Jenny Garzon bridge



Image removed due to copyright restrictions

Image 2.16 Inside the Iglesia sin Religion by Simon Velez(archleague.org)

OTHER KEY PROJECTS ACROSS THE WORLD

Structures following Vélez's practice of combining the traditional bahareque with concrete enclosure have progressed apace. The Anthrosophical Culture Centre and Church in Cali, Colombia is formed of a mix of vertical guadua culms, bamboo planks, plaster with lime, sisal fibres and concrete dust.

These base buildings have developed alongside loftier monuments, such as the Cathedral at Pereira, the bridge for Crosswaters Ecolodge and the Iglesia sin Religion, thereby proving that bamboo –long considered a poor man's material merely chosen out of necessity – could in fact be the material of choice for many purposes and people.

Other key projects around the world have also reinforced the perception that bamboo is no longer the poor man's timber. Vélez's design for the iconic Zeri Pavilion which was built in Germany, is a triumph of harmony between structure and intent (Minke, 2012). It was designed to reflect 'eloquent diversity' by combining bamboo from China, Bali, and Colombia to create a cohesive whole. Moreover, it validates bamboo as both an innovative and economical building material.

Images 2.17. 2.18 & 2.19 Zeri Pavilion designed by Simon Velez







Image removed due to copyright restrictions

Image 2. 20 La Selvia, Spain (bambusa.es)

In La Selva, Spain, washrooms combine bamboo with chicken wire, coconut fibre, straw, sawdust and cement to create a vault with a green roof. This design enables the structure to integrate with its surroundings and to create a co-identity and a practical and symbiotic relationship with the environment, whilst being environmentally-friendly.

Image removed due to copyright restrictions

In Hawaii, a Maui-based company has been developing prefabricated houses from bamboo. The Zen house can be erected in five days or fewer but it nevertheless reflects the cultural and social vernacular, mimicking local housing but in an economically and environmentally modernist way. Data for the Zen house can be found on the company's website: **https://bambooliving.com/.**

Image 2.21 Bamboo living Maui house Ohana (bambooliving.com)

Image removed due to copyright restrictions

The eco-house, built as part of the International Bamboo Architecture Biennale 2000 in Baoxi, China, demonstrates that the direction of bamboo construction can extend not only into innovation in public spaces and community buildings, but also into the smaller spaces of private housing. Moreover, bamboo construction addresses the pressing need for a greener future and better use of our increasingly limited resources.

Image: My Modern Met 'First Bamboo Biennale Creates Cutting-Edge Structures in Small Chinese Village' (world-architects.com)

Vélez's example has since led the way with many other ground-breaking designs around the world and an enthusiastic interest in bringing bamboo into use. As it is such a versatile material, able to withstand extreme temperatures and seismic activity, and excessive water ingress, while still being highly affordable and sustainable because of the speed and ease with which it grows, it has a multitude of uses with a diverse range of complementary materials. Bamboo also has another extremely desirable characteristic and one that is very relevant to our environment in the twenty-first century – it absorbs carbon dioxide and exudes oxygen in return. It can therefore also work in tandem with the global need to reduce carbon dioxide and actually help to ameliorate the greenhouse effect. Carbon storage depends on the methodology used, based on climate, species, and natural features of the plantation, but tests have indicated that guadua outperforms timber and all other construction materials in its sequestering of C02, with a significantly lower carbon footprint regardless of whether it is highly processed or less so, although highly processed products do appear to sequester more (Vogtlander & Van der Lugt, 2014).

Research institutions across several countries are now developing building systems, connections, and fabrication methods to enable a reliable and efficient construction system that is applicable to a three-dimensional building scale and able to resist fire and seismic activity, as well as to provide comfort and aesthetic appeal (Minke, 2012). Bamboo is also a quick growing material, thus making it inexpensive and renewable for the construction industry.

Other significant projects have emerged in recent decades that combine traditional vernacular construction methods with innovative computational design morphologies. The 2015 temporary ZCB pavilion in Hong Kong, for example, was designed utilising digital design methods informed by Cantonese scaffolding craftsmanship techniques, challenging the boundaries of conventional knowledge and methods. The lightweight grid shell structure, spanning 30 meters, utilised traditional hand tied methods correlated with computationally generated efficiencies of form that were derived from the physical properties of bamboo (Crolla, 2017).

Image 2.22 Base Innovation Center (BIC) in Manila – a research, testing and training facility for bamboo construction and other alternative building materials (base-builds.com)

This approach of utilising computational systems for bamboo design has emerged from the post-digital generation of design, producing revolutionary forms and material engineering.

From a global perspective, the most ambitious projects are those that aim to refine the performance of bamboo and the technical knowledge required to use it in order to advance the applicability of this material in line with the international sustainable development goals. As an example, ETH Zurich's Singapore Future Cities Laboratory has been researching bamboo composites to replace steel in reinforced concrete, which could significantly impact the sustainability of the construction industry (Hebel & Al, 2014). Another excellent example is the work underway at the Base Innovation Center in Manila, supported by the Hilti Foundation and the charity Habitat for Humanity, where over 10,000 homes have been built with bamboo by the local communities. The natural properties of the material coupled with intelligent engineering, design, training, and support, are transforming local economies and the lives of thousands of people.

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The International Bamboo and Rattan Organisation, consisting of over 40 country members across the world, aims to improve the cooperation, research, and policies in relation to bamboo design in order to raise standards, promote resilient construction, restore degraded land, and inform green policies for the wider acceptance and development of bamboo.

Another prominent architect using bamboo is the Vietnamese architect Vo-Trong Nghia. The example of Kontum Indochine Café features trumpet-shaped, prefabricated columns made of bamboo canes joined together in a low-tech fashion with rattan and bamboo nails. Steel fixings were avoided since these can generate too much load in one place, causing the bamboo to buckle. The bamboo was first soaked in mud and smoke-treated – the traditional methods for preserving wood and eliminating pests.



Image 2.24 Dezeen 'Kontum Indochine Cafe by Vo Trong Nghia Architects' (2013)



Image 2.23 Dezeen 'Kontum Indochine Cafe by Vo Trong Nghia Architects' (2013)

Ibuku, a design and building practice in Bali with over 50 bespoke buildings , involves creating very innovative organic forms using the natural properties of bamboo. The buildings are mostly handmade, showcasing the talent and ingenuity of locally trained Indonesian architects, engineers, designers, artisans and craftsmen.

A new generation of studios, led by young Asian architects, gained prominence and international awards for their creativity with bamboo. They include: Vo Trong Nghia (VTNA) and H&P Architects in Vietnam; Nattapon Klinsuwan (NKWD), Chiangmai Life Architects and Bambooroo in Thailand; Abin Design Studio and Mansaram Architects in India; Bambu Art in Bali; Atelier Sacha Cotture in the Philippines; HWCD, Penda (Chris Precht) and Li Xiaodong in China; and William Lim (CL3) in Hong Kong.

In addition, some long-established, internationally renowned architecture firms have completed projects with significant uses of bamboo. These include Japanese architects Kengo Kuma, Arata Isozaki and Shigeru Ban, London-based Foster + Partners and Italy's Renzo Piano.

CONCLUSION

Whilst bamboo is finally growing in currency and reputation, there are factors other than historical use and practicalities of use to overcome in ensuring its place in the future of architecture. Currently there is little by way of accurate inventory of species, location and volume. In Bhutan, INBAR (International Bamboo and Rattan Association) has recommended that this be a feature of future steps, alongside the development of official construction guidelines, noting at the same time that,

'...for vernacular, low-rise structures in rural settings, rigorous structural design guidelines requiring detailed calculations may prove to be unworkable in practice. Therefore the guidelines should probably focus on outlining general 'rules of thumb' and include some simple, pre-prepared design drawings. Previous research has shown that for traditional vernacular bamboo buildings, general 'rules of thumb' can provide adequate levels of safety' (Janssen 1995; 2000; Frith et al, 1997).

Also, socio-financial considerations continue to impact the use of bamboo, with it being regarded as a weed in some areas and as a protected species in others, making the supply potentially inconsistent. Further research is required into source and supply, performance, structure, application, management and how bamboo can be industrialised within non-industrial countries. Nevertheless, even with these limitations, its continued progress into the twenty-first century is already secured by the innovations that have been realised through key projects using bamboo around the world.

If current trends continue as anticipated, areas of low economic growth, slow advance in technology and seismic and ecological uncertainty will become increasingly populated. The need for safe, supportable, sustainable and financially viable housing is an undeniable truth that goes hand-in-hand with this. Bamboo would appear to be part of the solution to this challenge – prolific, low cost, low carbon footprint, and suitable within the principles of the circular economy. What then if its use could be streamlined to increase safety, technical design, and usability?



3.

DIGITAL DESIGN AND CRAFTSMANSHIP

Digital craftsmanship is a new concept that has emerged with the advent of digital fabrication, expanding on the intrinsic relationship between designing and making (Menges, 2012; Kolarevic, 2004; Carpo, 2011). It forges new dialogues between digital and physical technologies, enhancing the mind and the hand, the tool and the material. Applied specifically to architecture, it entails the process of creating form from material. This chapter examines the nature of digital methods in relation to material, fabrication and the people involved in the process, and also explores the relationships between material properties, culture and technology.

Image 3.1 ZCB Pavilion opening in Hong Kong

There are many kinds of fabrication processes, the most common being: cutting, folding, milling, punching, shearing, stamping and welding – all intended to cause a change in base materials. The relation of these processes to innovative architectural conceptualisations is discussed in later chapters, showing the manner in which innovative and precise fabrication methods can be applied to bamboo. Historically, the task of fabrication was allocated to the construction worker, rather than the designer (Carpo, 2011), but increasingly the roles of the crafter and designer are being forced to change, transforming into something more unique that combines vision with skill, technology with an instinctive feel for the potentiality of the material and how that material can transform into structures that express more fluidity and versatility than ever previously envisaged.

Fabrication has always fallen into the general parameters of construction – the territory of the constructor or the craftsmen, the practical workers – as opposed to the designer, the planner, the theoretical thinker. One conceives and the other actualises the conception. The interaction of both processes and both processors is essential to fabricate a new form out of basic material, that is to translate it into a structure of usefulness, meaning, and socio-economic significance. Between them, architects and craftsmen fabricate our surroundings from, often, the most fundamental materials – stone, stick, mud, and shape structures to reflect the cultures, beliefs, traditions and hopes that men and women aspire to. The soaring spire, the stately arch, the towering office block – these are the atmospheric, creative builds that now house our arts and museum collections, people and their activities. These builds are all material made into the image of man and his loftiest dreams, and thus through fabrication the essence of the material is changed from raw to processed, from amorphous to distinct, from unstructured to meaningful, just as the functions of materials in creating a building or structure are transformed by the mere process of combining sometimes disparate materials to create a cohesive whole.

Alongside technological progress, new methods are emerging with detail-oriented manipulation of materials and fabrication processes through parametric interrogation and digital modification. Architectural details define the conceptual and technical character of a building and not only impact the production process itself but also the method of assembly and even its ecological footprint. This new interest in architectural detailing is not merely a return to appreciating the skill of the artisan (Kolarevic and Klinger, 2008) but indicative of a developing involvement with the physical making of the building, made possible through the manipulation of digital technology. And that new 'digital master-builder' (Górczyński and Rabiej 2011) depends on '…file-to-factory processes, in which the morphology of construction details is directly related to the knowledge of the available production processes (Celani, 2014).

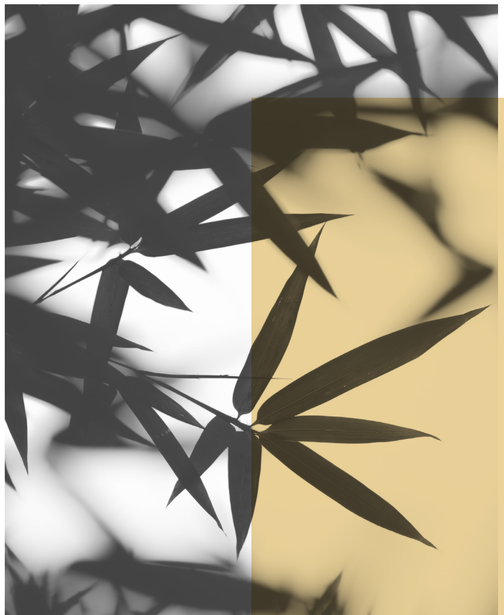




Image 3.2 Heydar Aliyev Centre by Zaha Hadid and Partners

MATERIAL AND MATERIALITY

Fabrication of course requires material with which to work. Theoretically, all material is capable of manipulation to a degree but in a world now looking beyond the ordinary, new techniques and methods of digitally-enabled fabrication are reaffirming the long-forgotten notions of craft and craftsmanship. Computation enables us to employ material behaviours and materialisation processes as a truly explorative agent in design, in which novel material and spatial effects may originate (Menges, 2016).

'Architecture provides the material context within which most of our material life unfolds. As a material practice it effectuates social, cultural and ecological relevance through the articulation of the built environment. This articulation is intrinsically tied to the processes of physical and intellectual production in which architecture originates: the processes of design and materialisation. Today the reciprocal effect of these two processes on each other can be seen through a different lens, and computation constitutes a critical factor for this contemporary reassessment of the relation between the generation and the materialization of form and space.' (Schumacher, 2016, p.78)



Image 3.3, 3.4 & 3.5 Parametric design and fabrication – ICD pavilions from the University of Stuttgart



Examples of the application of parametrics in design, such as the Heydar Aliyev Centre in Baku, Azerbaijan, designed by Zaha Hadid Architects (ZHA), and the ICD Research pavilions at the University of Stuttgart, demonstrate just how far the dialogue between material, machine and design can be taken using modern fabrication methods and parametric manipulation. The interaction between man, material and machine transcends crafter and designer to become a true synthesis of what imagination and technology can achieve in the world of creativity. With once-assumed limits now being challenged and overturned, as parametricism enables new archetypes to emerge, perhaps a new definition of materiality will likewise emerge as not so much material of fact but as material of application.



> FROM A CRITICAL PERSPECTIVE, THE CONSTRUCTION INDUSTRY TODAY IS STILL GENERALLY SEPARATED BETWEEN THE PEOPLE WHO DESIGN BUILDINGS AND THOSE WHO CONSTRUCT THEM.

In the discussions on craftsmanship, David Pye's (1968) dichotomy between properties and qualities is reminiscent of the polarization of mind and matter. Materials, according to Pye, are varieties of matter – that is, of the physical constitution of the world independent of the presence or activity of its inhabitants. Thus, the properties of materials are properties of matter and are in that sense opposed to the qualities that the mind imaginatively projects onto them (Ingold, 2007; Pye, 1968).

From a critical perspective, the construction industry today is still generally separated between the people who design buildings and those who construct them. 'Construction insight is wholly missing from the conceptualization of the design, and design insight is applied only sparingly during its execution.' (Bernstein, 2010, p.94). istorically, the implication has been that those who conceptualise, design and propose are not those who materially engage in the construction process. The architectural design process is so embedded in scaled drawings, specification, laws and regulations that the scope of works, skills and mindset are usually not those of a material craftsman. Walter Gropius argued enthusiastically against this separation and was sternly critical of the American Institute of Architects rule no. 7, which suggested that architects should not engage directly or indirectly in building contracting (Gropius, 1952). Three quarters of a century later, Deamer also iterates the dangers of the 'work aphasia' suffered by many architects in deeming themselves as the artists and deeming the constructors as the workers (Deamer, 2015). Richard and Daniel Susskind (2015) suggest that the possible consequences of the advent of enhanced technological advances may be a death threat to the professions in their current form. In this way the boundaries between professions start to fragment. Forms of practice interlace and the scope of design and fabrication, supported by technology are becoming a new form of creating yet what remains is the notion of craftsmanship. As per David Pye's (1968) definition, still widely used across the digital discourse:

'[craftsmanship]… means simply workmanship using any kind of technique or apparatus, in which the quality of the result is not predetermined, but depends on the judgement, dexterity and care which the maker exercises as he works. The essential idea is that the quality of the result is continually at risk during the process of making, and so I shall call this kind of workmanship "The workmanship of risk".' (Pye, 1968 p. 4)

The notions of predetermined and risk are critical for the judgement of the work. Digital tools have the ability to operate at a high tolerance, carrying out work that is very controlled and specific. Systems of component fabrication utilising robotic CNC tooling do not entail any craftsmanship. However, a big part of craftsmanship involves the qualitative and subjective elements involved in the crafting process that separate a normal worker from an artisan using the same tools. A material craftsman is true to the material and seeks to bring out its best qualities – a material unfolding, a development into something.

There is a relationship between the craftsman and the material that results in the emergence of an artefact. As Richard Sennet (1968) describes, there is a level of knowing and unknowing in the working process – a sublime intuitive leap allowing the unexpected to occur in both the material and the imagination (Sennett, 2009). Craftsmanship is a frame of mind combining imagination and technique. The craftsman masters the processes connecting non-linear thinking and behaviours of various systems to allow unique manifestations to take place (Jordan, 2012). The rational and the irrational join in the craftsman's mind and he must apply his own judgment to articulate and bring forth the magic.

However, does the fact that the parameters to tooling and design are set by a machine make the resulting object any less of a triumph of the skill of the human hand operating the machine or entering the data? If both digital craft and analogue craft can feed off each other in a cyclical process, the outcome is doubly skilful. Hand tools and tacit knowledge offer specific insights into our processes of conceptualising and creating. The craftsman allows knowledge to grow from the crucible of our practical and observational engagements with the beings and things around us (Dormer, 1994; Adamson 2007). This is merely extrapolated and enhanced by proficient use of modern technology. As Robert and Rivka Oxman assert:

'Architecture is reformulating itself as a profession, pointing to the fabrication of material systems as a new area of design practice and research for architects and structural engineers together.' (Oxman and Oxman, 2010, p.427)

The discussion suggests there is a need to rationalise and expand on roles – to cross-fertilise, adapt and integrate them in order to maximise the full potential of the fabricator and designer to amalgamate historical and contemporary understanding of materiality, fabrication and architectural exemplars and to move towards greater application, use and functionality – as well as aesthetic appeal.

Through the logic of craft, the material is the primary driver in the creation of the form. The maker and the material dance in a non-linear process. The maker (also a designer) has an image of a form in mind and rather than applying a material to that form (hylomorphism), the confluence of actions more naturally evolves into a morphogenetic process (Ingold, 2013; Simondon, 1992). The tool and the maker are following the material by 'entering the grain of the world's becoming and bending it to an evolving purpose' (Deleuze and Guattari, 2004, p. 452). "Making is a process of correspondence: not the imposition of preconceived form on raw material substance, but the drawing out or bringing forth of potentials immanent in a world of becoming" (Ingold, 2013, p. 31). To conceptualise ideas initiating from materials is to find 'the consciousness of the matter-flow' (Deleuze and Guattari, 2004, p. 454).

The hylomorphic model follows the principle whereby a form is an ideal, an archetype and the matter is a receptacle for those forms. Matter, in this perspective, is passive. The opposite paradigm would entail endowing matter with its own morphogenetic capacities, therefore rendering form the result of processes (DeLanda, 2009). These processes are resultant of properties (length, strength, density, etc.) and capacities that relate to the performance, adaptability and variation of the material. Morphogenesis is non-linear in a relational thinking perspective, more akin to natural biological processes.

The canopy designed for the Westend Gate tower in Frankfurt is a perfect example of how the use of digital fabrication optimises both structural performance, functionality and creative architectural detailing. The authors of the design say of it:

'…it was not designed in a conventional top-down design process, where the architect determines design and passes it on to engineers and fabricators for further processing. It was developed in a bottom-up interactive process, where all different team members agreed on a negotiated co-decision process through which they could enrich the procedure with their expertise. Architects, engineers and manufacturers were linked together in a constantly updated common flow of information.' (Agkathidis and Brown, 2013, p. 87).

The design amply reflects Deamer's assertion that, *'…contemporary practice revitalizes, through the new detail, the interest in "those who build them" and offers the opportunity to readjust the psychologically diminishing roles that all players in the design-to-build continuum have come to know…'* (Deamer, 2010, pp. 86-87).

Image 3.6 Tree structure canopy (Agkathidis & Brown, 2013)

Image removed due to copyright restrictions

DESIGN AND CRAFTSMANSHIP

The relationship between design and craftsmanship is in crisis. There is a continuing decline of craft in favour of industrial processes. This separation of skills and division of labour has existed for several centuries. It is a justified separation that has led to the quality and nature of our built environment, as well as the narrative of the history of architecture (Carpo, 2011).

This discussion about designing and making has revolved around a long-standing dilemma between material craftsmanship and the conceptualisation of the design carried out by the architect. Materials, construction techniques, joinery, stone masonry, and so on, were not considered avant-garde and were simply part of a technical discourse that was separate from arts and culture; whilst, historically, architecture, with its political power, spoke of buildings as typologies and styles (Deamer, 2015). A socio-economic shift separated the worker from those who conceptualised the object. Gradually, the roles of the architects and craftsman changed, progressively leading to a decline in craftsmen and a rise in cardboard architecture (Borden and Meredith, 2012). The practices of architecture lend themselves to a clinical relationship with materials, as the architect notationally selects, applies, and details materials as functional elements only.

'When tree trunks cease to be automatically understood as cylindrical fibrous bundles and can instead be conceived as stacks of veneer sheets laminated without consideration of wood grain, (…) we find that our nostalgic default material understanding has been fundamentally destabilised' (Borden and Meredith, 2012, p. 2).

The architectural historian and critic Mario Carpo articulated this evolution from a historical perspective, pointing to the narratives of architects like Filipo Brunelleschi (1377–1446) and Leon Batista Alberti (1404–1472): '… as the inventors of modern architecture. Brunelleschi essentially fought for his recognition as the sole conceiver and master of a major building program; and Alberti's radical claim that architects should not be makers but designers, and his definition of a modern notational system of scaled architectural drawings in plan and elevation that were the indispensable means to this end' (Carpo 2011, p. 16). Alberti's definition of architecture and of the role of the architect's mode of practice has prevailed until today.

The relationship between computational design and digital fabrication is instrumental to reshaping this relationship. Where designers once produced information on paper, to scale, that specified measurable instructions for the fabricator, digital fabrication has challenged this process. It is possible to fabricate artefacts directly from the digital 3D form to a 3D printer. The allographic, notational art no longer stands. Yet, beyond this, the notion of synthesising fabrication with design becomes even more exciting when observing the relationship between computational design and digital fabrication. The precision of the computer language is less tolerant than that of the traditional interpretation of a drawing by the maker but it has more flexibility in formulating new and radical design possibilities overall. In a sense it feels its way, computational design, to the outer limits of possibility in the same way as a craftsman, who knows his materials and tools so well that the use and application becomes almost instinctive for him. Where a carpenter would 'sense' the material's 'give and play' against the movement of the tool, the CNC tool on its own is unable to replace the craftsman's sensibility and experience. In combination, the craftsman and the computational design agents provide much more than was ever possible.

However, on the other hand, the CNC tool is capable of executing tasks that no craftsman would be able to achieve because the instruction to the robotic fabrication CNC tool is highly precise. A complex geometrical form might be too difficult for a craftsperson to execute because, firstly, the notational design process (drawing-based) is difficult to describe, and, secondly, the form is difficult to execute. For the CNC tool, there are fewer limitations.

> 'ARCHITECTURE AS PRACTISED AS AN AUTHORIAL, ALLOGRAPHIC, NOTATIONAL ART HELD SWAY UNTIL VERY RECENTLY, AND DEFINES MANY IF NOT ALL OF THE ARCHITECTURAL PRINCIPLES THAT THE DIGITAL TURN IS NOW UNMAKING.'
>
> *(Carpo 2011, p. 44)*

Utilising digital fabrication technologies, designers can probe into and evaluate their designed building components or full-scale building prototypes. The new tools provide new techniques for the production of building components out of either commonly used or new construction materials. Specific characteristics distinguish digital fabrication from traditional craftwork. In accordance with the concepts of embodied and distributed cognition, digital fabrication tools should not only be able to produce precise, complex and elaborate products but must also perform effectively as a design to fabrication tool for digital designer-makers (Sharif, 2015). As Clark (2001, p.122) states: 'the true power and beauty of the brain's role is that it acts as a mediating factor in a variety of complex and iterated processes which continually loop between brain, body and technological environment. And it is this larger system which solves the problem.' In both manual and digital fabrication domains, the technological environment is comprised of tools and materials. The CNC and robotic tools and the CAD/CAM systems that are currently adopted by designers were all originally developed for engineering product industries (Kolarevic, 2004). These technologies have been developed for industrial mass production of components with known problems and processes and predictable outcomes. In traditional craftwork, the craftsman initiates the design task with only the pre-conception of the design object and design process, permitted by the under-constrained fabrication setting; instead, in digital design and fabrication processes, which operate within more constrained environments, the digital maker has a comprehensive view of the design object and embeds detailed design and machining data in the digital model before the start of the fabrication phase (Sharif, 2015). As a result, the process of design to fabrication is mostly a one-directional workflow, starting from creation of a geometric CAD model, to the development of a CAM model, based on both geometric data and machining setting, followed by the transfer of machining data to CNC tools and setting up material on the machine, to the final production by the machine. Although there are some levels of interactivity in the initial stages of CAD/CAM model development, the designer would have no control over the process of fabrication once the machining process starts (Sharif, 2015).

Digital fabrication processes can preserve the logic based on the material. Rather than geometric form generation preceding the materialisation, material properties can be used in geometric form generation (Menges, 2012b). Digital fabrication allows for increased speed, scale, precision, and complexity and provides the opportunity for repetition and production of multiple instances of the same object. It can be concluded that digital fabrication technologies are bringing us closer to the reality of a designer as a maker and therefore future CNC machines have to assist designers in explorations and creativity, acting as a smart collaborators in the design to fabrication processes (Sharif, 2015).

The performance of the material provides a feedback system to the digital model so that the design becomes organic, based on the abilities and capabilities of both the material and the tool. Whereas in the traditional method the drawing and the made object were not directly connected, the digital model precisely correlates to the performance and capacity of the material fabrication. In this way, digital practices are increasingly designing and making at the same time. Crafter and designer become interchangeable, symbiotic. Thus, digital processes would appear to reduce the distance between the architect-thinker and the craft-maker in a manner unlike mere human interaction and discourse. Ironically, machines are creating an interface between man and man that man has been unable to effect for himself.

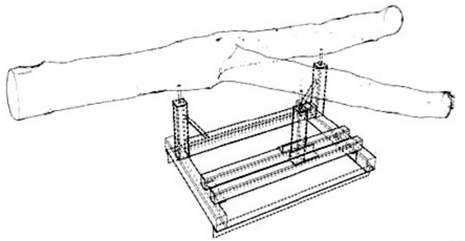
Examples of such synergy between man, material, design and machine can now be found worldwide. Some of the most exciting of these involve the use of neglected materials and new technologies and design systems to areas in which there are significant issues in creating structures that both function effectively and respond to the environment and socio-cultural needs of their users.

An exceptional example that illustrates an interplay of craftsmanship, material and technology innovation is the Wood Chip Barn project by the students of Design + Make at the Architectural Association's Hooke Park campus. In particular, this project illustrates a fabrication methodology through which the inherent form of large non-linear timber components was exploited by using 20 distinct Y-shaped tree forks ,with minimal machining, for the construction of a structural truss. Through this workflow, low-value branched sections of trees are transformed into complex and valuable building components using non-standard technologies. Computational techniques, including parametric algorithms and robotic fabrication methods, were used for the execution of the project. The project examined the various challenges encountered when processing irregular material, as well as limitations of the robotic tools (Devadass et al, 2016). The project demonstrates new methodologies for working with irregular materials within complex, large geometries requiring innovative approaches to design flow and craftsmanship within digital and non-digital workflows.

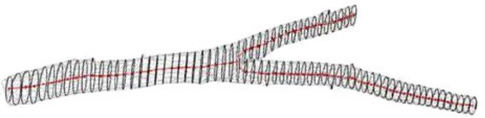


Image 3.7 Wood Chip Barn fabricated from non-standard Y shape tree trunks at the Architectural Association's Hooke Park campus

Image 3.9 Fabrication of the joint connections at the Wood Chip Barn at the Architectural Association's Hooke Park campus



5





7

5 Diagram of a fork with 3 points/pins, trolley, rail.

6 Extraction of centre-line.

7 Fabricated geometries: Truncated cone shaped tenon and mortise.

Another example is Hong Kong's 2015 'ZCB Bamboo Pavilion', by Kristof Crolla and Adam Fingrut of the Chinese University of Hong Kong. The project critically evaluates protocols set up to deal with errors resulting from precise digital design systems merging with inconsistent natural resources and onsite craftsmanship. In particular, the research investigates protocols, construction drawings and assembly methods developed to allow for the incorporation of large building tolerances and dimensional variation of bamboo. The research concludes that computational architectural design is needed to operate proactively within a field of real-world indeterminacy. Thus, greater focus is required on the development of protocols that deal with imperfections, to redirect design from the virtual world towards the latent opportunities of the physical (Crolla and Fingurt, 2016), as discussed later in this thesis.



Image 3.10 Bamboo scaffolders using traditional construction methods on the advanced geometrical design of the ZCB Bamboo Pavilion, Chinese University of Hong Kong.



Image 3.11 ZCB Bamboo Pavilion, a light-weight bending-active bamboo gridshell covered with a glass-fibre-reinforced plastic polymer membrane. Chinese University of Hong Kong.

The examples above focus on bamboo and its use, in line with the focus of this thesis, but there are many other materials being similarly tested and adapted in design to create a new paradigm that is not only functional but also beautiful, exciting and a confluence of craftsmanship and design, such as the Aviva stadium in Dublin. Here the geometric principles of the structural elements were defined in the parametric model and combined with an understanding of the fabrication constraints to create a building that is,

'…responsive and empathetic to the surrounding neighbourhood. It has an organic translucent form, allowing the maximum amount of daylight into the seating tiers and onto the surrounding environment, whilst minimising the impact of the new stadium on existing buildings. The form of the exterior skin envelops both the roof structure and the façade structure, combining both elements into one controlling form. This concept emphasises the importance that the form of the building had in the design process, as it needed to accommodate all tolerances and technical requirements of both the façade and the roof elements into one three dimensional set-out model' (Shepherd, Hudson and Hines, 2011, p.169).

The structure is a true homage to the success of parametrics and interrogating materiality to fabricate for the future.

The digital design process has significantly evolved over the last decade with the evolution in design tools from graphic design to 3D self-generating problem-solving algorithms. The computer has also begun to design; unlike physical models, computers incorporate the variable of time through the nature of their animation and their own growth or metamorphosis as well as external factors, which are continually modifying the needs of the structure being designed (Menges, 2006).

Designers who work with and are inspired by materials, techniques and forms originating from traditional contexts learn from the craftsmanship inherent in the methods, symbols and forms, and translate these into their work. This is a constructive process that brings additional value and meaning to the new work. This cultural transfer has always occurred throughout the history of design and construction. When the task of completing the long-unfinished dome of the cathedral of Santa Maria del Fiore was awarded to Brunelleschi in 1436, he drew on both existing architectural wisdom, evidenced in the great dome of the Pantheon, and

Image 3.12 Aviva Stadium Dublin – Scott Tallon Walker; Populous & Buro Happold



other ingenious innovations, such as the use of the catenary arch for support and internal horizontal stone and iron chains in octagonal formation to keep the dome rigid. Though the understanding of physical laws and the mathematical tools needed for calculating stresses was still many centuries into the future, Brunelleschi relied on intuition (King, 2013), resulting in large-scale models that, in a sense, mimicked contemporary 3D design methods, and in the innovative use of a combination of sandstone, marble, timber and brick. The hoisting machines that he devised for manoeuvring over 37,000 ton of material are his gift to contemporary architect's but his inspired use of historical knowledge, material, method and design is also a triumph of the craftsman as designer.

Thus, the value of culture is important in the definition of craftsmanship. Material culture is inextricably linked to tradition, people, places and emotions (Marchand, 2007). It is not only about the craft objects, as carriers of utility, beauty and meaning, but also about the makers and their relationship with a material and the environment (Greiner, 2016). Specific material (bamboo, for example) has a distinctive relationship with people and their culture. The methods, techniques and aesthetics of produced artefacts or buildings have a direct correlation with the place, the people, their traditions and the environment. Traditional architecture is the spatial expression of a traditional heritage that is passed down from one generation to another (Oliver, 1989).

From a cultural expression, structures can reflect vernacular traditions and these contribute to new dynamic solutions and possibilities. New technology can enable an improved use of existing resources and can offer opportunities to adapt those resources to the socio-economic situation within which they are used.

'I believe that a more dynamic approach that views tradition as a conscious and creative adaptation of past experience to the needs and circumstances of the present will significantly broaden the scope of the field of vernacular architectural studies, allowing for studies that focus on new and emerging traditions as well as enduring ones and, crucially, on the ways in which they interact and relate to one another…' (Vellinga, 2006, p. 83)

In the case of bamboo, we can observe cultural and regional differences in the way it is crafted. Whether it is applied to furniture, a house, a church or a stable, the quality of craftsmanship, detailing and symbology will vary as a result of the cultural context. Concrete has become present in most urban developments around the world and is recognised as a modern expression of architecture. Bamboo, on the other hand, has a more particular expression associated with rural, undeveloped buildings, poor people's housing, and expressions of ecological design and sustainability. This perspective changes depending on the geographical, social and cultural context (Minke, 2012).

The role of the post-digital architect is thus not to become the craftsman but to go beyond – to continue as the coordinator whilst also employing the skills of interpretation, aesthetics, refinement and application, to become symbiotically forward-moving, creating a synthesis of craft, culture, creativity and technical application as the process of transformation continues, to become 'the enabler', as envisaged by Paul Oliver (1998), focusing on the methods, tools and material processes, with particular care for the and the environment.



4. METHODOLOGY

INTRODUCTION

The aims and objectives of this research project have been formulated around the methodological principles of research by design. In essence, the most effective set of methods to determine new possibilities for using bamboo include a design process that engages in limitations and possibilities of bamboo. Though the design process could be externally observed, actively positioning the researcher as the designer renders a richer and comprehensive outcome and understanding of the analysis (Borgdorff, 2005).

The research by design enquiry has developed by well-established methods used in the field of architecture (Thomsen and Tamke, 2009). It included a combination of iterative scaled physical and digital drawings, prototype model testing, documenting sketches, case study analysis, diagrams, interviews and photos, which, in conjunction with textual research, collectively produce a theoretical design enquiry that meets the aims of this research project to contribute to the advancement of bamboo in construction.

Image 4.1 Bamboo crafting by Roger Martinez

The synthesis of material culture, anthropology, digital fabrication, bamboo and bamboo architecture, which was identified through a literature review, served as the basis for a conceptual framework and for the design enquiry, precedent analyses and fieldwork investigations.

Bamboo, because of its unexplored potential for the construction industry was used as a focus to guide the examination of the interaction between the mind (the cognition, spatial and material-cultural experience of designers), tools (digital, non-digital, drawings, etc.) and matter (material behaviour and performance). The research also focused on different architectural scales, human processes in working with the material, and the use of architecturally scaled bamboo structures, as well as on analysing the detailed technical components. The research considered precedent studies of similar projects in parallel to physically constructing and manipulating the material in different design environments (in-studio, field workshops, digital software, drawings, diagrams, etc.).

Digital technology is not intended to be a primary focus of research but instead a vehicle for notating and instrumentalising the intricate relationship between form, material, structure and ultimately space (Hensel & Menges, 2006).

Image 4.2 Ricardo Assis Rosa interviewing Carlos Correia from the Universidad Javeriana, Colombia.



Historically, there has been a disassociation between digital design and construction, and currently new means are being developed to facilitate a closer relationship between conceptualisation and production, particularly exploring new ways of engaging in materiality and performance (Kolarevic, 2004; Menges, 2006a). Through investigating digital fabrication with bamboo, the aim is to let the nature of the material determine the path of investigation, informing the conceptual development, the tool and the architectural form.

The fieldwork fabrication in Colombia, literature review and precedent analysis identified the existing tools and methods used in traditional and contemporary constructions using bamboo. The fieldwork (detailed in Chapter 7) was based in Colombia, which traditionally uses Guadua for the construction of houses and other architectural structures and where cultural meanings are derived from the social and environmental context of the building material. There is an active transmission of traditional knowledge from one craftsman to another as to how to work with Guadua, enhancing the engagement with the material at an architectural, spatial and cultural level (Santos, 2015; Hidalgo-Lopez, 2003).

Contemporary architectural practices in Colombia include cultural-material layers in their design and specification processes that are tailored to working with Guadua (discussed in Chapter 2). Thus, the research examined the importance of the role of the designer and maker, specifically with regard to material and procedural knowledge, within the broader theoretical context of architectural production. Focusing on Colombia enabled the study to consider the cultural, social and environmental contexts of Guadua architecture. By analysing case studies and precedents in Colombia, aided by the conceptual and theoretical framework, the research determined parameters of enquiry for the design investigations and propositions. These design processes aimed to contribute not only to the development of innovative applications of bamboo through digital fabrication methods but also to an anthropological analysis of the relationship between maker and material. Details of the resulting fieldwork and subsequent design application are covered in Chapters 7 and 8.

Image 4.3 Ricardo Assis Rosa Interviewing Simon Velez.



Image 4.4 James Palmer working with the digital fabrication tool in colombia on the research fieldwork.



Image 4.5 Roger Martinez guiding us throught the technicalities and details of the base of bamboo column.

ACTION RESEARCH AND RESEARCH BY DESIGN

This research thesis uses various methods, some of which are described in the literature as 'action research' (McIntyre, 2007). This approach integrates action and research, whereby the researcher is actively creating the conditions that are being analysed. Similar to the design process, action research is iterative, with its efficacy contingent on a constant process of revisiting the problem, re-analysing it and synthesising revised solutions (Swann, 2002). The goal of action research is to develop practical and relevant solutions to the problems identified. This goal distinguishes action research from other forms of research that primarily seek to develop new theories or to produce new knowledge about phenomena in the world (Crouch & Pearce, 2013). Therefore, action research allows the researcher to be involved in the research in a practical, as opposed to theoretical, manner.

Action research was chosen as the methodology for this thesis because it has many similarities with the design process. A traditional design process, outside of an academic context, is overly subjective at times and lacks rigour. Many practitioners use the term 'research' to mean 'searching' and essentially focus on the final object rather than on legitimising the research process itself. The act of designing *"needs to be more self-critical and more systematic in providing evidence of the process of creating from beginning to end, with methodologies in place for objective evaluation."* (Swann, 2003 p.10).

Design research is a difficult term to define and varies based on the author's background, perspective and context; different descriptions focus on characteristics and nuances that change the nature of the definition. A suitable working definition of architectural design research is presented by Murray Fraser as:

"... architectural design research can be described as the process and outcomes of inquiries and investigations in which architects use the creation of projects, or broader contributions towards design thinking, as the central constituent in a process which also involves the more generalised research activities of thinking, writing, testing, verifying, debating, disseminating, performing, validating and so on" (Fraser, 2013 p. 1).

Image 4.6 Roger Martinez and Oscar Giraldo teaching me to craft bamboo joints.



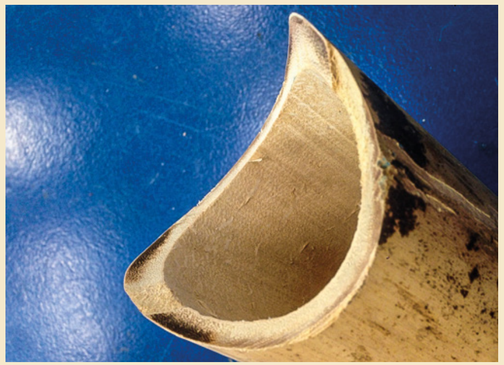
This definition clearly encompasses a 'woven' mode of operating between 'designing' and 'researching', making the act of doing inseparable from pejorative definitions like "what designers do is 'not' research" (Groat, 2002 p. 102). Arguably, not all design activity aims to contribute to novel knowledge yet it is nonetheless important to establish that research by design can result in:

"The creation of new knowledge and/or the use of existing knowledge in a new and creative way so as to generate new concepts, methodologies and understandings" (Classification for research by the Excellence in Research for Australia, based on the 2002 Frascati Manual cited in Fraser, 2013, p.2).

Donald Schon has held a long-standing philosophical position in the characterisation of the architectural design process since publishing The Reflective Practitioner in 1983. He is still widely referenced in current literature that describe the design process.

"...doing and thinking are complementary. Doing extends thinking in the tests, moves, and probes of experimental action, and reflection feeds on doing and its results. Each feeds the other, and each sets boundaries for the other" (Schon, 1983, p. 280).

Image 4.7 Fish mouth end piece milled using the CNC machine developed as part of this research project.



The discipline needs to move beyond the limited descriptions of Schon (Webster, 2008) regarding "how design works" and instead view design research as something distinctive from Schon's 'reflective practitioner', as the latter does not take into account the key process of knowledge creation in architecture (Fraser, 2013). More useful definitions stem from the 'front line' of design. Designers, architects and theorists who are confronting the current reality of research and design, contributing to state of the art modes of practice, are arguably the true definers of "how design works". From the line of the controversial parametric design movement, Patrik Schumacher has launched Parametricism 2.0 to address the flaws of digital form-finding architecture, with more emphasis on functional principles and societal purposes. He states: *"Design research should continue, but must become more strategic, applied and performance oriented"* (Schumacher, 2016, p. 12)

This thesis combines a design proposition and a theoretical framework, creating an important dialogue between modes of research. The final aim of the research is to create new knowledge and understanding for current practices. In this way, the interplay between the 'written' and the 'designed' is merely a strategic approach to finding new ways of looking at 'a reality'. Action research and design research both include the researcher within the framework of inquiry, using the unique abilities and skills of the designer to develop the work. Designer-researchers differ from other researchers through the use of specific tools and methods, operating in a visual form by utilising graphics, drawings, diagrams, physical and digital models as tools for analysis. Architects operate with a more specific set of tools and further distinguish themselves from other designers and artists through the use of multi-scaled studies and precedent case studies that are specifically centred around the human occupation of spatial-technical form in our physical environment. The important point, as summarised by Swann (2002), is that *"a visual form is a form of knowledge. It is a means of encapsulating ideas and, indeed, some ideas are expressed more powerfully through the visual medium than via any other form of communication"* (Swann, 2002, p. 52).

As Swann states, *"The 'act' of designing is a problem-solving 'performance' that is not necessarily the same as research and analysis"* (Swann, 2002, p. 52). Action research can be used to appraise one's own way of practising, providing insights that can critically transform the nature of practice. In this way, action research is research in and for action (Crouch & Pearce, 2013). Arguably, all professionals engage in the process of questioning, analysing and reflecting. However, action research is distinct from other such forms of reflection in that it is deliberate, planned and systematic, with a clear purpose and deliberate strategies for moving from reflection to research (Crouch & Pearce, 2013). In *The Handbook of Action Research: Participative Inquiry and Practice* (Reason & Bradbury 2012), the editors explain:

"good action research emerges over time in an evolutionary and developmental process, as individuals develop skills of inquiry… [it] leads not just to new practical knowledge but to new abilities to create knowledge. In action research, knowledge is a living, evolving process of coming to know rooted in everyday experience; is it a verb rather than a noun" (Reason & Bradbury 2012 p.92).

With action research in mind, this project was carried out through a series of design investigations rather than predetermined projects. Each of the investigations was carried out in response to findings and reflections from practical work and complementary theoretical explanations. In particular, this thesis questions the role of the architect in the process of making. This approach allowed me to move beyond my original assumptions and ideas and to reflect on my own practice while conducting the investigations. As Swann suggests, *"because of its inherent flexibility and openness, action research is a particularly suitable methodology for a design project where the final outcome is undefined"* (Swann, 2003, p. 58)

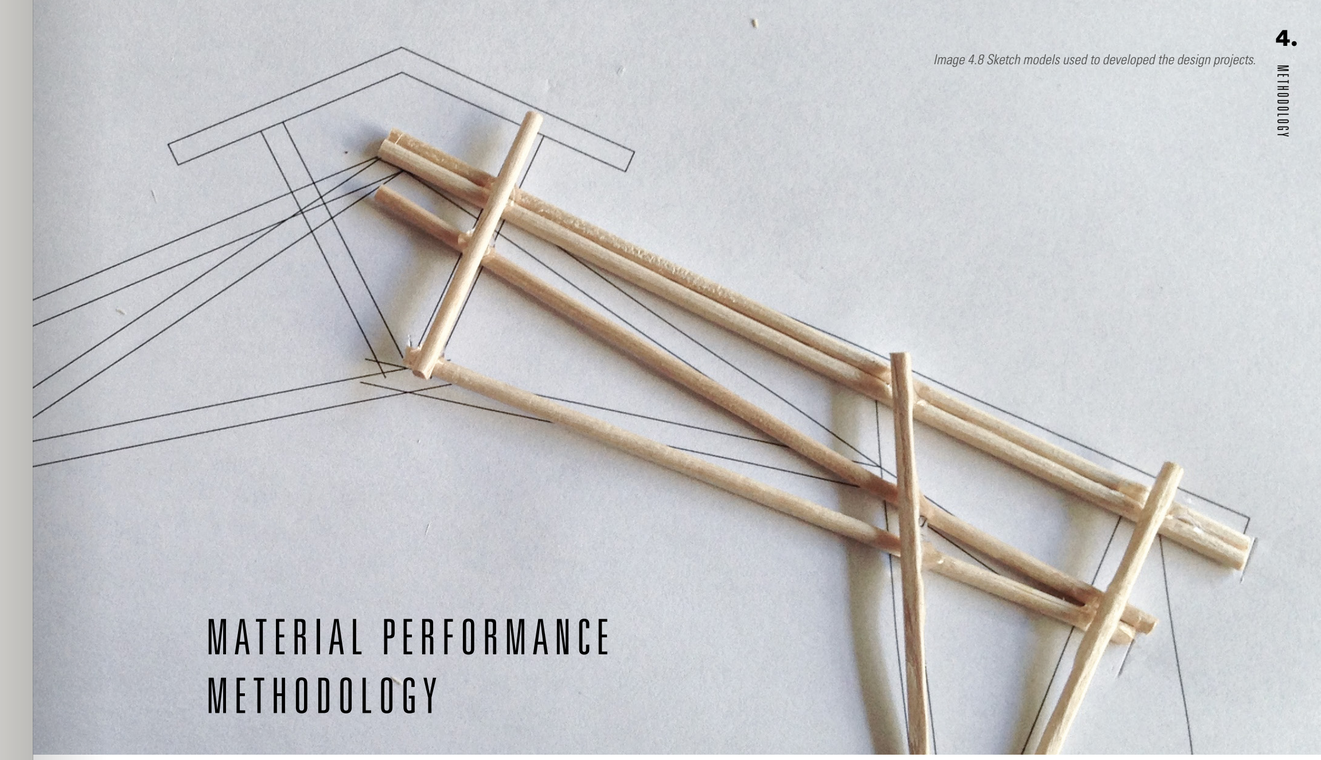


Image 4.8 Sketch models used to developed the design projects.

MATERIAL PERFORMANCE METHODOLOGY

As this thesis aims to contribute to the applicability of bamboo, the design methodology is critical to achieving innovative solutions. This innovative approach to the applicability of bamboo for architectural scaled applications distinguishes this project from existing research projects on bamboo, which have focused primarily on engineering rather than the applicability of the material in an architectural design framework. Importantly, the underlying premise implies that the way in which architects, designers and craftsmen have historically conceptualised and constructed bamboo structures is limited and its potential for advancement had been exhausted, as outlined in chapter 3. This traditional methodology has limitations from the perspective of digital parametric fabrication methodologies.

This research promotes an approach that can enable architects to exploit the resources of computational design and manufacturing through the development of performative capacities and spatial qualities inherent in the material systems" (Menges, 2012, p.44). As Menges summarises, "[w]hile in most architectural design approaches a scheme is conceived and drawn, modelled or even digitally generated as a construct of geometrically described, inert parts, in computational design material elements can be defined by behaviour rather than shape." (Menges, 2012, p. 45). As such, the objective of the research is to broaden the definition of bamboo beyond how it has traditionally been perceived. Thus, the study will engage in a holistic analysis of material parameters, environmental performance, spatial resolution, socio-cultural and technical perception, considered in detail in Chapters 7 and 8.



Image 4.8 Ricardo Assis Rosa and James Palmer setting up the digital fabrication machine at the site of the research fieldwork.

CONCEPTUAL METHODOLOGICAL PRINCIPLES OF THIS RESEARCH PROJECT

By closely reviewing the literature, conference materials and pilot fabrication projects, I was able to establish the key issues and research topics in computational design and digital fabrication.

During my field research visit to Colombia in 2014, I visited research facilities at Los Andes University, Universidad Tecnologica de Pereira and processing and fabrication plants, and I met with key engineers and architects. This visit afforded me a strong basis to develop the aims and research questions and to contribute to extant knowledge.

The objectives were established by creating a project that integrates computational principles with traditional knowledge. This evolved from evaluating existing methods of working with bamboo and proposing solutions to the problems identified and known within the field of bamboo architecture.

Over the last half century, many commentators have highlighted the distinctiveness of the knowledge, skills and values that underpin craftwork (Dormer, 1994; Frayling, 2011; Adamson, 2013) and that give rise to a 'workmanship of risk' (Pye, 1968). More recent literature places particular emphasis on the embodied and situated practices that take place in local environments (Parolin & Matozzi 2013; Gibson, 2016). The fieldwork carried out in Colombia provided an ideal opportunity to work with local material and craftsmen. The process entailed fabricating a small pavilion on the fieldwork in Colombia with three different methods of construction, one being the proposed digital system, which enabled a series of points for analysis and comparison.



Image 4.9 Ricardo Assis Rosa and Roger Martinez assembling the research pavilion at the site of the research fieldwork.

Image 4.10 View of the digital fabrication machine milling a fish-mouth joint.



With the experience gained from fieldwork, the aims of the research became clearer. The digital machine became a central methodological tool (Chapter 7) as it shaped the scope of the thesis – in particular, the fieldwork testing and interaction with existing craftsmanship and the subsequent validation for the design applications.

The fabrication of the digital tool was guided by the problems identified in traditional bamboo fabrication using hand tools. Thus, the tool was created using simplified technologies of more industrial machines, through a design process of testing and iterating the prototype until a successful solution was found.

The main aim of the fieldwork was to test the usability of the machine in the context of a live project and to develop a method for investigating how contemporary bamboo craft practitioners engage in their processes. Rather than testing principles of the machine in a laboratory setting, the objective was to test these with the people and the environment, for which the tool was designed.

The CNC machine which developed as a response to the limitations identified in the first visit to Colombia, through research workshops, interviews and literature, structured this research project as this technological system became the central methodological tool for discussion and analysis. The fieldwork itself was an opportunity to test ideas on making and fabrication, craftsmanship, design, conceptualisation and materialisation. This lead to conclusions and principles which established the basis for validating the design propositions presented in Chapter 8.

The conclusion from the fieldwork provided an understanding for future research and development and importantly corroborated the premises established in the research and the validated design proposals. Overall, the contribution to knowledge is evidenced by the successful application and development of the principles set out in the proposed fabrication system to advance bamboo for architectural construction.

METHODOLOGICAL SUMMARY

In summarising the research methods utilised in this research project, the image 4.11 diagramatically explains the key principles and approaches. The literature review established the ground basis for the work in contextualising the vairous fields of study and identifying key opportunities for discussion and to highlight the gaps in knowledge and of practice. This included the analysis of architectural case studies and construction detailing which highlighted the focus and understanding of this research project. Through the fieldwork and interviews there was a possibility to validate principles and test hypothesis. This enabled a more focused project where the aim was to resolve the technical challenges faced by bamboo and the construction industry. Once the CNC machine emerged as a solution to the problems identified and the way in which this technology could interact with the existing craftsmanship, the research required a more practical approach. Active research became the natural way of further engaging in the process as designing, making and testing through lab work at the university and fieldwork in Colombia. The collective participation of all individuals in the research process gave a richness and a depth which otherwise would have need lost.

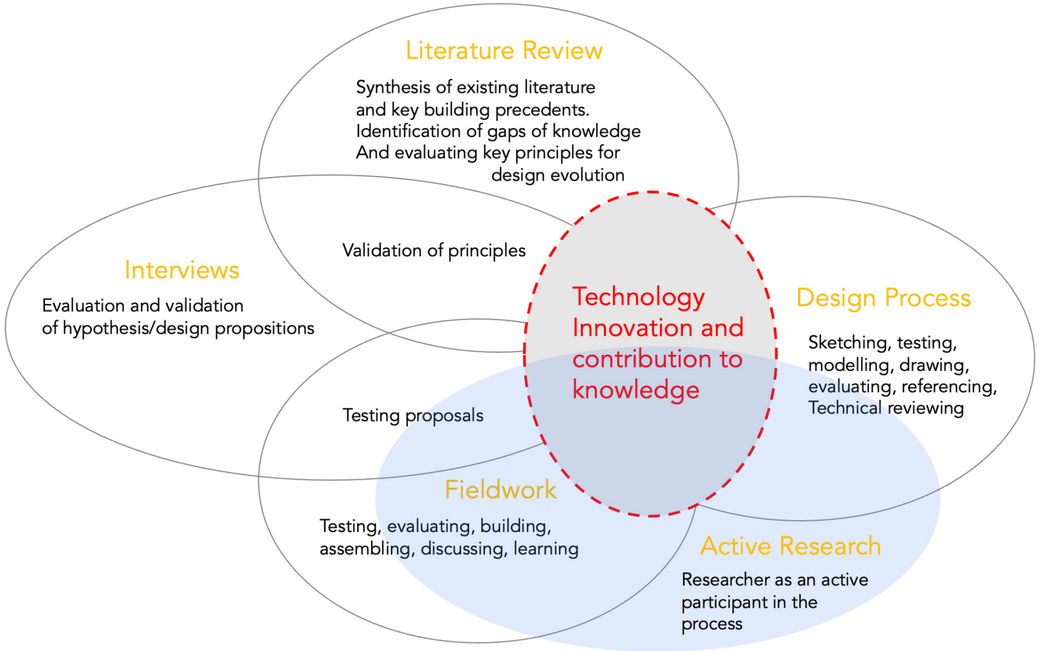


Image 4.11 Diagramatic overview of the methodology applied to this research project

5.

BAMBOO AND DIGITAL FABRICATION



INTRODUCTION

Bamboo presents an exciting new design and construction alternative to more conventionally used materials, with firmly rooted cultural and historical significance across Asia and the Americas. Historically, Guadua, the bamboo species that is the focus of this thesis, has been utilised as the preferred construction material by the indigenous population of Colombia. It has an established place in the region's architecture because it is readily available locally, economically viable and valued historically and culturally.

The engineering of bamboo more generally and Guadua specifically is a complex, delicate and precise process. Guadua can produce some of the strongest and most exciting structures but requires unique design and fabrication methods in order to produce optimal results. One of the key challenges of using bamboo is the level of technical expertise that craftsmen require throughout the construction process. Joints are considered to be the most critical structural weakness, which gives rise to complications in construction. With the advent of technology and increased confidence and interest in Guadua as a material for the modern world, many innovations in design and applications using Guadua have emerged. Such developments necessitate sophisticated and comprehensive planning and crafting that exceed that which local craftsmen can offer using basic tools. This research project seeks to address some of these challenges, offering innovative methods within the social, technical and economical context of bamboo in Colombia.

This chapter provides an overview of the issues arising from the use of Guadua as a construction material, the digital technologies that might be used to overcome these issues, and a review of existing projects that combine digital fabrication techniques with bamboo construction.

CONSTRUCTION CODES

The current shortage of building codes, regulations, guidelines and established practices adds to the difficulties of using bamboo for construction. Despite the current lack of an international building code for the use of bamboo in construction, regulations from individual countries set some standards. *The AC162 Acceptance Criteria for Structural Bamboo, California,* US issued in March 2000 by the ICBO Evaluation Service, Inc., sets out how to test bamboo structures and how joints should be constructed. Similarly, the International Network on Bamboo and Rattan (INBAR) issued a set of general regulations on detailing, including how to deal with the parameters of moisture content, compressive strength, tensile and bending strength and the measurement thereof. The Indian building regulations *(National Building Code of India, Part 6: Structural Design, Section 3: Timber and Bamboo)* also established guidelines for permissible strengths for construction, such as the strength of bamboo members and their joints across the range of bamboo varieties found in India. However, the most detailed guidelines for working with bamboo hail from Colombia, including details on the physical and mechanical properties (ISO 22157-1), seismic strengthening (NSR-10), drying and preservation (NTC 5300 and 5301), structural jointing (NTC 5407) and the terminology applied to bamboo and its miscellaneous processes (NTC 5727), amounting to a significant knowledge base.



Image 5.1 Zeri Pavilion by Simon Velez – prototype built in Colombia for the Hannover Pavillion 2000

Establishing reliability for the entire construction process is therefore an ongoing process, with specific parameters for each individual building. As part of the process of gaining construction permission for the Zeri Pavilion at EXPO 2000 in Hanover, tests were undertaken to establish compressive and tensile strength, ultimately establishing that a 3.5m long Guadua culm with a 10cm cross-section and 1.5cm-thick wall could sustain a load of 7040kg. A key element that facilitated this testing process was the previous construction of a prototype in Manizales, Colombia. This prototype provided construction calculations and therefore served as a structural basis that allowed planning authorities to evidence its structural viability (zeri.org, 2015).

Quality remains an ongoing issue wherever bamboo is used in construction. Whilst bamboo can be used to fabricate unique and complex structures on account of its lightness and low mass-to-flexibility ratio, compared to wood, its structural behaviour can vary widely. Age, moisture content, variations between parts of the stalk used, treatment, sensitivity to light, fungal and pest attack, the inherent tendency of the culm to *never* grow straight, the faster dulling of crafting tools, and the need to obtain individual structural calculations related to each piece of bamboo used, all render bamboo a complex material with which to work (Minke, 2012).

A FRAMEWORK TO VALIDATE DIGITAL FABRICATION

Image removed due to copyright restrictions

Image 5.2 Zeri Pavillion – Drawing by Simon Velez – Expo Hannover 2000

So why use bamboo? For precisely many of its features delineated above. Complex, intriguing, intuitive, adaptable, environmentally-friendly, bamboo has a place in cultural history but is also increasingly gaining a place in modern design. For example, bamboo is ideal where seismic activity requires flexibility yet strength, where extreme temperatures require resistance to degradation, and where economic limitations require cost-efficiency. Bamboo is also ecologically sound and does not disturb the surrounding environment – indeed, it is proactive in sustaining and enhancing the environment. The challenge is to apply this complex yet simple material to an architectural form that responds and correlates to a context, a specific site or the environment itself – to create a form with a function or to embellish a building to enhance its structure.

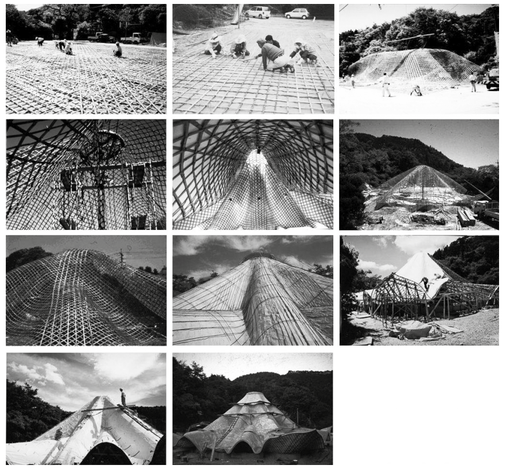
The Kindergarten and Community Centre, built in Naiju, Japan, is an excellent example of applying bamboo to create an architectural structure that is expressive of the local community, both functional and beautiful, and that responds to local cultural, historical and environmental needs. It is a blend of old and new materials, utilising the flexibility of bamboo to achieve the extreme curvature of the design, and utilising concrete for rigidity and solidity (Minke, 2012). Initially, a bamboo framework is constructed and overlaid with a protective membrane. These layers are subsequently reinforced with concrete. The curving form and graceful outline of the resulting structure are representative of the exemplary traditions of iconically beautiful Japanese structures. The curvilinear structure, apart from being a unique piece of architecture in its own right, is also strong, practical, and welcoming to the whole the community (Minke, 2012).



Image 5.3 & 5.4 Naiju Community Center & Nursery School, Chikuho, Fakuka, Japan. 1994

The overarching difficulty of designing and constructing buildings with bamboo lies in the constraints and opportunities of the existing systems related to craftsmanship and tooling, as well as the multiple scales of application, from vernacular to industrial methods. Traditionally, an architect would design by creating 2D drawings to scale that represent the proposal. A structural engineer would interpret the drawings in terms of mathematical calculations to establish loading and resistance of materials, determine stresses, tolerances and formulate a structural design plan from which a 3D scale model would ensue. The Zeri Pavilion was designed and constructed using this tried and tested method. Eventually, this system developed, alongside evolving technology, into a more advanced design methodology using 3D digital models that apply parametric relationships linked to structural analysis.

With bamboo, an innovative approach can be developed in which there is an integral relationship between digital 3D design and fabrication, to use bamboo efficiently and effectively in construction. Bamboo as a material is variable in quality, consistency, control and craftsmanship. For a digital methodology to function, there needs to be a relationship between digital and non-digital methods, expressing the experience and knowledge of traditional craftsmanship with CNC machining suited to the social and economic context.



DIGITAL FABRICATION AS A SOLUTION

If bamboo is to advance further into the modern construction industry, designing with bamboo cannot simply rely on traditional methods but instead requires a revolutionary design paradigm. Using digital fabrication and parametric design, bamboo can bend, transform and mutate into a plethora of unique forms, curvatures and spaces. Aesthetic judgement can be related back to social and cultural needs whilst also integrating environmental, technical and structural elements. Innovative methods of fabrication can be formulated for appropriate jointing and suitable combinations of materials, as well as tailored to specific styles and types of bamboo elements: planks, canes, strips, laths, belts and laminated pieces. Digital design and fabrication methods so far enable an efficient transition from design to structure that is far more comprehensive than that provided by traditional 3D model structural analyses. These methods also enable both the designer and the construction worker, before, during and after construction, to evaluate and analyse how the design, materials and sequences might function, and with which tooling. By establishing a system that advances bamboo in architectural construction and that enables a strong relationship between designing and the tools required to construct with bamboo, we can create a design methodology that can adapt itself to existing constraints and limitations, thereby enabling both the designer and crafter to innovate and improve the construction process.

Digital design and fabrication are key to working with bamboo, enabling the building to evolve in response to the characteristics of the material and the people constructing with it, together with the application of available technology. With the advent of sophisticated systems that are able to quantify and qualify each element of design and the material utilised in the construction of that design, the potential of bamboo is actualised: its flexibility can be tested and enhanced; its tensile strength can be challenged to extremes; its weakness can be quantified and supported; and its versatility can be employed in inspirational and intriguing designs, reflecting both its uniqueness and its symbiosis with the natural environment. Designing with bamboo in mind thus becomes a process built around the material itself and all of its inherent strengths and weaknesses, allowing architects to design with both technical needs and aesthetic aims in mind. The form can correspond to the expression of the cultural, social and economic contexts of the building and yet these can also relate back to basic structural elements of the building – the materials and design – as digital fabrication methods allow innovative aesthetic responses.

Tooling, of course, is key to output and results. A straightforward design, using traditional jointing and construction methods, will require the least sophisticated construction tools. The most basic fabrication mode of all is that using traditional tools, local labourers and bamboo in its basic form. The exterior layer of bamboo is extremely hard and therefore saws and drill bits intended for cutting metal are required. Drilling has to be carried out at high speed and low pressure to avoid edges cracking or fraying and as wood saws blunt easily, working with bamboo offers construction challenges. Given the lack of available digital technology to facilitate more complex designs and tooling, structures must be simple, basic and traditional. As Stéphane Schröder, founder of Guadua Bamboo S.A.S in Colombia points out:

"Conditions of the roads and building terrain, availability of water and electricity, availability or lack of local labour, availability or lack of local materials (hardware store)…The design shape and grade of difficulty of the bamboo house are more significant and important than the total area of the construction itself. Big structures can proportionally turn out to be cheaper than smaller structures…The architect decided to use 6 bamboo poles for each of the supporting columns for a total of 6 columns. As a result of this, a total of 36 bamboo poles were used. All of the poles have different and very challenging angles, which in order to join together, required hiring a very talented and experienced building team." (Schröder, 2010 p,10).



Image 5.5 Playa Sombrero house by Guadua bamboo (2010)

The Colibri House in Cali, Colombia, illustrates more traditional design and fabrication methods, in which local craftsmen work with simple technology. It is composed of three modules, with Guadua used for the structure, walls and roof, and river-stone for the foundations. Its columns are composed of canes bundled together, with 13 canes on the first floor, 9 canes on the second floor and 4 on the third floor. The roof is composed of trusses and struts, with bamboo planks situated on purlins and covered by a layer of lime, sisal fibre and cement. The canes are joined with palm wood pins and galvanised wire anchors (Minke, 2012). Whilst such construction methods are basic and functional, they have created an imaginative building with the use of modules transforming it into a more complex structure. Nevertheless, it is a traditional build, without digital design flexibility. Its originality lies in the architect's creative combination of modules and materials that collectively overcome the restrictions of local crafting and fabrication mentioned above.

Buildings using pre-fabricated panels, planks and sections, created from bamboo laminate and bahareque, evidence innovative digital technology and the possibility of creating a small industrial plant that prefabricates the building components. The model houses were developed by the charity Hogar de Cristo in Ecuador, using various typologies and technologies that suit the region's socio-economic and environmental constraints. Similar systems can be found across the geographical bamboo belts and could be further developed. Digital design and fabrication allow for further improvement and optimisation of methods, particularly enhancing efficiency, and of the performance of houses. Small industrial plants can offer systems that create and replicate panels, trusses, and construction elements in a series of stages, which are then exported to the building site to be reassembled.

Image 5.6 , 5.7 & 5.8 Casa Anadina, a model house made with bamboo components by Hogar de Cristo in Ecuador



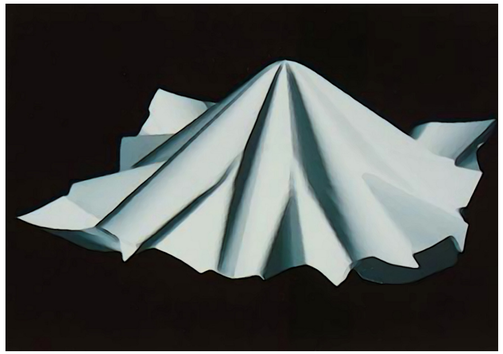




More sophisticated architectural forms are those created by parameters that both defy yet mimic nature. The Kindergarten and Community Centre built in Naiju, Japan, (mentioned above) is a triumph of design defying nature. Its tensile bamboo network, determined by parametric design, functions as the underlying form on which reinforced concrete is overlaid. The result is a sweeping, surging form of extreme and yet elegant sophistication, opening its inner space to the community by means of domed entrances emerging from the canopy like the edges of a scallop shell opening to the curious. It embodies a playful yet impressive composition entirely fitting with its dual function – a place for children to grow and learn and a place for the community to bond and be inspired.

Parametric design gives designers relationality, versatility, and flexibility, simplifies diversification and presents programmatic solutions. Indeed, as Schumacher writes, "Parametricism emerges from the creative exploitation of parametric design systems in the course of articulating increasingly complex social processes and institutions." (Schumacher, 2009 p.30)

Image 5.9 Naiju Community Center and Nursery School, Chikuho, Fakuka, Japan (1994)



Combining computational parametric design, structure and materials, complex and sophisticated structures can evolve and propose innovative solutions and methods yet still employ basic hand tools and local labour. An excellent example is the above-mentioned 'ZCB Bamboo Pavilion' developed by Crolla and Fingrut in 2015 at the Chinese University of Hong Kong. Following logical structural principles like those of Frei Otto, computational physics in form-finding and traditional scaffolding jointing methods, the project demonstrated the potential of computational design, traditional craftsmanship and bamboo. The incorporation of digital real-time physics simulation engines in the workflow defines the most suitable form for a bending active gridshell (Crolla & Fingrut, 2016). The structure consists of an extended triangulated diagrid that folds down onto itself to form three large hollow columns. The digital design sequence was set up using Kangaroo as a computational form-finding tool. Kangaroo is a plug-in for Rhinoceros® and Grasshopper® that uses particle systems in which interconnected networks of geometry control points respond to applied forces following laws of physics. The resulting intersecting curve model was developed further to a non-intersecting axis model incorporating bamboo diameters and individual lengths of overlapping poles.

Other developments in research have focused on 3D-printed joints. Amtsberg and Raspall (2018) from Singapore University of Technology and MIT developed a workflow to optimise a design and fabrication methodology for small section bamboo for low load-carrying truss structures. They utilised visual sensing methods for the individual material properties of various bamboo poles to inform the digital model. The load-carrying capacity of the bamboo pole and the structural requirements of the design were analysed, and the poles were then digitally placed in a geometrical arrangement, allowing the joints to be designed. Conventional 3D printers produced the nodes and connectors, enabling the merging of natural and "digital" materiality. The defined research approach used bamboo poles as the bars in a node-bar system, and 3D-printed nodes serve as the connectors. As hollow straight tubes, bamboo poles are the ideal base material for trusses and bar-node systems. Scanning of the bamboo sections informs a Grasshopper® Script, which customises the nodes as a whole and in detail.

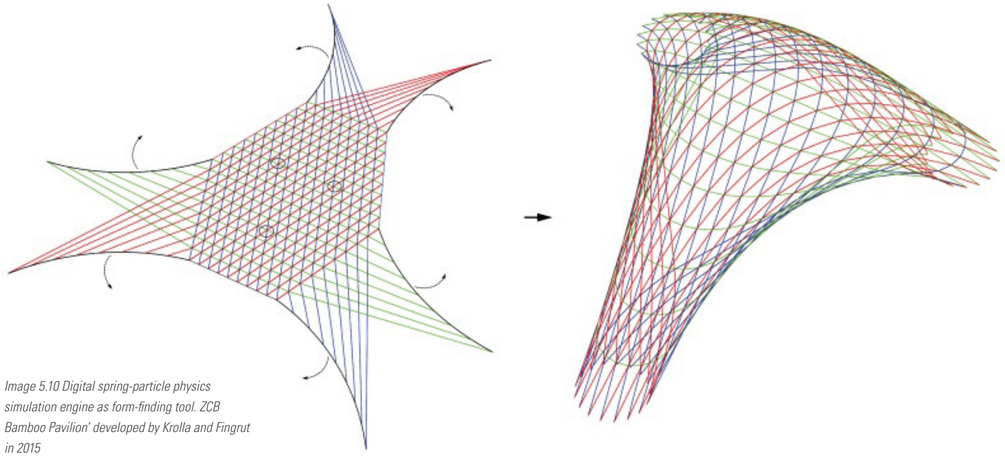


Image 5.10 Digital spring-particle physics simulation engine as form-finding tool. ZCB Bamboo Pavilion' developed by Krolla and Fingrut in 2015 at the Chinese University of Hong Kong

Image 5.11 Workflow diagram 3D printed joints Amtsberg and Raspall 2018

Image removed due to copyright restrictions

ETH Zurich developed a research project for the fabrication of non-standard timber frame structures. Whilst this did not directly use bamboo, the use of robotic assembly in the fabrication methodology is an example that could improve the fabrication of bamboo components. Implementing automated systems in the fabrication and assembly of timber frame structures expands the digital chain from design to construction and enables the introduction of non-standard automated production processes (Willmann et al. 2016). This research capitalises on the ability of robotic arms to assemble timber beams into bespoke modules (Thoma et al. 2018), which enables the efficient production of non-standard multi-storey timber buildings.

Image 5.12 Workflow diagram ETH Zurich (Willmann et al. 2016)

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This computational process allowed for the integration of cross-disciplinary parameters in the design of the timber frame structure. The generative design logic provided the possibility to modify the design completely at any time, without the hurdles of a conventional phase-based approach (e.g., revising a whole set of construction documents) (Adel et al, 2018). Therefore, it is possible to adapt to changes induced by new requirements even at a late stage of the design process. Furthermore, the robotic fabrication workflow enabled the integration of a wide range of fabrication procedures into a just-in-time process, which allowed the algorithmically generated structure to be fabricated without any breaks in the digital chain. This highlights one of the main potentials of implementing a continuous digital chain from conceptual design to final materialisation (Adel et al, 2018).

Schumann, Hauptman, MacDonald (2019) conducted very interesting research and a new method on the fabrication of standardless materials presented at the ACADIA 2019 conference. The method comprises (1) material stock analysis using sensing technology, (2) parametric best-fit part selection that optimises a given piece of material within an assembly, and (3) parametric feedback between available material and the design of an assembly, which allows for the assembly to adjust its geometric features to a set of available parts. The species Dendrocalamus strictus (also known as Calcutta Bamboo or Iron Bamboo) was selected for this study due to its unique solidity, which makes its structural application more viable after part reduction via CNC routing. Its relative solidity, when compared to other species of bamboo, allows for applications more akin to a wood product than traditional hollow bamboo (although Calcutta Bamboo does contain a central hollow chamber that typically appears in a pole after the first six feet, which are solid, and increases in scale as the pole grows vertically). Careful pre-selection of bamboo stock creates opportunities for constructing consistent and reliable joints in which bamboo can be joined to itself, rather than to the more typical steel connector or wrapped joints (Fish mouth). Prior to the introduction of a 3D scanning system, Calcutta Bamboo poles were systematically dimensioned, marked, cut, photographed, and digitally traced in order to build a series of accurate 3D digital models. Structural testing in the form of axial tension and uniform bending tests were performed to understand how removing faces of the bamboo pole alters its structural performance. This data serves as the basis for the parametric part selection, according to the structural needs at each part of the assembly.

Image removed due to copyright restrictions

Image 5.13 Schumann, Hauptman, MacDonald. 2019 – CNC Milled Joint Prototypes

A scanning system was incorporated in which it is possible to interpolate a rotated mesh, thereby obtaining a 3D digital model that retains the eccentricities of the pole (oval cross-sections, bulges at nodes, bends and kinks in elevation, etc.). The use of comparatively solid Calcutta Bamboo allowed the strategies for joining bamboo poles to be developed as is common in timber construction. A series of prototypes were digitally created as a parametric model that was composed of bamboo pole centerlines and solid objects that would become voids through the process of CNC part reduction. A library of possible joints was produced, demonstrating different strategies for bamboo-to-bamboo connections – keying, interlocking, nesting, etc. In using this system, the designer can readily combine existing joints, or they can design and implement new joint connections, as a standard output of bamboo joinery techniques.

Image 5.14 Schumann, Hauptman, MacDonald. 2019 – CNC Milling machine

Image removed due to copyright restrictions

SUMMARY – INTERMEDIATE TECHNOLOGY AS A SOLUTION

Whilst digital fabrication is a solution for the future, there are limitations to the use of high-end digital fabrication methods and robotics as used in projects above. In some regions around the world , in which the preferred means of construction may not be digitalised tooling but rather using hands and skilled eyes, sophisticated fabrication methods are simply not feasibly applied. This does not signify that digital methods have no place in regions where technology is less economical, but merely that at the moment there is a distinct need for lower cost, accessible solutions.

Robotic equipment is costly, with a single robotic arm costing up to $150,000 – far exceeding the economic reach of the small rural community that relies on bamboo for construction of its homes and community spaces but still uses saws and chisels for this construction. By focusing on appropriate low-cost technological solutions that build on local wisdom, communities can utilise innovation to counter low economic capability. Not all technology has to be upscaled; indeed, there is a pressing argument for technology to be simplified to equipment that can be mass-produced and can itself enable mass production at the hands of local labour hitherto only skilled in the use of hand tools. Using Building Information Modelling (BIM), it is now easy for computational information regarding fabrication modelling to be translated into design. However, for that design to be realised, it is important to develop simplistic digital fabrication methods as an intermediate solution to accommodate for the gap between low-skilled labourers and BIM-inspired designs. With such tooling, small local industries could have access to technology that supports and enhances their hammers and chisels, modernising their work without the excessive and often impossible cost of full industrialisation. For this reason, this research project developed this type of tool, with a development cost of around $2,000. This forms part of the methodology of the thesis to identify the opportunities and constraints for implementing digital fabrication with bamboo into mainstream architectural construction.



6.

MIND, TOOLS & MATTER IN PRACTICE

"...THERE IS A MUTUAL RECOGNITION THAT KNOWLEDGE-MAKING IS A DYNAMIC PROCESS ARISING DIRECTLY FROM THE INDISSOLUBLE RELATIONS THAT EXIST BETWEEN MINDS, BODIES AND THE ENVIRONMENT."

This chapter focuses on the processes behind craft, how the transmission of knowledge takes place and how these processes relate to design thinking, tools and material. Addressing these characteristics provides insights for the development of innovative systems in which digital fabrication can contribute to the advancement of bamboo design and fabrication.

Both craft and design are complex cognitive processes requiring a coordinated mind, body, tool, material, social context and environment (Malafouris, 2004). Throughout the creative process, different emphases occur for different activities and with the further utilisation of digital fabrication there are new crossovers between traditional and innovative methods of working. The current digital fabrication movement has a stronger emphasis of fabrication, 'pushing' the designer more into the space of the maker, which in turn influences the generative properties of design (Menges, 2012a). This calls for new possibilities in the field of machine-human interaction, which is where this research project is contributing to new knowledge in the field.

In advanced digital fabrication research, complex sophisticated CNC machines (like robotic arms) are used to replace the skilled craftsperson. As Gramazio and Kohler (2010) argue "today the action of material handling is indirect through the use of CNC machines as opposed to the instant feedback about the work in progress the skilled manufacturer received through the tool in his hand. With CAM, the tool is controlled through explicit routing data, which leaves no room for interpretation and adaptation." Whilst this has advantages in the field of design and fabrication, it removes the actual skill and knowledge which comes from the experience of manipulating material, to feel and to sense the particularities of the interaction between human sensitivity and matter. Realising that cognitive activities are an essential part of the craftsman process (Keller & Keller, 1993; O'Connor, 2006; Malafouris, 2004) can benefit the synergy between digital fabrication and traditional methods of crafting.

Cognitive processes are not restricted only to mechanisms which occur inside the brain of the individual. All cognitive activities are closely related to embodied action, representing a space of operation between mind and matter (Holland et al., 2000; Malafouris, 2004). Based on this framework, tools and matter are an integral part of the design process, knowledge and creativity (sharif, 2015). Furthermore, in support of this argument, Keller and Keller (1993) argue that there is an inherent and dynamic interrelation between knowledge and action.

In the example of workings with bamboo, the social, cultural and economic context of the designers and the craftsmen (if different persons) have a significant influence on the ideas and actions applied to the material. The craftsman's knowledge is derived selectively from prior production experiences and ideas about the world (Sharif, 2015). When working with craftsmen in Colombia, the transmission of knowledge about the material, the particularities of the construction process, tools and fabrication processes were unique and specific to the person teaching me. Upon action, the cognitive thought processes were influenced by the larger environmental, social and cultural contexts which lead to specific decisions and a unique outcome of the artifact in creation.

LEARNING CRAFT

Learning is a process that entails the transmission of theory into practice. The transfer of knowledge into action requires many processes of both mind and body operating in synchrony with a constant flow of information, articulating hundreds of decisions and coordination – to apply, adapt and refine practical skills derived from theoretical knowledge and to thereby translate thought into action. The academic and conceptual principles are received from either a combination of external and internal stimulations lead by the project brief, the working environment, the people and their emotional state.

"making knowledge is a process entailing co-ordinated action between interlocutors and practitioners with their total environment. As a minimum, the latter consists of artefacts, tools-to-hand, and raw materials; space, place, and architecture; paths and boundaries; timeframes and temporal rhythms; light, darkness, and weather." (Marchand, 2010, p. 2)

Above all, the transmission is a holistic process; a process of doing, repeating, doing, repeating, and so forth, such that it becomes less of a process and more a natural flow. In the fieldwork carried out in Colombia, it was very evident how the transmission of the carving of bamboo joints was done from one experienced carpenter to the apprentice. There was particular emphasis on the method of holding the hammer and chisel, the seating position in which one holds the bamboo between one's legs and the ability to carve the expected form with precision. The articulation and skill of the hands, arms, and body require a lot of experience and practice. I have been working with tools and building with materials since I was a young boy, so I could rapidly adapt to the new learning and progress to a more advanced stage of working with bamboo. For someone with less experience, this process would have taken much longer and would have required more teaching and practise until the skill and ability were achieved.

Nevertheless, bamboo is a unique material and therefore responds with uniqueness in resistance and flow. This relationship between the mind, body, tool and material is unique to each moment, and this is indeed the act of craftsmanship. No other moment is the same for the mind, body, tool and material relationships are in reciprocity, and here the craftsman is in action.

Ingold's theory of "embodied cognition" (Ingold, 2000), suggests that the mind is essentially part of a biological system that adapts and assimilates the results of interactions between individuals, environment and experience. Marchand comprehensively indicates: *"Studies of motor cognition, and especially research into the relation between motor execution and stimulation (e.g. jeannerod 1994; 2006) have propelled our individual thinking about the mind-body complex; the fluid composition and mechanics of 'intelligent action' and the 'uncoordinated' trials of novices; and the nature of embodied communication and cognitive interface between 'seeing' and 'doing'.* (Marchand, 2010, p. 6)

An example of the transmission of skills for using bamboo as a construction material was the construction of the Zeri pavilion, the design and construction of which involved 58 people (Zeri, 2012). In order to obtain a German building permit, the pavilion was first constructed in Manizales, Colombia. The prototype underwent a series of scientific tests on a 1:1 scale and these tests were subsequently repeated in Germany. The structure, joining 4500 bamboo pieces, was erected by 41 Colombian wood workers in less than three months, without previous experience of constructing with bamboo at this level. The labourers and craftsmen received certificates recognising the new skills and techniques of working with bamboo that they had learned during the construction. The design and construction team presented the craftsmen and labourers with certificates for seven new building techniques and two new construction techniques (De Flander, 2011).

Image 6.1 Juan Santos demonstrating how bamboo lashing is used on furniture. Research fieldwork, July 2017 in Cali, Colombia.



The notion of travelling craftsmen, to whom new workers are apprenticed and from whom they receive training on-site where eventually they master their skills and subsequently transfer their knowledge to other workers at other sites has been a historical system of master to apprentice. Craftsmen and tradesmen generally learn from the job rather than a formal school and this method of transference of knowledge is most common. It also has the beauty of employing all the facets of learning and the transmission of crafting skills:

- learning in situ, on-site, so that the use and function of tools are 'real',
- learning by repetition and thereby developing new patterns of neuron firing,
- learning through hands-on experience so that the learned skills become organically rooted in the craftsman.

The craftsmen share and learn whilst working on the construction itself, creating an 'organism' for learning. The constituent cells are the craftsmen – some new and unskilled, some skilled in some areas but not in others – working together to self-teach and to combine knowledge so that the organism can operate as a cohesive whole to achieve the end product: the structure or project. Maurice Bloch (2005, p. 97) suggests that how we know and what we know is always a result of *"our species-specific perceptual apparatuses, cognitive architecture, and biological constitution, which, together, give us life and enable us to survive."* (Marchand, 2010, p.11). Eventually what we do does become a way of life.



Image 6.2 Bamboo crafting by Oscar Giraldo

THE ANTHROPOLOGY OF LEARNT SKILLS

By immersion in the activity of how craftsmen do their work, by observing, feeling, hearing and being part of it, is an appropriate way to anthropologically understand and study the skills of the people in their socio-historical context (Ingold, 2008). This apprentice style method of learning about practice by practically doing (Marchand, 2010) enables an embodied discovery that cannot be experienced or discovered in a research laboratory.

Practicing by doing involves engaging in the process with the teacher, employing all forms of transmission of information. The most obvious form is language – we learn by explanation in various forms, but a particular effective form is verbal explanation. As the language of learning comprises many modes, it is key for instructors and pupils to use a common language in order to promote the transmission of understanding, as abundantly demonstrated by Marchand's assessment through his research training in London:

"The vast majority of technical teaching and learning was nevertheless achieved with a paucity of oral explanation or textual instruction, and more readily relied on demonstration, imitation, and repeated practice. Words and utterances were regularly used for deictic purposes: to highlight the salient aspects of a tool-wielding practice' to stress particular bodily positions and postures; or to draw attention to aspects of a tool or qualities of the timber being worked." (Marchand, 2010, p. 8)

This description very much reflected my own experience during my fieldwork, during which I aimed to establish the ease of use and application of the digital fabrication tool. The indigenous population spoke Spanish, which I was familiar with. However, demonstration, non-verbal acknowledgement, encouraging touches indicating whether my use of tools and techniques was appropriate, and repetition of correct usage following errors, were an effective replacement for formal lectures on the how, why and what of the skills that local craftsmen were teaching me.

Repeated demonstration, correction, repositioning and retrying enabled my mirror neurons, as comprehensively documented by Giacomo Rizzolatti and Laila Craighero (2004), to fire in sequence and to mirror the neuronal patterns of my instructor. This process enabled me, the novice bamboo workman, to replicate the joint that he so skilfully demonstrated to me.

Understanding both the skill itself and how it fits into the role of craftsman and the culture within which the craftsman operates is essential. Though I could have practiced the techniques and processes in a workshop at my university, I would have missed the subtleties of non-verbal transmission, social and cultural awareness and all the observed actions of those experienced in working with bamboo in their context; the experience of using bamboo in the real world, the experience of actively constructing something that is going to be used, rather than merely observing. This experience of applying skills in real-world settings is what renders apprenticeships so effective. Learning a skill or craft by directly engaging with it is a highly effective and affirming experience – as shown by the craftsmen working on the Zeri pavilion (Zeri, 2012), who assimilated new techniques, concepts and innovations while developing their craft. Other places, such as the UNESCO sites in Djenné and San'a, and Yasmeen Lari's work in Pakistan follow this mode of learning by offering work programmes to 'apprentices' that allow them to work, live, and ultimately learn – not so much by being taught but as a by-product of participating.

In addition to the mechanical mastery of tool and material, the lack of formal learning encourages learning of a different but essential skill,– being able to identify good examples of craftsmanship compared to faulty ones, possible only by understanding the materials, equipment and environment embodied in the craft in a deeper, more organic way – a way of life.

The growth of confidence, derived from practice, repetition and understanding, stimulates greater innovation and the impetus to expand the skill base and extend practices for learning into other – as yet untested – areas. The inspiration to innovate, adapt, revise and create new skills and craft develops from the deepest understanding of the craft involved, and how it applies and interacts with its environment, the design concepts it seeks to embody and the craftsmen's ability to emulate those concepts. The apprentice eventually becomes the master, refining and propelling their craft towards a new future, extending into new avenues, new ideas and new crafters. The transmission of learning and skills between craftsmen, learner and master, apprentice and skilled user becomes what Marchand refers to as,

"a kind of 'knowing in progress.' The state of 'knowing is one of constant flux, update, and transformation; and careful study of this reveals the underlying processes of social and cultural change." (Marchand, 2010, p. 12)

This 'kind of knowing' is derived not only from the assimilation of knowledge but also its application. To know is to test; to test is to evaluate; to evaluate is to change; to change is to advance knowledge, understanding and application. As Marchand writes, it is a 'dynamic' process, born of not only learning and the transmission of learning, but of self-evaluation that enables the learner to learn more and to learn better, *"The dynamic nature of interaction presents constant opportunity for new and possibly divergent ways of thinking and speaking about things."* (Marchand, 2010, p.12)

Image 6.3 Ricardo Assis Rosa being taught how to use a hammer and chisel by Oscar Giraldo. Research fieldwork, July 2017 in Armenia, Colombia.



KNOWLEDGE AND INTERACTION

The interlocking of old and new enables progress and thus the creation of new systems and processes. The dynamic nature of the transmission of knowledge and that of the creative design process requires space for adaptability, feedback and reiteration of techniques and skills. The application of digital technology onto existing methods requires a dynamic interaction so that the more traditional processes of mind, tool and matter which give definition to craftsmanship continue to exist in the new digital paradigm. In this way, the digital tool should be an evolution of the traditional tools and methods of creation rather than applying sophisticated mechanical engineering tools (e.g. robotic arms) directly onto materials, bypassing the innate craft knowledge, social, technical and cultural systems created by people over decades of verbal and non-verbal transmission. Obtaining such understanding was a benefit of working with bamboo during my fieldwork, which is described in Chapter 7. Without this understanding, the digital fabrication tool that resulted from my research would have been misaligned with the needs of the end users. Through on-site collaboration, I came to understand not only the ways of the tools in use but also the minds of the men using them – the way they utilised, applied, and manipulated the tools. Originally, the architectural process entailed design from drawings, which then provided the unchanging framework from which a structure was built. The incorporation of materials such as bamboo required innovative and tactical handling paired with the new and far-reaching approaches of digital recording and tooling to achieve this, rendering the architectural process reflective of the learning process. Trevor Marchand (2010. P.8) asks,

"what role [too] does the environment of tools, materials, fellow actors, artefacts and physical setting play in the interpretation and generation of activity?"

I believe the answer is that it plays the role of the self-propelled learner, the thinking craftsman and the self-evaluator. Here I bring emphasis on the mind aspect in discussion throughout this thesis. I suggest that these aspects are just as crucial as the ability to carve with the hammer and chisel and that they differentiate an individual who is technically operating a tool to one who is a craftsman able to create and adapt to the problems as they are in flow.

The proposed digital system in discussion in chapter 7 & 8 has evolved from the principles discussed here because it relies on the skill of a craftsman to operate through the complexities of both the tools, materials and body, but in this case some of these technologies are digitally operated yet the synchronicity of thinking and of feedback is equally present.

In my experience, learning the technique of bamboo construction involved various means of transmission of knowledge via language, demonstration, repetition, base texts and diagrams. Transmission also involved the process of trial and error, including failure, from which I was able to evaluate why the technique had not worked and determine what I had done wrong. Understanding is an essential part of the process, not only in understanding the qualities of a technique and why it works but also why it does not work, what error in action, what missed step or wrong footing occurred. This feedback is essential in a system that requires calibration and adaptation to the problems present in the flow of the project. This creative loop is again a mind characteristic present in the working of the accomplished craftsman.

We learn through a rich array of experiences but essential to applying these experience is the ability to self-evaluate – to calibrate the design and making it flow to reiterate and to meet objectively with our aims. We review what we have learned, how well we can execute the learned skills, and then move on to the next stage. In her observation of Kazakh women's craft practices, the anthropologist, Anna Odland Portisch concludes that they are able to make skill-based assumptions not because of isolated knowledge-based mental processes but because,

"…reflection and assessment are integral to the practices of both novices and accomplished craftswomen… assessments are based on somatic-sensory interactions with practical tasks, with tools and materials. Learning to make such assessments involves developing an increasingly detailed and complex understanding of the whole production process." (Portisch, 2010, p. 73)

Naturally, self-evaluation, language, repetition, demonstration, cognitive assimilation and new synaptic patterning are not the only components of the making process. Instead, it is a complex tapestry of all aspects of a design to making process, including supporting documentation – materials, diagrams, notes, text and so on. The lace-makers observed by Nicolette Makovicky in her paper "Something to talk about" also needed to work from diagrams in order to recreate the complex patterning of the lace they were weaving,

"Notation, however, is not simply a neutral tool for the recording, exchange, and dissemination of information. Indeed, precisely because notation affords procedure to be separated form practice and disembeds craft knowledge from its geographical, social and historical context, its use has concrete consequences for lace-makers' understanding of skill, proficiency and design composition. The construction of diagrams and drawings creates an ongoing dialogue about the relative merits of manual dexterity, mental representations, drawings, improvisation, and creativity. In turn these discussions and disagreements become central to divergent concepts of style, tradition and heritage." '(Makovicky, cited in Marchand, 2010, p. 76)

Not dissimilar is the way the diagrams depicting the construction sketches for the Zeri Pavilion, which evolved as result of building and testing process, illustrated in the drawings below, show the nature of discussion at multiple scales and in multiple views.

Image 6.4 Detail sketches by Simon Velez to the craftsmen on site.

Image removed due to copyright restrictions

Image: Zeri, 2012, P22

During the construction fieldwork in Colombia, the drawing medium was an essential method to articulate ideas and to solve problems. This means of communication is an essential tool to share ideas but essentially enables the craftsmen to solve complex problems between form, scale and sequencing of works. A digital model was an essential component in the workflow yet the manual sketching was essential to clarify and 'work through' the project. The design process is actively participating in the whole project and travels from the mind of the architect/designer to the mind of the craftsman/maker in order for it to manifest into the material 3D form.

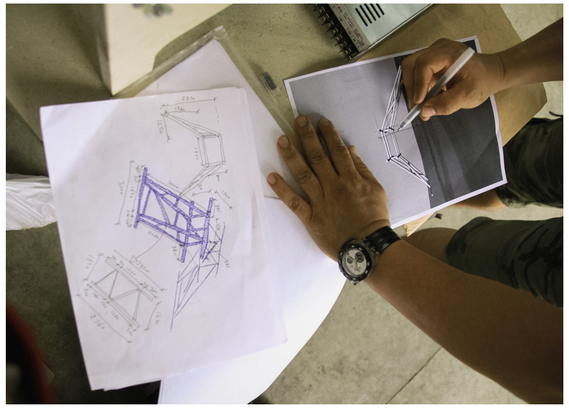
As with the lace-makers, the Zeri Pavilion and the fieldwork pavilion in Colombia, the project became a live act of creation, derived from and involving many individuals, variations in knowledge and cultural, social and professional understanding and experience. All these elements formed a cohesive experience resulting in a design based not just on the original



Image 6.6: Oscar Giraldo demonstrating a fish mouth cut with a hammer and chisel.

instruction, or the structural tolerances requiring the revisions annotated on the original drawings, but on the combined experience and expertise of all involved in each of their areas of expertise. And as with anything human-related, the dispositions, experiences, ways of engagement, and aims of each individual involved will affect how learning is achieved, be it positive or negative, forward-looking or constrained by old ways and old beliefs. The relationship between mind, body and the process of learning is as individual as the individual himself. Equally, as discussed by anthropologists (Marchand, 2010; Ingold, 2000; Makovicky, 2020) it is the each individual's model of knowledge that shape their agency and action, as well as, the role of the cognitive, motor and social mechanisms in the making of knowledge.

Image 6.5: Ricardo Assis Rosa and Roger Martinez discussing through sketches the assembly of the research pavilion.



The employment of visual imagery in learning is effective because it is directly transmitted to motor domains, where it is translated into specific postures, gestures and actions. In contrast, sound is the medium of ideas and therefore requires more extensive comprehension. Hearing requires the brain to process the concept before it can duplicate the associated action. Visual demonstration translates more easily into basic understanding through imitation, with visual stimulation quickly and effectively allowing our brains to mimic what we see via motor neuron activity. Both are necessary to comprehensive understanding (Farmer, Ciaunica & Hamilton, 2018). My learning during fieldwork benefited the most from listening to the subtleties, looking with attention and replicating in precisely this way which I adapted to my thinking, my body and my skill.

Marchand's summary of how craft-making is learned is the following:

"…when we see an object, what we possess in mind is not the 'thing' itself but rather a representation processed by our visual apparatus and subjected to our faculties of reasoning about what it is. Likewise, when we hear an utterance (or think with language), it is not the words themselves that are entertained in our conceptual understanding of what is said, but rather the concepts they map onto and the propositional representations they combine to create in what Fodor (1975) coined the 'language of thought' (LOT). Therefore the notion of 'context', too, refers not to external surroundings (as usually implied in anthropology), but rather context is individually possessed as a mind-internal repertoire of existing concepts and representations, acquired, constructed, and modified in an ongoing manner from environmental stimuli." (Marchand, 2010, p. 101-2).

Image removed due to copyright restrictions

Image 6.7 Digital Maker Cognitive System (Sharif, 2015)

COGNITIVE INTERACTIVITY

The great advantage of operating through the domain of craftsmanship is to allow for a richer creative process from design to artifact. Digital fabrication by utilising CNC machines naturally lends itself to a more rigid automation process where little input along the process can be adjusted, while a craftsman would have more flexibility and adaptation to change the course of the work to an adapted outcome. The act of making requires the designer-maker to have an organisation of knowledge of the process and the intended outcome. This process is however never sufficiently detailed and precise as the designer-maker cannot adequately predict all the possible situations which might occur during the process. In addition, the craftsman can never fully control his actions as they are affected by materials, tools and environment (O' Connor, 2006). As Keller and Keller (1993) discuss, the craftsman builds on three dimensions: conceptualisation, actions and operation of similar previous production tasks (feedback). The coevolution of design conception and artefact production is influenced by the under-constrained tools and material conditions that allow for creative development (Sharif, 2015 p.687). As a premise, one can state that the conceptual task (mind) is the source of the outcome of the materialisation of the craftsman's actions. In this sense, it is of great importance when developing a new digital tool that the interactivity and dynamic adaptability of the system allows for the creative conceptual process to evolve and interact with the process. This further emphasises the relationship between the mind of the designer-maker and the tool, to dialogue and interact in a system of feedback loops, allowing the nature of craftsmanship to pervade the system, particularly if you want a traditionally trained craftsman to engage with a system which can enhance his/her actions.



The workflow of CNC technology naturally doesn't provide interactivity and a dynamic space of exploration in the fabrication zone (diagram). The creative process, in this model resides with the designer in the space of computation and not with the tool. In order to enhance the craftsmanship and give more scope for interactivity and creation, a different work flow has been researched in this project by looping the mind, tool and matter across the workflow and within the social and physical environmental context, creating a system more akin to the methods in practice.

Research in the field of human-computer interaction and augmented fabrication systems are developing projects which address the levels of engagement in the fabrication space of the digital process. Innovators like Gramazio and Kohler have contributed to human and machine as equivalent partners in collaboration (Gramazio et al.,2010; Gramazio and Kohler, 2008). The nature of computation is pragmatic and operates on explicit knowledge as opposed to tacit knowledge like that in traditional craftsmanship, which is more personal, gained through observation, induction and participation (Eraut, 2000). In discussion throughout this chapter, as observed in the fieldwork, the knowledge transmitted by the craftsmen was much more tacit. The premise of the fabrication system proposed in this thesis looks at the parameters of interaction between the machine and the human, on the flow between mind, tool and matter and on the particularities of how tacit knowledge in the fabrication space can interact with the whole workflow for the fabrication of bamboo components.

THE CREATIVE PROCESS, IN THIS MODEL RESIDES WITH THE DESIGNER IN THE SPACE OF COMPUTATION AND NOT WITH THE TOOL.



Image 6.8 Oscar Girlado in making a flute tip cut with a hammer and chisel.



Image 6.9 Differnt samples fabricated with the CNC machine.

Image 6.10 Ricardo Assis Rosa, Roger Martinez and Oscar Giraldo working on the asssembly and fabrication of the pavilion using different methods.



CONCLUSION

Each of us is different and this richness gives scope for a more diverse range of solutions to problems and different possibilities of a creative flow in achieving a final artifact.

Applying the process of learning to craft in the field was the logical first step when planning the design and function of the digital fabrication tool discussed in the next chapter. This was inspired by my attendance at the Bamboo Research Conference in 2014 and the research fieldwork in 2017 in Colombia. Understanding that bamboo had a permanent and exciting place in the future of construction, I wanted to design a tool that would enable the skills and abilities of the bamboo craftsman to work in synergy with a digital design and fabrication system. The conceptual and academic understanding that bamboo could be used more innovatively and effectively by local craftsmen and builders is one thing, but actually employing it in the real world where communities are limited by technological and economical resources is another.

The development of the digital fabrication tool – how it was devised, tested and revised, using locally gained knowledge and experience – will be expanded on in Chapter 7, but the role of learning as discussed in this chapter had particular impact on the development of the tool. Entering the field and beginning life – for a period of time – as a local craftsman, an apprentice even, brought me into contact with not only the stark reality of what could and could not be achieved with existing tools, techniques and knowledge, it also made me more aware of the work and lifestyles to which the machine needed to be able to adapt and respond.

Thus, the research processes I chose were immersion in the social cultural environment of the working environments and understanding of the anthropological basis for specific crafting. Social interaction also enabled me to understand the cultural and ecological environment of my co-workers, my teachers as I was able to bring a new digital dimension to their world.

Understanding precisely how to cut a joint and construct a 3D component enabled me to understand the process as a whole and therefore understand where this innovative system could contribute to the existing forms of practice. Interacting with craftsmen (including myself) in how to use the tools enabled a more detailed understanding of what had to be done, and how to ensure that the proposed system would work effectively.

In the next chapter, I will document how the digital fabrication machine developed into a tool that is functional across many scenarios, with the development informed by the understanding of how one interacts with the flow of design to making, encompassing the triad of mind, tool and matter.

7.

DIGITAL THINKING – DIGITAL FABRICATION WITH BAMBOO

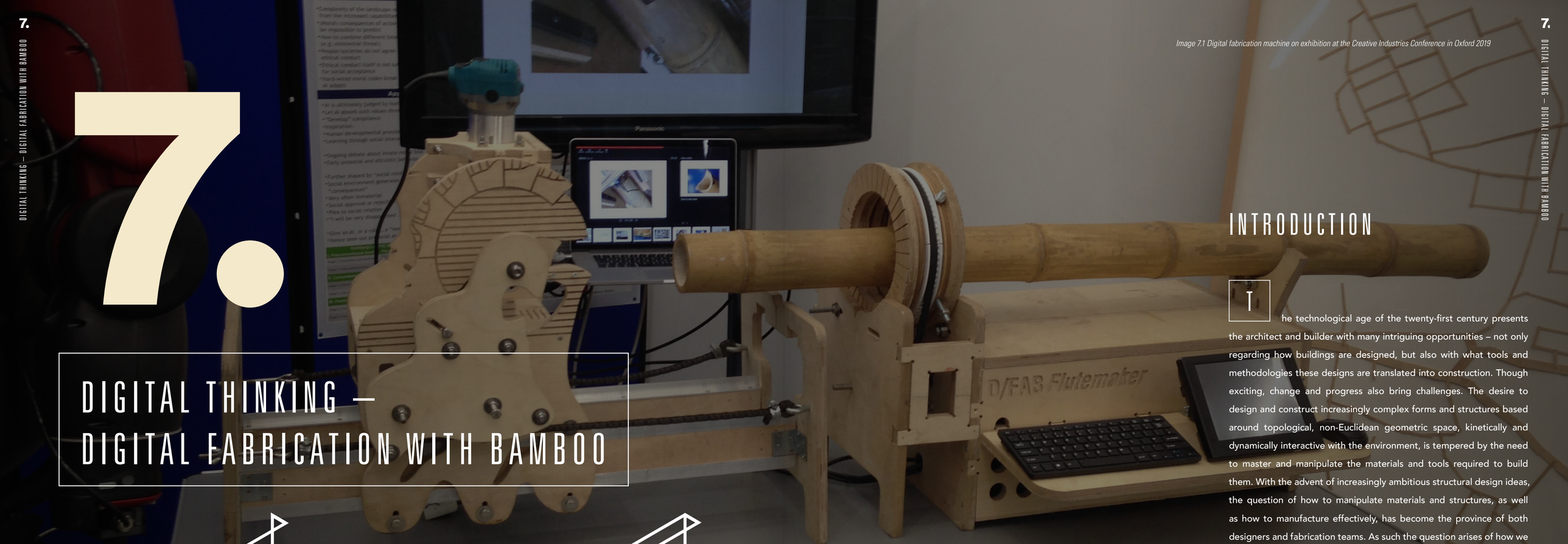


Image 7.1 Digital fabrication machine on exhibition at the Creative Industries Conference in Oxford 2019

INTRODUCTION

The technological age of the twenty-first century presents the architect and builder with many intriguing opportunities – not only regarding how buildings are designed, but also with what tools and methodologies these designs are translated into construction. Though exciting, change and progress also bring challenges. The desire to design and construct increasingly complex forms and structures based around topological, non-Euclidean geometric space, kinetically and dynamically interactive with the environment, is tempered by the need to master and manipulate the materials and tools required to build them. With the advent of increasingly ambitious structural design ideas, the question of how to manipulate materials and structures, as well as how to manufacture effectively, has become the province of both designers and fabrication teams. As such the question arises of how we design such complex forms based on accurate testing and manipulation of materials and concepts to their efficiency?

This chapter will suggest that digital technology offers multiple avenues to innovative design and material applications. The advancement of solutions to the limitations of bamboo through the CNC machine have developed as part of this research project by maintaining a close transmission of experience from existing craftsmanship. The chapter further discusses the holistic approach to design from material to constructed form utilising the most effective way to achieve innovation and advancement in fabricating with bamboo for architecture.

Image 7.2 Frank Gehry, Zollhof Towers, Dusseldorf

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THE HISTORY OF ROBOTICS AND DIGITAL FABRICATION

Experiments with computer numerically controlled (CNC) milling machines to design architectural models were first carried out in the United Kingdom in the early 1970s and were shortly emulated and developed in the US, with automated milling machines in use in the late 1980s. Such machines were soon producing construction components (Mitchell 1995). Thus, the early digital fabrication (DF) and robotic-aided construction practices became part of the fabrication flow. Designers have since been developing and advancing their designs to translate their innovative concepts into physical reality. With the continuing advances in the generative and creative potential of digital tools, alongside existing manufacturing advances in the automotive and aerospace industries, new dimensions in architectural design have become not merely state of the art but also state of play. Computer-aided design (CAD) and computer-aided manufacturing (CAM) technologies have been impacting building design and construction practices for many years. With the development of these techniques, new opportunities to produce and construct complex forms – previously extremely difficult and expensive to design and assemble using traditional technologies – have become more common. The intensely curvilinear surfaces that feature so prominently in much contemporary architecture required new design methodologies to calculate the spatial and tectonic aspects of such non-Euclidean forms. Non-Uniform Rational B-Splines (NURBS), along with CNC fabrication processes, such as cutting, formative, additive and subtractive fabrication (known collectively as CNC cutting or 2D fabrication), have become the most commonly used digital fabrication techniques to produce these designs.

A paradigm shift in construction technique and design was therefore evidenced by these developments and quickly progressed into other areas of design strategy. CNC milling has since been applied in increasingly new ways in the building industry. For example, formworks can be created for off and on-site casting of concrete elements. Using this process, Gehry utilised 355 different curved moulds for his design of the Zollhof towers in Dusseldorf (Rempen, 1999). In subsequent years, basic processes were gradually supplanted by more sophisticated design and fabrication processes, using technological advances such as Selective Laser Sintering (SLS), Laminated Object Manufacture (LOM), and Fused Deposition Modeling (FDM). Amongst a myriad of other processes using CAD/CAM technology that are now standard, builders can now be supported with digitally-driven technologies, integrating design, analysis, manufacture and assembly of buildings.

Cutting technologies, such as plasma arc, laser beam, or water jet, are regularly employed in design work. These involve two-axis machines of a moving cutting head, a moving bed, or a combination of the two. The use of lasers, water jets and plasma arcs inevitably requires a fine degree of control and safety margins. Consequently, the design of supplementary and controlling robotics has developed alongside such processes. Plasma-arc CNC cutting was first used to construct the steel supports for the walls in Frank Gehry's Zollhoff Towers in Germany, and CNC water-jet technology was used to cut the aluminium space frame for the ABB Architects' BMW Pavilion using digital data (Kolarevic, 2001).

Contouring, triangulation (or otherwise polygonal tessellation), use of ruled and developable surfaces, and unfolding are also common construction strategies used in digital fabrication. They involve the extraction of two-dimensional components from geometrically complex curvilinear forms that are generally produced by triangulation or conversion of surfaces from double-curved to ruled, generated by linear interpolation between the curves. An excellent example of this process is Frank Gehry's design that used CATIA software to "rationalise" the double-curved surfaces and convert them into rule-developable surfaces. The surfaces were then 'unfolded' and fabricated out of flat metal sheets to construct the Experience Music Project in Seattle (Linn, 2000) creating sleek metal skins for buildings. The advantage of generating surface data is that it can also be used to conceptualise a building's structural framework, which can then be processed using structural analysis software to generate the precise definition of all structural elements.

In 1983 in Japan, Shimizu designed the first construction robot, the SSR-1, to spray fire-proofing material on steel (Cousineau, 1998). In 1993, automation of construction was first applied to a building project by Shimizu in Nagoya, and in June 1994, the Chicago Institute presented a seminar at the Graham Institute on automation and robotics being developed in Japan and Europe, with a focus on the use of robots in the construction industry. Japan continued to invest heavily, whereas robotics in construction in the US was hampered by issues regarding material size and volume and the need to physically station robots in the correct place onsite. Whilst robotics were already regularly used in industry, there remained the question of how to bring digital fabrication technologies successfully into the construction industry as a whole (Cousineau, 1998).

Shimzu Corporation and The Takenaka Corporation invested extensively in developing robots for tasks such as material handling, excavation, concrete placement and finishing. Whilst much of the technology that Shimzu and Takenaka developed failed to be widely adopted, their developments nonetheless provided a pathway towards the successful adaptations of systems from manufacturing use into practical utilisation in construction (Cousineau, 1998).

In June 2018, Autodesk and MassRobotics, a Boston-based robotics innovation hub, held the first Robotics in Construction summit, focusing on how to progress the use of robotics in the construction industry. A number of initiatives were already ongoing; for example, ECOnnect's solution for future housing shortages, prompted by the Haiti earthquake in 2010 that caused widespread devastation and required innovative technological solutions. Alastair Parvin's WikiHouse and Peter Stoutjesdijk Puzzle house both offered an innovative concept with digitally fabricated pieces that are interlocking, made of CNC-milled panels of reused wood, digitally fabricated, quickly assembled, and practical. These types of projects challenged many current design assumptions and are contributing to innovative thinking in housing fabrication and design.

WITH THE CONTINUING ADVANCES IN THE GENERATIVE AND CREATIVE POTENTIAL OF DIGITAL TOOLS, ALONGSIDE EXISTING MANUFACTURING ADVANCES IN THE AUTOMOTIVE AND AEROSPACE INDUSTRIES, NEW DIMENSIONS IN ARCHITECTURAL DESIGN HAVE BECOME NOT MERELY STATE OF THE ART BUT ALSO STATE OF PLAY.

Image 7.3 Robotica frabrication of bespoke timber frame modules. ETH Zurich (Thoma, et al, 2018)

Image removed due to copyright restrictions

3D printed houses are also in development and offer sophisticated solutions to housing construction. The printing technologies are mainly based on two technologies, namely extrusion-based, typically concrete which is layered horizontally from a gantry or crane, and powder-based (particle-bed) which binds sand with a liquid agent providing a finer and more detailed finish to the 3D object (Nematollahia, 2017). The printing process consists of two repetitive work steps: (1) application of a layer of dry particles and (2) selective deposition of a fluid phase onto the particle packing by means of a print head or nozzle in order to bind the particles. The extrusion based method typically results in a linear cross-section, layer above layer, whilst the powder-based permits a broader range of form possibilities. Powder-bed 3D printing techniques open new design opportunities for micro and macro scale structures, enabling topology optimization in terms of mechanical strength and ornamentation possibilities. For example, the design of topologically optimized slabs to make light weight structural elements with fibre reinforced concrete and post-tensioning structural slabs (Lowke, 2018).

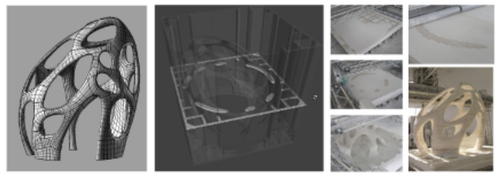


Image 7.4 3D model of the Radiolaria – Powder-bed 3D printing.

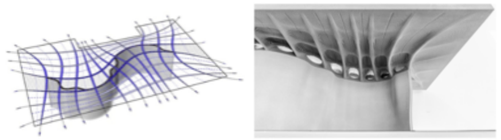


Image 7.5 Structural smart slab based on 3D printed formwork and post-tensioning computational design.

THE DESIGN AND DEVELOPMENT OF THE DIGITAL FABRICATION MACHINE

The research established that given that bamboo is an inherently a unique material, widely varying in quality, size, density, tensile strength, positioning of nodes, means of treatment and drying, age, and geographical and environmental influences on growth, the design of a machine to work with bamboo would necessarily be based around the need for flexibility and adaptability. The issues of working in situ requires portability, endurance and ease of manipulation and programming. The specifics of positioning, precision cutting, movement and manipulation of the bamboo during fabrication are important factors and therefore the machine would need to overcome these.

Finally, the machine must be operable with ease, and so training, accessibility and ease of use by local craftsmen and construction workers would have to be considered as major factors.

Considering all of these elements, the central aim of this thesis was to design a digital fabrication machine, both cost-effective and economical. The machine was designed to be readily available, even to low economic communities, and easy to use, but effective in enabling a well-made and functional jointing system when working with bamboo, particularly in tropical or geographical areas where bamboo is an easily and locally sourced construction material. In consideration of the need for flexibility and adaptability, the development of the machine required the possibility for iterations on a process of design, redesign, field-testing and yet more redesign.

THE CENTRAL AIM OF THIS THESIS WAS TO DESIGN A DIGITAL FABRICATION MACHINE, BOTH COST-EFFECTIVE AND ECONOMICAL.

Image 7.6 View of the first CNC machine prototype made in this research project.



Image 7.7 -6 axis plasma steel tube cutter

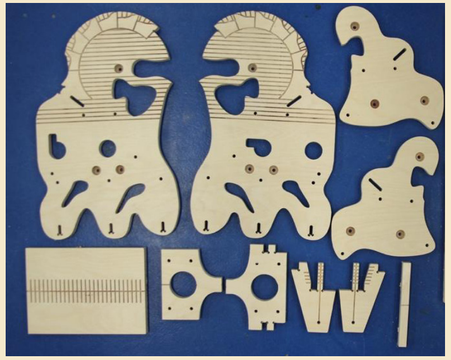
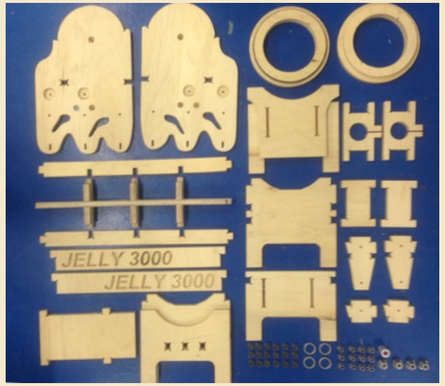


Image 7.8 & 7.9 The cut panels to assemble the first and second prototype CNC's of this research project.



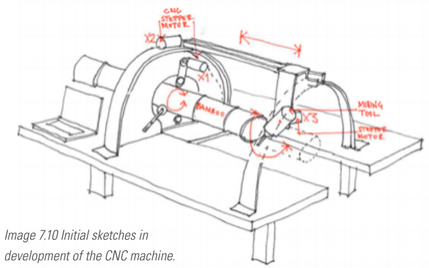


Image 7.10 Initial sketches in development of the CNC machine.

THE 'FLUTE MAKER'

The fundamental idea was to cut the end pieces of the bamboo accurately so that it would be possible to connect 2 bamboo elements; one end piece connecting to the side surface of the other. The components to the machine needed to be as simple and as common as possible so that anyone with appropriate instructions could construct their own machine, like a Wikihouse approach or building your own 3D printer. The first successful design combined many iterations and design variation. A 6-axis plasma CNC steel tube cutter was quite influential as it set the principles for positioning the axes in relation to each other.

The combination of stepper motors via chains and sprockets, a desktop computer and plywood enabled the creation of the first prototype. The logic of the hardware had to follow the software coding where, with the help of a research assistant - James Palmer, we were able to define the required language of communication between the digital bamboo intersection and the physical counterpart. The graphic below describes the key principles: from the required digital intersection of the bamboo elements, a geometrical surface is described from which numeric information is extracted based of X, Y & Z parameters. This information is split into 3 codes which instruct each of the 3 stepper motors to action, overall across the same timeline. The fabrication of the digital machine is based on "housing" these principles so that the end result is as desired. The design process iterated these relationships, through a process of fabricating 2 prototypes.

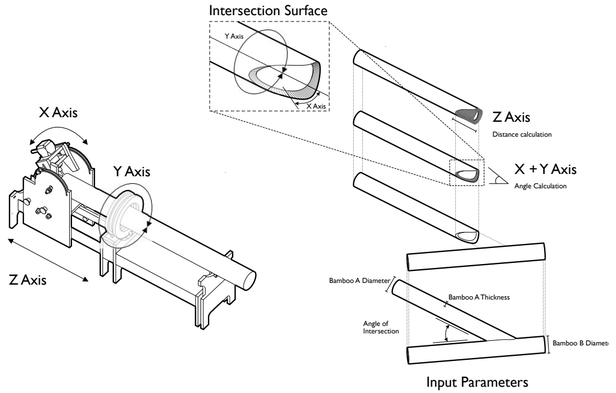


Image 7.11 Explanatory diagram of the relationship between the CNC axis's and the cutting of a fish-mouth or flute-tip

Images 7.12 & 7.13 Views of the first CNC prototype - Jelly 3000



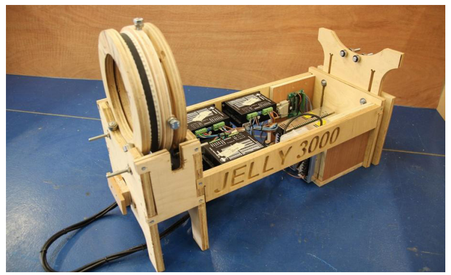


Image 7.14 Ricardo Assis Rosa assembling the CNC machine



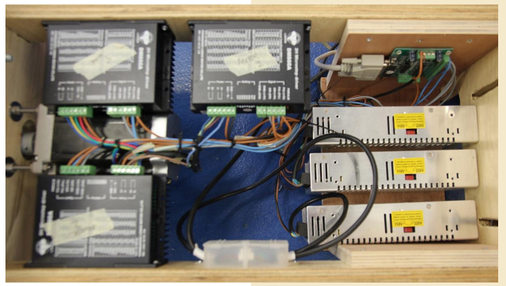
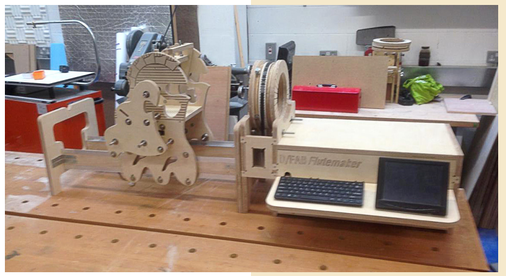


Image 7.15 The inner electronics controllers.

Image 7.16 View of the D/Fab Flutemaker





Each of the axes is controlled by a stepper motor, receiving data from the PC, which works with the 3D model in identifying the position of the intersections of the two cylindrical bamboo poles in order to create the appropriate cut to form a joint –referred to as the 'intersection surface'. Adjustments can be made to the angle, rotation and curve by adjusting the axes as required. The wheel holds the bamboo horizontally and can turn 360 degrees (Y). On the opposite side, a spindle milling cutter is housed in a moving containment (Z) which rotates (X) according to the required angle cutting into the lips of the bamboo which kisses the side of another.

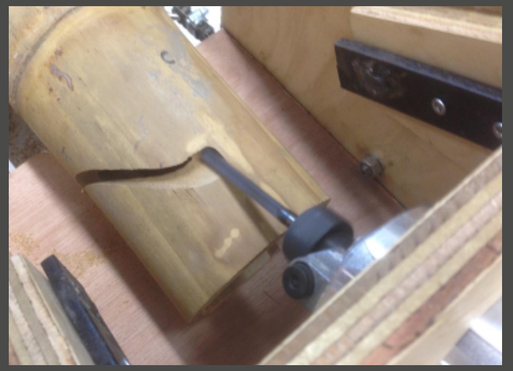


Image 7.17 X Axis spindle milling a flute-tip cut.

The "dance" of the 3 axes comes defined by the G-Code, the information-language extracted from the digital geometry, which tells what each stepper motor does at a particular time in synchrony with each other. The milling spindle (X) changes the angle of cut as each step of the 360 deg rotation (Y) adjusts the distance (Z) from the furthest point of the calculated geometrical intersection surface to the closest. Each moment in the cutting process will increase or decrease the angle of cutting to match the required curved surface.

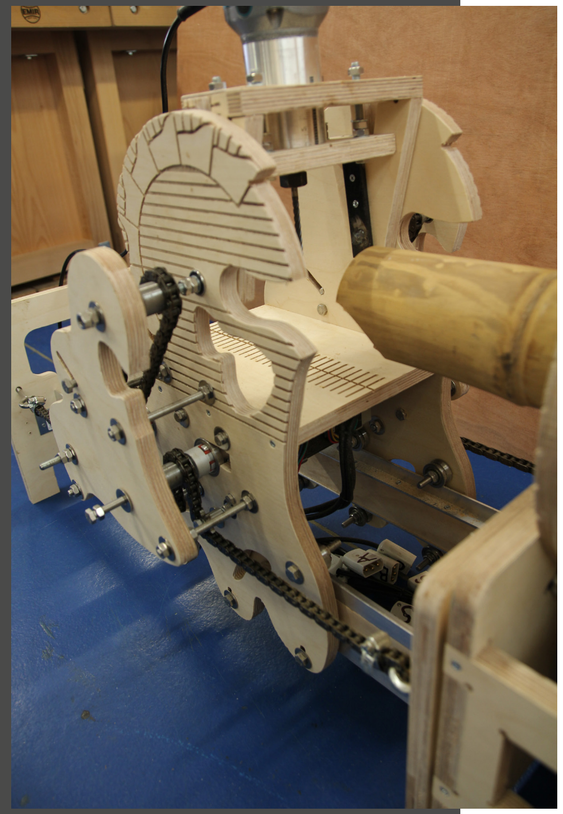


Image 7.18 Detailed view of the D/Fab Flutemaker



Image 7.19 Typical cuts.

With the design of the machine being easy to replicate with limited resources, the aim was to make the project open source, together with build and use instructions, thereby contributing to 'creative commons' and enabling the widest use within small, local and underfunded communities. The prototype performed adequately well in the workshop where it was built, as can be seen from the success of the cuts and joints depicted in the images above.



Image 7.20 Fishmouth joint cut by the CNC machine.



FIELD TESTING

With interest in testing the machine and the correlated processes from material to architectural form, we travelled to Colombia to test and further research with bamboo craftsmen. The machine had to be able to integrate the existing knowledge and contribute to the existing methods of fabrication, as an addition and enhancement of how bamboo can be applied to architectural construction.

We based the research fieldwork at Induguadua, a bamboo processing factory located in the heart of the bamboo region of Colombia. It processes Guadua culms from the forest, treats the material with Borax as an insecticide, dries the culms in heated chambers and prepares them for wholesale to construction firms by categorising them by culm diameter, wall thickness and length. The research was carried out at these industrial premises but simulated a similar context as if it had been on a functioning residential construction site. The reason for this choice was the access to processed bamboo, avoiding the need to pay for transportation costs.

Induguadua sell the bamboo culms typically at 6 m lengths. Though the bamboo naturally grows taller, using longer culms results in greater variation in culm diameters along the length of the bamboo. The deviation of the central axis also increases as the bamboo bends in its length.

For the above reasons, we decided to use 3 m length pieces to maintain more control over the diameter variation and curvature. For this, we sectioned 6 m pieces into parts that were geometrically more stable. With a selected source of bamboo, we were able to digitise the bamboo components and replicate these in the digital model.

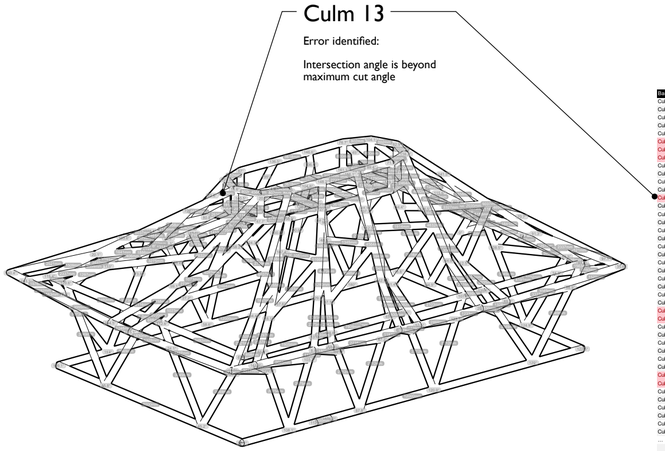
SELECTING THE BAMBOO WITH CONSIDERATION OF DESIGN IS JUST AS IMPORTANT AS DESIGNING THE JUNCTION DETAILING.

THE DESIGN PROCESS

Generally speaking, design is a feature that is present at all stages. Selecting the bamboo with consideration of design is just as important as designing the junction detailing. However, this section intends to focus on the integration of all the principles, methods and the process from conceptualisation to creation of the 1:1 form.

At the core of the process, the 3D digital model is the main 'holder' of the design proposal. It is the channel through which information is transferred to the digital fabrication machine, the manual fabrication and the assembly. In the pre-digital era, the designer would integrate this information in 2D drawings (plans, sections and elevations) at scales typically 1:100, 1:20, 1:5 and 1:1. 3D physical models were used to test individual components and the overall form. In utilising 3D digital computational methods, the model is built to scale in the computer, thereby enabling the design plan to be tested in a realistic manner. In contrast, 2D drawn methods have limitations, particularly in exploring 3D volumes and complex angular geometrical intersections and in viewing both the smaller detailing and the larger form. In utilising parametric methods, as in this project, along with the additional software of Grasshopper, the dynamic changes and variations of the geometry can be directly linked to parameters set by the designer. The parameters used entailed a design control related to the length and diameter of the bamboo and the angles of intersection. This enables dynamic control over these parameters, which can be adjusted in accordance with the limitations of the material, the technological methods of fabr ication possible and the desired form output until the most efficient form is identified.

Image 7.21 Design and form control through parametric data management



3D Model with Integrated Fabrication Data

Bamboo Identifier	Length	Culm Diameter	Culm Thickness	Intersects with...	Intersection Angle	Diameter of Intersection Culm
Culm 1	3048mm	80mm	22mm	Culm 4	55.1°	67mm
Culm 2	3073mm	73mm	19mm	Culm 23	55.1°	80mm
Culm 3	3073mm	68mm	17mm	Culm 26	97.8°	78mm
Culm 4	4000mm	85mm	25mm	Culm 152	124.9°	70mm
Culm 5	4500mm	67mm	16mm	Culm 153	59.9°	78mm
Culm 6	4500mm	71mm	18mm	Culm 168	138.6°	66mm
Culm 7	3000mm	81mm	23mm	Culm 191	140.8°	81mm
Culm 8	4037mm	74mm	19mm	Culm 2	99.2°	68mm
Culm 9	4632mm	69mm	17mm	Culm 3	55.4°	85mm
Culm 10	4037mm	65mm	15mm	Culm 59	109.1°	71mm
Culm 11	4632mm	80mm	23mm	Culm 97	124.6°	80mm
Culm 12	800mm	69mm	15mm	Culm 138	134.9°	79mm
Culm 13	800mm	65mm	15mm	Culm 158	138.3°	66mm
Culm 14	800mm	75mm	20mm	Culm 181	129.3°	73mm
Culm 15	800mm	73mm	19mm	Culm 3	124.9°	85mm
Culm 16	802mm	71mm	18mm	Culm 60	82.9°	78mm
Culm 17	802mm	75mm	22mm	Culm 73	91.3°	78mm
Culm 18	802mm	70mm	17mm	Culm 97	56.4°	80mm
Culm 19	802mm	80mm	22mm	Culm 138	55.4°	79mm
Culm 20	802mm	65mm	15mm	Culm 157	70.7°	66mm
Culm 21	802mm	67mm	16mm	Culm 180	141.3°	80mm
Culm 22	802mm	70mm	18mm	Culm 4	90°	67mm
Culm 23	802mm	72mm	18mm	Culm 6	90°	81mm
Culm 24	4382mm	80mm	22mm	Culm 140	67.4°	70mm
Culm 25	4191mm	83mm	24mm	Culm 141	112.6°	74mm
Culm 26	4062mm	81mm	23mm	Culm 143	67.4°	78mm
Culm 27	5188mm	78mm	22mm	Culm 144	112.6°	76mm
Culm 28	5188mm	84mm	24mm	Culm 146	69.4°	77mm
Culm 29	4062mm	67mm	16mm	Culm 147	110.6°	83mm
Culm 30	1447mm	79mm	22mm	Culm 5	90°	71mm
Culm 31	1558mm	84mm	24mm	Culm 150	55.1°	82mm
Culm 32	1447mm	85mm	25mm	Culm 151	124.9°	69mm
Culm 33	1558mm	67mm	16mm	Culm 153	124.9°	78mm
Culm 34	1073mm	80mm	15mm	Culm 6	90°	81mm
Culm 35	1641mm	72mm	18mm	Culm 119	180°	81mm
Culm 36	1073mm	82mm	23mm	Culm 119	180°	81mm
Culm 37	1641mm	79mm	22mm	Culm 121	112.8°	79mm
Culm 38	1958mm	80mm	22mm	Culm 122	67.2°	78mm
Culm 39	1403mm	79mm	22mm	Culm 124	69.1°	80mm
Culm 40	1958mm	67mm	16mm	Culm 125	110.9°	72mm
Culm 41	2464mm	66mm	15mm	Culm 127	67.2°	68mm
Culm 42	3275mm	70mm	18mm	Culm 128	112.8°	69mm
...	...	...	...	...	...	...

Output Data for Fabrication

As exemplified in the image above, the 3D model, in association with the data extracted from the parametric system, enables the designer to adjust the dynamic form in accordance with the parameters set by the system. This process enables the designer to adjust the 3D form to overcome the fabrication constraints (maximum angular cut).

The form utilised in the workshop was designed to incorporate complex angular, rather than parallel and perpendicular, sections of bamboo. This complexity forces a departure from conventional 2D thinking and enables the research to investigate more specific complexities that are possible only when utilising digital methods. This design was deliberately used to challenge the traditional craftsmen working on the project to build an object which was not predetermined in their construction experience. Thus, knowledge is formed, not from theory but from practice. The skilled workman is taught by his materials and his resources, and knowledge enters through his hand and therefore to his mind (Thompson 1992).

Typically, a craftsmen or builder relies on their experience of previous projects and replicates these without the need for a set of design plans. If the project were the construction of a typical barn, the craftsmen would know how to build the structure if they had built one before. This would also resemble construction from the pre-digital era, where the linearity and logic of the design would have evolved from the 2D conceptualisation of plans, section and elevation.

In conversation with Oscar Giraldo, our participating bamboo construction craftsman, he explained his approach to be quite distant from drawings. He builds the frame of the bamboo building using his knowledge of how joints are made and using general dimensions. The information from the architect is more of a guidance and relies mostly on the builder's ability to achieve the final form. Giraldo has worked with architect Simon Velez on several projects, in which the architect and lead craftsman would create typical details, prototypes and mock-ups of the building. The drawings were more of a tool for the architect, client and lead craftsman. The majority of the work is done by logical assumptions and prior experience of building similar projects. In reflection and discussion with Simon Velez, the craftsmen generally do not know how to read the drawings and how to conceptualise the 3D architectural form from 2D scaled drawings.

Roger Martines, the second bamboo craftsman participating in the research workshop, trained as a landscape architect. His experience with bamboo construction is quite extensive including overseeing the overall construction process from design to completion. For him, the drawings are a fundamental part of the process. This method of conceptualisation through scaled drawings and physical models helps him to study the building's form methodically. Roger had never used any 3D computer software to develop the design and construction process. but had expressed being open to using new technologies and innovative methods for fabricating with bamboo. Instead, Giraldo remained more conservative with the traditional hammer and chisel. This exemplifies that there are differently skilled craftsmen who work with bamboo. Whilst both craftsmen are clearly able to build structures out of bamboo, their methods of managing the design information and technology differ.

The research project was based on the notion that the collaboration between craftsman, designer and computer can generate innovative methods of designing and fabricating with bamboo. In this case, the structural form is clearly a result of computational design and the fabrication process must follow. Few projects that build with bamboo have been the result of a computational methodology and therefore my fieldwork research required the craftsmen to apply these methods in conjunction with their traditional approaches. In combination, these factors contribute to a greater capacity for innovation and the reinvention of craft practice (Blundel and Smith 2013).

'If making is knowing, it does not follow that all makers "know" their craft. They might know how to produce an effective, economical, or detailed result. But this does not mean that they can change completely, reverse, or deconstruct their techne in such a way as to challenge established thinking about this craft.' (Lehmann 2012: 151)

By physically working alongside the craftsmen, the knowledge gained in the research furthered the understanding of the challenges, opportunities and constraints deriving from the engagement process. By working as a team, we were able to share perspectives, experiences and skill in achieving a 1:1 form. We all worked with different technologies and methods to both conceptualise the design to fabrication and contribute to a richer understanding of where innovation can improve the process.

Working with computational design methods was challenging for the participating craftsmen, showing the difficulty of integrating the proposed system with existing craft and therefore the need to translate the design interface into an accessible language for building instruction. The integration of computational systems and craftsmen needs to be translated into a simple platform that resembles the traditional method of 2D plans, section and elevations. This therefore entails that the digital designer and digital fabricator have a different set of skills to the current designer and craftsmen working with bamboo structures. The design-to-machine system could be integrated into the construction process already under way but would require new individuals with distinct educational and skill sets.

FABRICATION METHODS

On the research workshop we tested and compared three different fabrication methods: Hammer and Chisel (HC), Cup Saw (CS) connected to a drill and the Digital Fabrication (DFab) tool. The analysis is presented in three main categories of Mind, Tool and Matter.

The following table analyses the performance of the fabrication process. A grading from A[4] to D[1] has been given to each category in relation to the three fabrication methods.

	Hammer & Chisel	Cup Saw	DFab
MIND			
Design information	C 2	C 2	A 4
Overall aim, understanding of architectural 3D form	D 1	C 2	A 4
Experiential knowledge of bamboo crafting	A 4	A 4	D 1
Subtotal	7	8	9
TOOL			
Skill level (manual)	A 4	B 3	D 1
Skill level (digital)	D 1	D 1	A 4
Accuracy	C 2	B 3	A 4
Control over tool process	C 2	C 2	A 4
Safety	D 1	C 2	A 4
Jig setup	D 1	C 2	A 4
Speed	A 4	A 4	C 2
Subtotal	15	17	23
MATTER			
Cut output as per intended	C 2	C 2	A 4
Material behaviour/resistance	C 2	B 3	A 4
Connectivity of joint (edge surfaces)	C 2	B 3	A 4
Contribution to form/accuracy & stability	C 2	C 2	A 4
Subtotal	8	10	16
OVERALL PERFORMANCE	**30**	**34**	**46**

Image 7.22 Criteria analysis during the ststem testing

Mind here refers to the mental process of the craftsmen, in particular their ability to conceptualise both the design intent, to apply their tacit knowledge of their craft and to execute the manufacturing process in relation to the final output. The low scores signify the disconnect between the overall design information, the fabrication of that specific element and the overall architectural form. The craftsmen tend to be dissociated from the overall architectural design process and instead focus on the fabrication of a specific component. This is typical of the hierarchical, segregated method imposed by the annotative nature of traditional design and build, 2D plans, section and elevation (Carpo, 2011). The design information is broken down into fragments and into craftsmen skill sets. Whilst this is unavoidably complex in architectural projects, it reveals that the scope of knowledge involved in the design and therefore the responsibility of delivering components with consideration to the limitations of the craftsmen's mind are disconnected in terms of design to fabrication flow. The Dfab tool is intrinsically connected to the design information, the 3D model and the physical form output. Whilst we do not want to argue about the nature of the mind in regards to a computer, the design information is embedded in this thread as the knowledge is embedded in the computational system. The digital craftsman operating the system is much more aware of the holistic design process, while their manual craftsmen counterparts view the process in a more fragmented nature.

The experiential knowledge required of each non-digital craftsman is high as this knowledge is imperative. Both the Hammer and Chisel and the Cup Saw methods require years of experience to master. The nuances of the mind, tool and matter require experience, skill and ability (Pye 1968, Dormer 1994). In contrast, in the case of the Dfab, the ability to perform the same operation (to intersect bamboo culms to construct joints) requires little experience as the computational process encompasses this ability. This is a great advantage in the advancement of the use of bamboo for construction as fabricators therefore require little craft skill to achieve the same results. The counterargument, of course, is that these digital operators require computational training. However, if the Dfab system's interface is developed through a simplified set of computational functions, the application of this method can be trained over a period of a few days. Operating a machine nevertheless requires a different set of mind skills compared to the subtle nuances of art found in the craftsmen using traditional methods.

In analysing the knowledge required for working with the tools for the task, the Hammer and Chisel method has a higher level of uncertainty and risk. The skill required, exemplified by the extensive cutting experience of Oscar Giraldo, is higher than the other tool sets due to the need to hit the chisel manually with the right force at the correct angle as a result of the resistance of the material. Issues arise due to the linear grain of the bamboo, which creates a deviation from the intended cut path. The best output occurs when the fewest strikes are performed because each movement against the grain has a stronger resistance and therefore forms a less accurate overall cut. In contrast, making subsequent adjustments to improve the intersection cut is more difficult.

The Cup Saw method, operated by Roger Martines, afforded more control over the cutting process as the speed of the drill and the teeth of the saw overcame the resistance of the bamboo. The problem with this tool is the pre-imposed diameter set by the cup itself, so many adjustments of partial cuts are used to create the overall intended elliptical surface. This results in a wavy approximation of the intended line of intersection and therefore the wall surface of the bamboo's intersection does not adjoin the diameter of the receiving bamboo culm.

The Dfab system knows the precise intended elliptical intersection pathway as the computer records the diameters of both culm participants in the joint. This is a complex geometrical form which is almost impossible to be retained in the mind of a person, particularly if the intersection is not 90 degrees. The manual craftsmen guess this line of cut by testing an approximation against the receiving culm until they find an approximated intersection surface. This approximation and guess work is a skill controlled by the craftsmen but implies a lack of accuracy and quality, particularly if the overall architectural form is more complex and requires specific angles to be constructed. This further exemplifies poor control over the process of cutting the correct joint connection.

The safety of working with the tools is also a key issue as the manual processes are generally executed on the ground, with craftsmen having to kneel with the bamboo between their legs or holding it with their feet on a stool. This further exacerbates the lack of precision and control, as well as increasing the danger of cutting oneself with the tools. Instead, the Dfab system securely holds the bamboo and the cutting process is done without the operator needing to be close by. The inherent jig set-up in the Dfab machine allows for full control and safety whilst the joint is being cut. The downside of the Dfab system is the required time to set up the bamboo, prolonging the cutting process. In the competitive tests that were carried out, both manual processes took approximately 10 minutes to perform a cut whilst the Dfab system took 17 minutes. The latter system could be further optimised by redesigning the bamboo clamping system to use springs rather than being bolt pressured.

In the overall analysis, the Dfab system scored significantly higher, with 35% greater performance compared to the Hammer and Chisel method and 27% compared to the Cup Saw method. The key features being design control, accuracy, control over the process, jig set-up and safety.

ASSEMBLY AND FINAL FORM

The conversion of drawings and digital simulations to physical reality always presents a challenge and much of computational design and digital fabrications are researching ways to optimise this (Carpo 2011). The fabrication of the bamboo joint elements only makes components but these then need to be assembled to ultimately complete the structural form. This process requires innovative solutions to improve accuracy and precision so that the final form closely resembles the intended design form. Variations occur and tolerances increase, angles change, the material adjusts, compresses and varies in tension in ways not previously predicted. This is especially true when working with natural materials that have specific responses to physical and environmental conditions (Hensel 2013).

In the fieldwork research we had specifically designed an architectural form that did not follow the conventional parallel and perpendicular geometry. This forced a more direct relationship with the computational design information as each component of assembly required a geometrical relationship to its neighbouring component specific to angles of cut and assembly. This became a problem specifically when working in conjunction with the Hammer and Chisel and the Cup Saw fabrication methods. On account of its inaccuracies in achieving the specific angles, the architectural form started to divert from the original geometry. The Dfab was able to fabricate more accurately as the precision of intended cut was directly correlated with the digital model.

As the architectural form started to emerge this became the design model. A departure from the digital model became necessary. To adjust the design model to the realities of the physical and material form, the model was measured against the physical model and this data was transmitted back to the computer. For this, we utilised cloud scanning to create a new model that we could impose on the original form to correct the deviations. This approach introduced another innovation to the system by creating a feedback loop between the design form and fabrication to physical 1:1 form. Utilising scanning methods is therefore ideal to construct a live model.

We also devised a solution for providing greater precision for manual fabricators by printing the intersection line onto paper which would then be rolled over the bamboo giving the craftsmen a more precise cutting guideline. This is an innovative solution not found elsewhere in the literature, which created a semi-digital method of fabrication, improving on existing manual tooling and crafting systems.

Despite these areas for improvement, overall the development of the DF tool is a success. The cuts it created were certainly usable in a construction setting, and the automation of cutting suggests that building with bamboo could be done faster and more accurately by circumventing the need for the craftsmen to be skilled beyond the ability to operate the machine. The traditional method of cutting joints is a time-consuming process. The “Flute Maker”, even in its prototype form, can certainly improve on efficiency, as well as accuracy.

Moreover, following the field testing, the following areas for potential improvement were identified:

One limitation of the prototype design was that the range of the x-axis was small and thus the angle between the two pieces of bamboo was restricted. The angle could not be cut too acutely as the more acute the angle, the further the milling machine had to reach along the bamboo pole. The range could be extended on future designs. Moreover, improving the x-axis range would also increase the range of possible angles for the machine to cut.



The distance between the centre of rotation of the x-axis and the length of the milling tool creates less tolerance in the system and thus overall tolerances could be improved by adjusting the centre of the x-axis rotation.

The position of the y-axis rotator (the 360-degree rotator) makes it difficult to insert and remove the bamboo pole. Therefore, a grip-lock system could be introduced to reduce the time needed to insert and remove the bamboo and to improve the ease of setting the central axis of the bamboo in the central x-axis rotation.

The further away the z-axis is from the y-axis, the greater the turbulence in the cutting, as the y-axis is the only point holding the bamboo. Identifying a better way of stabilising the bamboo would improve the quality of the cut overall.

The knowledge gained from the fieldwork should be used to determine how it could be used to empower small communities, in which resources are few and technology limited, to enable greater self-management with regard to bamboo construction.

A compendium of knowledge that is shareable and accessible could be created, which can be built on as resources improve and knowledge is disseminated. This should be done whilst ensuring that traditional crafting methods are still honoured, passed on to new craftsmen and also used to inform how we might combine old and new to create better futures and better structures for all.

The Dfab machine itself was conceptualised to address the joint technology, yet the system is larger than just this technical component. The research aimed to investigate the holistic process from a bamboo culm to an architectural form. This resulted in four major sections of analysis: The source material, the design process, the fabrication technologies, and assembly and final form.

Overall the research workshop was a great success, providing useful data for analysis by testing the digital systems against the non-digital processes. The conclusions of the fieldwork provided clear guidelines as to how the overall system from material to form can be achieved and clearly evidenced the innovations and contributions regarding the ways in which bamboo and digital fabrication can be utilised for architectural design and construction.

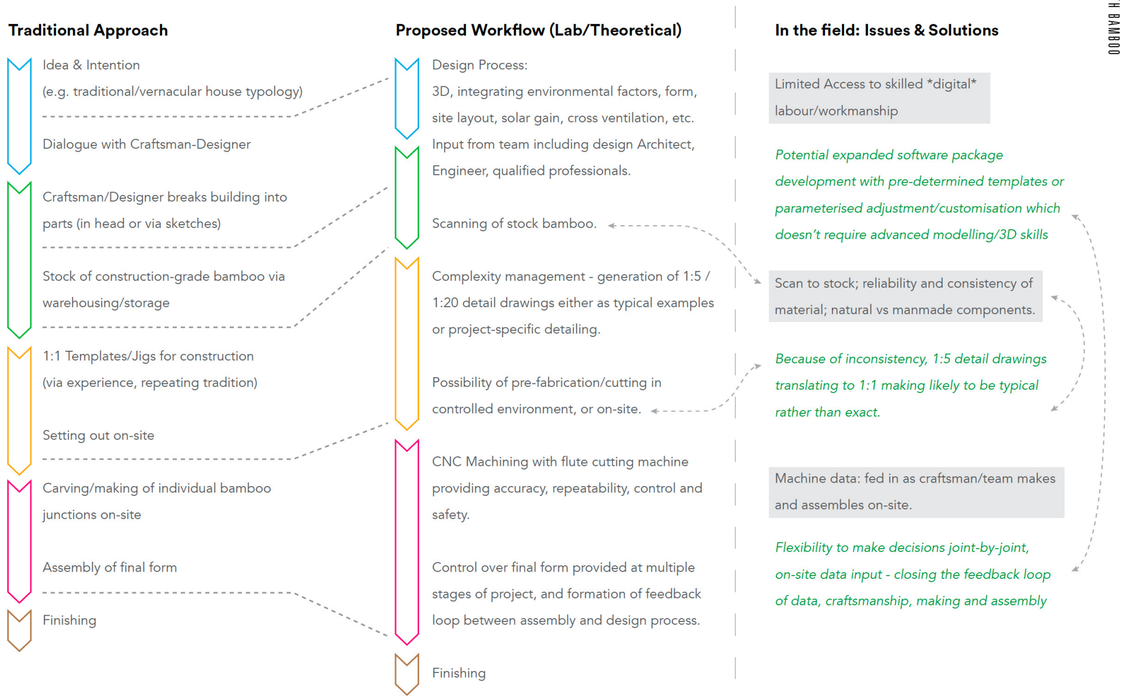
Summary of innovations and contributions to knowledge:

- Digitalisation of bamboo stock to construct 3D digital models specific to the dimensions and characteristics of the material.
- Computational model which contains all necessary information for fabrication and design.
- Parametric control over a dynamic design feedback loop.
- Dfab system required little previous experience of bamboo crafting and tooling to achieve higher accuracy of joint fabrication and architectural form.
- Precise cutting and higher accuracy for multiple angular junctions.
- Higher control over tool and material through Dfab jig set-up.
- Higher safety in fabrication process.
- Feedback loop between 3D physical 1:1 architectural form and digital model through cloud scanning.
- Printed cutting template for manual fabrication of a higher accuracy for joint connections.

Image 7.23 Table analysis and evaluative comparaison between existing digital fabrication technologies and the Flutemaker.

Category	**Existing Digital Fabrication Technologies** *CNC Tube Laser Robot Arm etc*	**Flute Maker**
INPUT/INSTRUCTIONS	CAD curves / 3D model data in form of mesh/NURBS. Generated by external CAD/CAM software, translated into toolpath/G-Code by propietary drivers/software. Generally requires understanding of both CAD software for generation of cutting files, and operation of machine for optimum toolpaths.	Simple input of known/measurable parameters such as bamboo radius, desired angle of joint, thickness of material, etc. Internal software converts this to cutting path.
ADAPTABILITY IN CONSTRUCTION PROCESS	Designed and optimised for pre-fabrication of individual elements in a controlled environment off-site. Designed for extremely low tolerances of raw material (flat sheets, perfect cylinders), and corresponding high degree of accuracy.	Equally suited to on-site use as off-site pre-fabrication. Designed for use mid-assembly to fit with traditional craft approach and to maximise craftsperson expertise on-site.
COST	High or extremely high cost per unit, designed for return on investment when used in a rapid production, controlled and repetitive manufacturing environment.	Extremely low comparable cost per unit, designed for small/medium-sized enterprise.
ABILITY TO CARRY OUT GENERALISED VS SPECIFIC TASKS	Designed for extremely generalised tasks. Larger effort in setting up a "job", but can handle arbitrary degrees of complexity. Generally bad for single cuts (long time to set up per job), good at jobs requiring multiple cuts of a single stationary material.	Designed for specific task (flute tip cut of a particular bamboo species). Quick setup of each job/set of cuts. Designed for quick changes of raw material. Unable to handle completely arbitraty degrees of complexity without providing alternative g-code.

Image 7.24 Diagramatic explanation of the proposed workflow contributions to the traditional approach, highlighting too the theoretical and "in field" issues and solutions. This also highlights areas for further research and development.



8.

SYMBIOTIC DESIGN APPLICATIONS AND THE CIRCULAR ECONOMY

To demonstrate the applicability of the principles established in this thesis, in digital technologies and in traditional craftsmanship, and as a way of evidencing the advancement in bamboo design and fabrication, this chapter will outline the applicability of the research principles in four design projects. The aim is to address the problems identified in the existing landscape of bamboo fabrication, namely (1) the level of skilled labour; (2) the dynamic between design, making and craftsmanship; and (3) quality control, engineering and aesthetics. This chapter further places the discussion in (4) the socio-environmental-economical context of the circular economy.

Image 8.1 Rendered view of the bamboo, ETFE and steel canopy proposed for Bogota

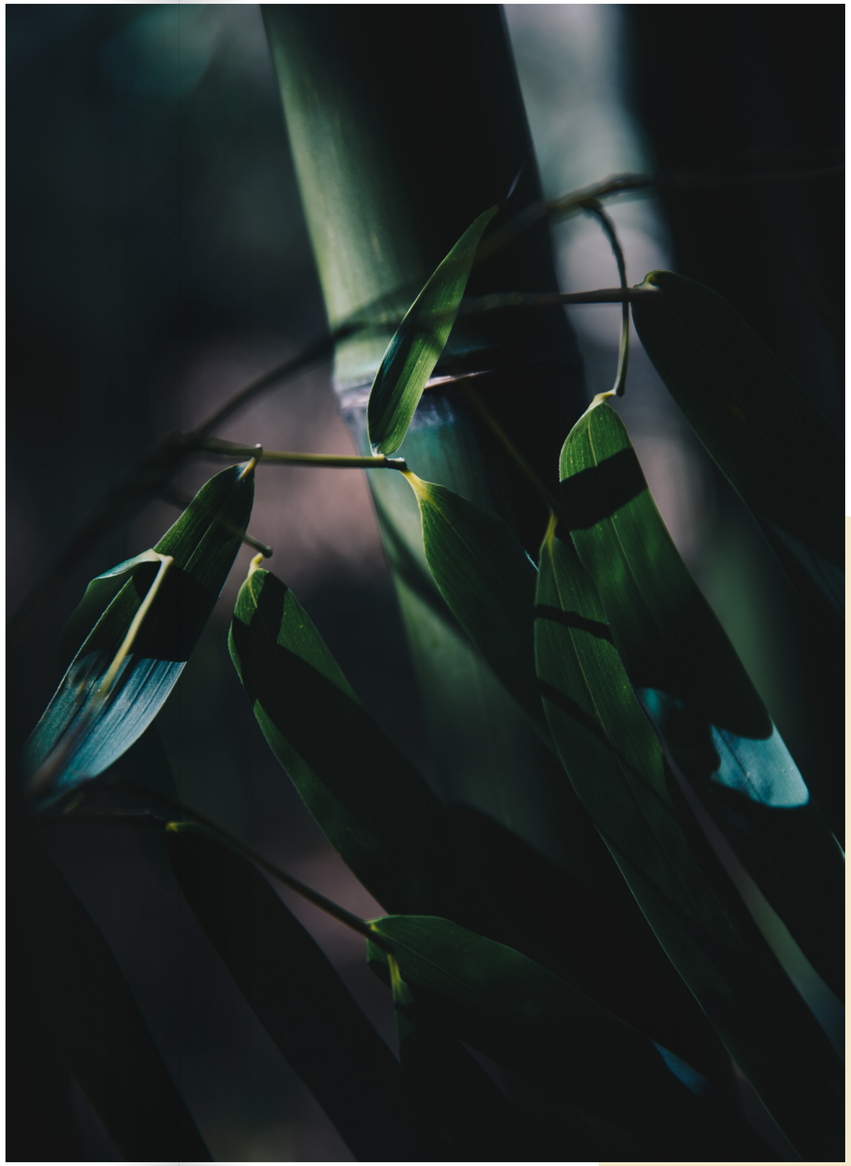
THE CIRCULAR ECONOMY SHOULD BE A CONCEPT FOR SUSTAINABLE GROWTH INVOLVING DESIGNING PRODUCTS, SERVICES AND SUPPLY CHAINS THAT ARE 'REGENERATIVE'.

THE CIRCULAR ECONOMY

In a world in which human consumption and production practices are having increasingly detrimental effects on the global environment, social equity and long-term economic stability (Rees, 2010; Vlek and Steg, 2007), the challenge is to devise new strategies which sustain an economic structure whilst simultaneously supporting the environment. The concept of the Circular Economy is one that is increasingly attracting support from policymakers, academics and environmentalists. It proposes a cycle in which production and consumption have negligible environmental impact yet still enable economic growth (Geng, 2009; Webster, 2015). Better still, the model not only promotes growth in a non-degenerative way for the planet, it also encourages social equity and improves material usage through reducing the rate of extraction of raw materials by promoting the recycling of those already in use.

The Circular Economy model seeks to focus on those processes that provide positive progress for the economy and the environment by creating a backstop between the consumption of finite resources and the production of waste by seeking to employ renewable energy sources, materials and processes and by seeking to progress the removal of waste from the model as a whole.

By comparison, a linear economy – the "take-make-dispose" principle which we have operate until now – cannot enable sustainable development because resources are finite. The environment is fragile and becoming increasingly so. Overall, the current process of continual depletion and contamination, requiring waste-treatment at best and waste-burial at worst, offers little possibility of the global renewal of resources or infrastructure. Nor does it enable social equity by empowering communities and individuals to best use the resources and facilities that they have on hand to improve, build and grow their economic stability (Hoekstra and Wiedmann, 2014; Costanza et al, 2014).



As yet, a sufficiently all-encompassing definition of the Circular Economy has still to be established, leaving wide gaps in understanding when seeking to apply it. Julian Kirchherr, Denise Reike and Marko Hekkert. (2017) have created a base definition:

"an economic system that replaces the 'end of life' concept with reducing, alternatively reusing, recycling and recovering materials in production/ distribution and consumption processes." (Kirchherr et al., 2017)

This definition, however, does not sufficiently encourage the use of materials that are naturally more circular, such as bamboo culms, which are used in their natural state and subsequentially returned to the ground to decompose. The above definition focuses on there being allowed use of non-sustainable materials, requiring high levels of energy to reuse and recycle. The Circular Economy should be a concept for sustainable growth involving designing products, services and supply chains that are 'regenerative' – that is, based on renewable energy and resources. A 'regenerative' system does not generate waste – it keeps products and materials in use, while building economic, natural and social capital. "Bamboo could be a critical component in the transition to a circular economy, by providing a viable, bio-based alternative for non-renewable, carbon-intensive 'techno-cycle' materials" (Lugt, 2019, p. 1). Despite the resins, laminates and glues which are used in bamboo construction, many durable bamboo materials are still a preferable, more 'circular' alternative to abiotic materials. There is particularly a strong case to be argued and subsequently researched in significantly minimising the use of concrete in the construction of buildings by using bamboo and timber alternatives. Finally, because bamboo products typically generate numerous valuable by-products, this plant is naturally well-suited to use in 'closed loop' circular value chains, in which all parts of the plant are used for value-added applications and minimal waste is generated. In certain parts of southern China, these value chains already exist and have the potential to be replicated elsewhere (Lugt, 2019). In short, bamboo offers an available, scalable circular solution to current, linear models of production and consumption.

FRAMEWORK FOR THE CIRCULAR ECONOMY

A conceptual framework has been developed in this thesis which adheres to the three dimensions of sustainable development:

- Social integration: to contribute to a system of equality of opportunity by the creation of a low-cost digital fabrication method which can be adopted by small industries, workshops and individuals in regions where typical investment in digital technologies would be inaccessible. This can enhance social opportunities with a regional character, evolving the vernacular and cultural knowledge. This can further enhance both the quality of life and sustainable human development, thereby liberating individual capacities and enabling fulfilment of human needs, offering a secure life with full rights and liberties through socio-economical cohesion.

- Environmental responsibility: by utilising local natural resources, without undermining the equilibrium and integrity of ecosystems, whilst also reducing the burden on the environment by not utilising materials which undermine the sustainable vision of this system. The proposals in this chapter, therefore, are formed on the distinctive identity of the particular socio-environmental context, avoiding generalist architectural proposals which are globally more common, utilising excessively and unnecessarily concrete, steel and glass in favour of environmentally responsive forms and natural local materials.

- Economic efficiency: efficiency of economic and technological activities, fostering investment and productivity, economic growth and economic output, without detriment to social integration and environmental responsibility.

Amongst the challenges is whether the framework should be applied 'top down' or 'bottom up'. A 'top-down' approach – commonly applied by government institutions or similar – often fails to take into account the perspectives of all the parties involved, imposing rather than implementing, and is therefore vulnerable to a lack of support. A 'bottom-up' approach – instigated by individual action – is often not widespread enough in its implementation (Cairns, 2003). Both approaches can cause friction and conflict between involved parties, whereas the most effective form of implementation is one in which a collaborative approach is adopted. In this approach, the planning process includes the exchange of responsibilities, needs and control, including all stakeholders in the processand thus reducing conflict and encouraging support (Simon, 1989).

This approach to the Circular Economy could be applied in the design, production, and building processes as an innovative approach. Indeed, collaboration between all stakeholders involves the development of social equity by empowering all individuals and organisations involved in the process, thus making best use of knowledge, skill, available technology, cultural tradition and local resources. As such, issues such as social welfare, training, establishing and sustaining local communities and disseminating knowledge and resources between all stakeholders can also be incorporated into the process. Even the most high-tech production line can benefit from the local craftsmen's skill, and even the smallest of technological advancement of resources can be a boon in a small-scale community seeking to be self-supportive.

We should adhere to the principle of 'design global – manufacture local' (Kostakis, Niaros & Dafermos, 2015). This approach encourages the sharing of knowledge, training and know-how from practices and experiences around the world whilst utilising local materials, labour and equipment. This would avoid, for instance, steel being shipped from India to South America by using local bamboo processing plants and construction firms.

The world of construction has still quite some way to go before it embraces a truly circular model; however, a transitional phase could be one in which sustainable material are re-used and unsustainable materials are replaced. From an architectural design perspective, it is not just the materials that need to align with the principles of a Circular Economy but the appropriate form of the building in response to the climate, the spatial organisation to meet a long-term social-economical use, and intelligent construction to optimise the use of material, as well as the performance required to service the building for long-term use. The life expectancy of buildings needs to improve, as well as the efficiency of the construction to de-construction cycle. There is no point in speaking only of the circularity of the materials without emphasising the importance of designing buildings which meet the social, economic and environmental needs for a long-term lifespan, minimising therefore the need to re-use and recycle.

The concept of resilience is also an important aspect of the Circular Economy as this provides important considerations for projects, particularly for new innovations – these being resilience of methodology, resilience of process and resilience of strategy. The first time the aim of the 'green economy' was stated to be strengthening the level of resilience of the built environment was in the UNEP's 'Global Green New Deal' documents in 2008, and it was later stated in the OECD's 'Towards Green Growth' in 2010 (UNEP, 2008 and OECD, 2010). These stressed that there are two areas in which the green economy and its circular process might influence the built structures of the future: first, adaptation to macro-climatic change and the micro-environmental impact that this has; and second, adaptability in dealing with the problems caused by the increased scarcity of source materials and the non-renewability of some natural resources.

The four projects developed in this chapter respond to the parameters of a Circular Economy and to the proposed technology of this research project. The first project proposes a small industrial model where, in a workshop, trusses and wall components are fabricated using digital fabrication methods to standardise, control and produce pre-fabricated components for residential developments. The second design project seeks to demonstrate the applicability of the portable digital fabrication system on-site where bespoke components can be constructed for specific individual buildings. The third project is an innovative node connection for a grid shell structure, demonstrating how digital computation and fabrication can advance both the design of the geometrical form of bamboo as well as the construction-joining technology. The final project is a façade structure applied to an existing high-rise building which alters the environmental condition of the building following a computational design process, demonstrating the applicability of bamboo in larger construction projects that use more industrial high-end tools in urban environments. A core essential of any sustainable design is to combine spatial and material organisation within a project, enabling the design to respond to the local environment.

The proposed design projects respond to the challenges discussed throughout this thesis:

1. Overcoming the limitations of bamboo culms (variability of dimensions, shape and density)
2. The skill required to execute the proposals
3. The tools and technologies needed to fabricate proposals
4. The control of design and engineering throughout the process
5. Quality and aesthetics at multiple scales
6. Integration with the principles of the Circular Economy (within local communities: the use of local labour and local materials that are spatially and aesthetically suitable).

PROJECT 1: SMALL INDUSTRIAL FABRICATION PLANT

Image removed due to copyright restrictions

Image 8.2 Types of tooling used in the fabrication of joints. Note the lack of precision in the jigs and the reliance of the user on 'eyeing out' the accuracies. Note also the level of safety. Images source Gernot Minke

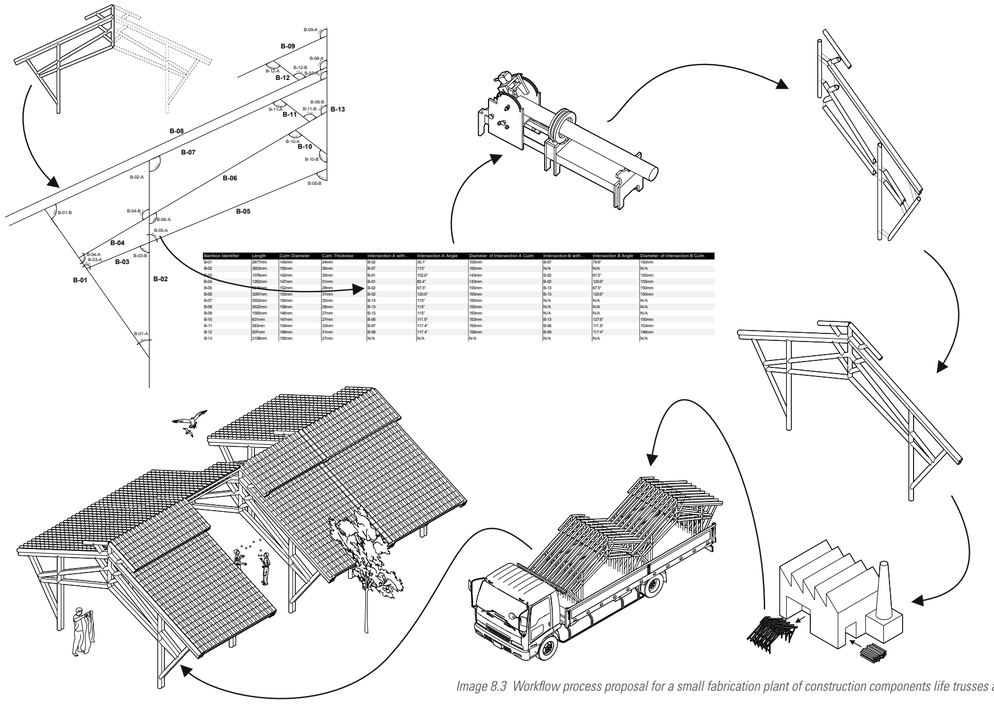
One of the key challenges observed in the research is the tools and methods available to bamboo carpenters. The methods for fabricating joints on site, as shown in the images below, are quite basic and offer little opportunity for precision, safety and control.

As discussed in the previous chapters, the CNC machine developed as part of this thesis offers a direct solution to this problem as the machine setup itself offers a fabrication jig with high precision and control, thereby addressing existing shortfalls and providing new methods for controlling the quality of workmanship. In this proposal, the fabrication system, from design to components, is achieved by setting up a workshop in which the contractor can fabricate replicable components, for example, a truss component for a dwelling.

The management of bamboo stock is done in the workshop, where it is prepared and graded to suit different components of the truss. The computational system, previously set up for this component, permits the technician to input the numerical data into the system and helps set up the bamboo for cutting. The technician follows a procedure by sequentially cutting members and assembling the truss on a large setup table. Once this task is completed, the technician repeats the protocol until several trusses are cut and assembled. This proposal is common in timber, steel, aluminium, etc, where fabricators build components which are delivered onto construction sites. However, from the research carried out there is no bamboo system like this. When this idea was presented at Induguadua, the bamboo processing plant in Colombia, they were very keen and thought it would be a great contribution to the industry.

Whilst this system required little craftsmanship and design, other than setting up the components, the process is about replicability and consistency. This system clearly controls the variability of the material through the design coordination of the stock and computer data management system, which feeds the right dimensions for the required node connections. Utilising the CNC machine in a workshop setting, the quality and aesthetics of the joints is under full control.

This system overall is an excellent contribution to the principles of the Circular Economy as it is empowering members of the community to set up a small industrial business contributing to the local construction industry and thereby supporting the local economy.



Bamboo Identifier	Length	Culm Diameter	Culm Thickness	Intersection A with	Intersection A Angle	Diameter of Intersection A Culm	Intersection B with	Intersection B Angle	Diameter of Intersection B Culm
B-01	2817mm	142mm	24mm	B-02	35.1°	102mm	B-07	152°	152mm
B-02	3635mm	155mm	28mm	B-07	115°	152mm	N/A	N/A	N/A
B-03	3139mm	140mm	22mm	B-01	35.1°	142mm	B-02	115°	155mm
B-04	1585mm	142mm	24mm	B-01	95.6°	102mm	B-02	125.6°	155mm
B-05	N/A	152mm	28mm	B-02	97.5°	155mm	B-13	57.5°	152mm
B-06	5387mm	158mm	31mm	B-02	120.5°	155mm	B-13	126.6°	152mm
B-07	3922mm	150mm	26mm	B-13	115°	152mm	N/A	N/A	N/A
B-08	3622mm	158mm	28mm	B-13	115°	150mm	N/A	N/A	N/A
B-09	1585mm	148mm	27mm	B-13	115°	152mm	N/A	N/A	N/A
B-10	835mm	147mm	27mm	B-08	111.5°	153mm	B-13	127.5°	150mm
B-11	985mm	154mm	29mm	B-07	117.4°	152mm	B-08	111.9°	153mm
B-12	1870mm	148mm	31mm	B-08	117.4°	158mm	B-09	117.4°	148mm
B-13	2139mm	150mm	27mm	N/A	N/A	N/A	N/A	N/A	N/A

Image 8.3 Workflow process proposal for a small fabrication plant of construction components life trusses and wall panels.

This is a great example of a globally light, locally heavy system, as the machine set-up and know-how is available through creative commons and the resources and delivery are local. Examples of this approach are Peter Stoutjesdijk's puzzle house, which was constructed with digitally fabricated pieces that are interlocking and erectable in five hours, and are made of CNC-milled panels of reused-wood, waterproofed with nano-coating chemicals; Alastair Parvin's WikiHouse project – an affordable and accessible alternative house design (Archdaily, 2013); and Bensonwood's automated timber frame home build kit, now manufactured and assembled in Keane, New Hampshire, US (Bim360.com). Each of these projects uses a digital fabrication tool programmed to cut a reproducible basic fabrication system that can be used for a

multiplicity of construction projects, from small business and factory units to homes and larger scale communal buildings. The beauty of the concept is that it enables easily erectable and accessible building elements to be formed and cut from a variety of materials (many are sustainable – timber, bamboo, and composites thereof) and then put to use by local workmen and craftsmen, working on-site with local knowledge and skills but making use of basic technology. The projects themselves can be complex – Peter Stoutjesdijk's puzzle house is so-called because it resembles a puzzle – or simple – Bensonwoods self-build kit is a master of simplicity – but what they each do is bring ease of build to small local communities where technology is limited but communal need is great. These projects power the circular economy by empowering local tradesmen to achieve what one would once have expected only from far greater industrialisation. As Stoutjesdijk claims, an internet connection is all that is needed:

"where the first industrial revolution democratized consumption, the next one is expected to design and democratize production through digital networks of shared knowledge and digital fabrication devices." (Archdaily, 2013)

Stoutjesdijk's homes were designed to counter the desperate need for housing in Haiti after the massive earthquake of 2010 left hundreds of thousands of people homeless. They are indeed an iconic example of the circular economy in action, supporting, and raising up a community in the throes of disaster, enabling it to return to stability, and growth. It seems that both the spread of urban poverty in the future and the results of natural disaster – perhaps attributable in at least some part to global ecological issues – has found a champion in open-source design in this way.

The excellent work being carried out in the Philippines by Base Bayan is a perfect example of where this system would really contribute to working methods. They have implemented one of the most successful development projects that I came across in the research that utilises bamboo in social housing. The project has regenerated and socially integrated an appreciation for bamboo as a housing material and has provided for many years training and research development to suit the local social, cultural and environmental conditions. The system presented in this research would merge seamlessly and aid in the fabrication of housing components.

Image 8.4 - 8.9 from the BaseBahay project in the Philipines demonstrating the current fabrication methodology of housses in components . This examplifies a working methodology where the CNC machine could be integrated as a way of automising aspects of the fabrication and to enable the advancement, improvement and innovation of housing construction with computational design and fabrication workflows. This would aid to the skills and abilities of the already well functioning craftsmen teams. These types of case studies are excellent for other location globally where bamboo is native , contributing significatively to the resources and knowledge of house building in communities.

Images removed due to copyright restrictions

8.
DESIGN APPLICATION

PROJECT 2: COMMUNITY HUB

The anatomical features of bamboo offer unique functional and structural properties. Unlike trees, bamboo growth is mainly longitudinal with differentiation in the anatomical distribution of fibres and cells along the height of the plant. The percentage of fibres is much higher in the outer third of the wall than in the inner, and in the upper part of the stem compared to the lower part. "The distribution of fibres and bundles is differentiated according to the height and slenderness, so that the upper parts of the stem consist mainly of smaller vascular bundles with a higher proportion of fibres, ensuring that, as the slenderness increases, so too does the material strength increase appropriately to the increased loading stresses of wind and water on the higher parts of the plant" (Weinstock, 2006, p. 30).

These morphological characteristics are key design principles that can be optimised and integrated into design. Building upon this knowledge, the design of the joint system and the overall geometry of the form can collaborate to achieve the potential of both.

Design influences – Joint technology

The most important aspect of bamboo construction is the formation of joints that transfer forces from one element to another. The most common of these connections is called a 'fish mouth' and is perpendicular to the receiving bamboo section. If the cut is inclined, it is called a 'flute tip' (Minke, 2012, p. 41). The flute tip is the specific joint type that this thesis has developed and applied as a joint typology. As the flute tip deals with the multiple angles to the centre line (see image below) it also includes the fish mouth which is one of the possible angles within the range – the moment in which the bamboo is symmetrical to the centre line.

Generally, flute tips are avoided in favour of fish mouth joints because of the difficulty in knowing how to cut the angles. The typical system employed in cutting fish mouth ends is to cut symmetrical diagonal lines from the centre line of the culm. This is easier to control and determine during construction than when working with asymmetrical angles. This is one of the reasons that flute tip cuts are less used in the construction process.

Image 8.10 Cut lines for flute tip (left) – asymmetrical to centre line and fish mouth (right) – symmetrical to centre line.

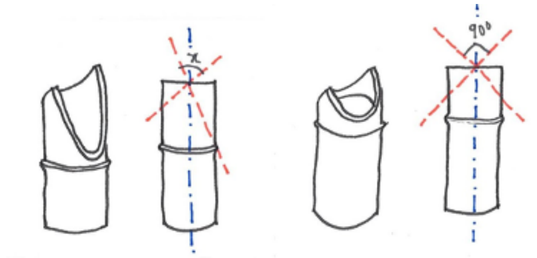
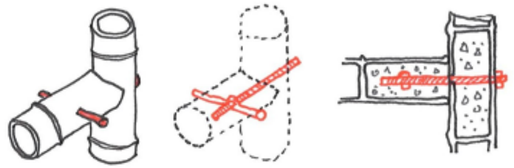


Image 8.11 Typical example of a mechanical joint using concrete



With the proposed fabrication methodology, the CNC machining can cope with any angle and variation, making these joints more applicable in the design process. This research focuses on these joints in order to develop a system in which the 'wall end of the mouth' of the cut is precise for an 'as close to' perfect 'coupling' onto the receiving bamboo. As discussed in previous chapters, when constructing on site, the carpenters cut the bamboo with rough dimensions, generally 'eyeing' out the intersection geometry. This brings a lack of precision and implies a weaker structural connection.

In practice, the common system is to use metal threads, rods or pins to connect the elements by filling the internodes adjacent to the joint with concrete (see image above). This helps to bond the mechanical fixings. In the case of bamboo, the culm can be cut with a higher level of precision, perfectly sized to the diameter of the receiving bamboo, and is thus able to manage the complexity of varying angles over the cutting path. With this system, the bamboo itself is bonded and more naturally supports the transfer of the load from the external edges of the bamboo (where the inherent strength lies) onto the external surface of the receiving bamboo.

In principle, the aim of the detailed design of the intersection is to express the natural properties and qualities of bamboo, working with the inherent features of the bamboo by connecting bamboo with bamboo and avoiding exposed steel connectors. With a richer variability of possible geometries of intersecting elements, the scope of design widens significantly. As the current applicable architectural designs are limited to the technological constraints, with the system proposed the architectural form can take on new geometrical forms and open a broader application of bamboo for architecture.

Image 8.12 Triangulated node connection fabricated with the CNC machine



Triangulated geometrical node

Following from the above discussion on the triangulated nature of the geometrical intersections of the node, a design project was developed to work on the principles of a reciprocal relationship of bamboo members. Rather than a node being 'an end piece meeting the side of a piece of bamboo', the node is a triangulation. In this scenario, tension and compression are balancing-out each other, forming a more solid structure.

Reciprocal connections are well known in architectural design and many small pavilions have been built but not many buildings. This construction methodology is not very flexible in terms of form variation and thus lends itself to being symmetrical in nature. If a project seeks to be more playful in its geometry, then there are more efficient methods as we will discuss in Project 3.

Nevertheless, what became important was the focus on triangulations and angled intersections in which the end of the bamboo culm meets the side of the other bamboo member and not end with end.

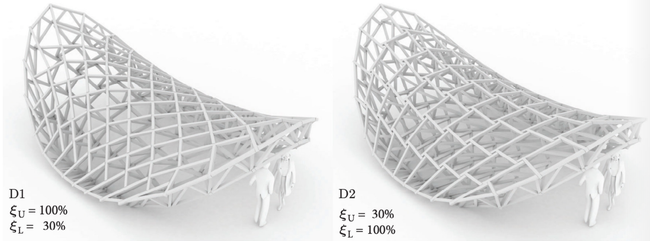


Image 8.13 Saddle-like structures developed by Apolinarska_ ETH (2018) with two negative Gaussian curves and algorithmically controlled into reciprocal structures.

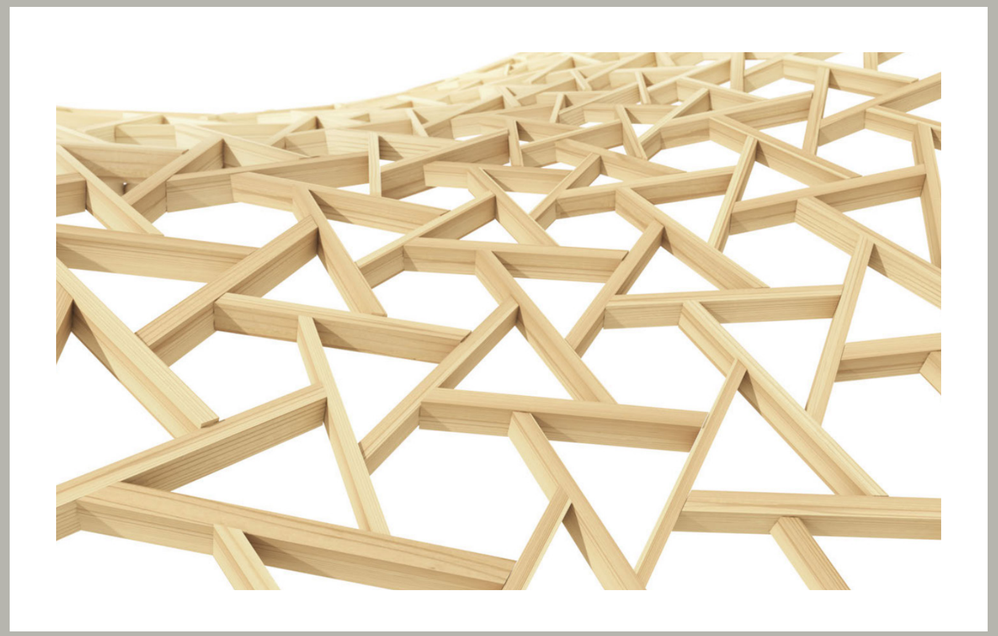


Image 8.14 A fragment of the reciprocal model developed by Apolinarska_ ETH (2018)

a)

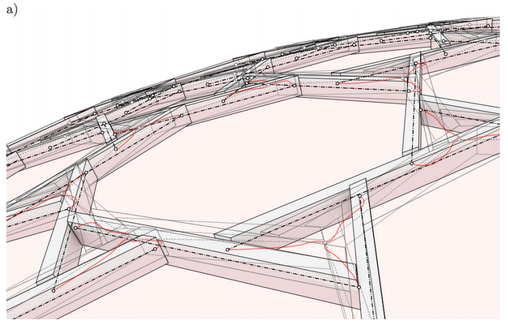
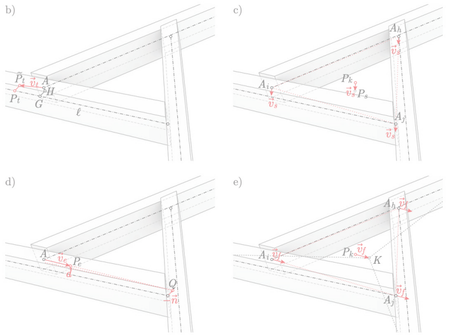


Image 8.14 Example of a reciprocal grid as developed by Apolinaria (2018) showing the algorithmic variation on the formation of the grid and junctions



MORPHOLOGICAL CHARACTERISTICS ARE KEY DESIGN PRINCIPLES THAT CAN BE OPTIMISED AND INTEGRATED INTO DESIGN. BUILDING UPON THIS KNOWLEDGE, THE DESIGN OF THE JOINT SYSTEM AND THE OVERALL GEOMETRY OF THE FORM CAN COLLABORATE TO ACHIEVE THE POTENTIAL OF BOTH.

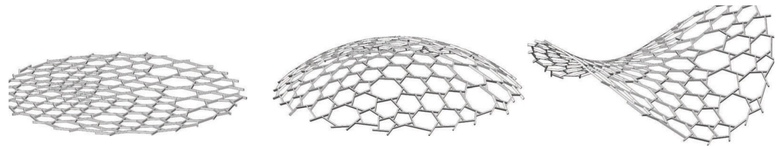
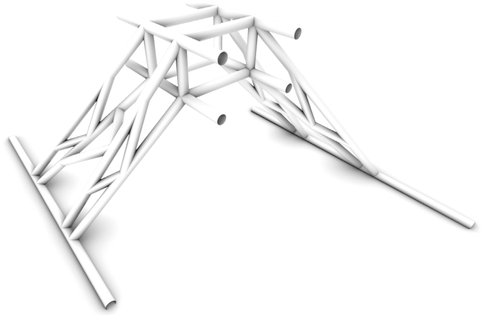


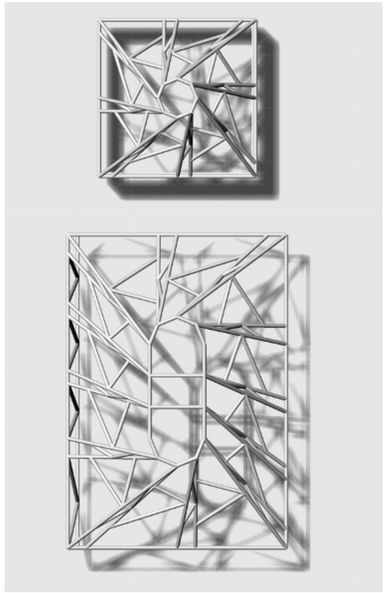
Image 8.15 Reciprocal from modelling across the algorithmic range Apolinaria (2018)

Through a design process of interrogating the building of a roof structure and the utilisation of triangulated, flute mouth joints, a form was developed to articulate an alternative method of fabrication and construction.

The design is based on a shifted truss that rotates across the plan. A central double ridge also offers an opening for natural light and cross ventilation, which is particularly important in hot climates like in Colombia. Shown below, the truss can be repeated until the desired floor plan is placed centrally for a single unit. This topology is suited for residential schemes or public spaces.

In the rendered image a public space is explored on the edge of a park in Cali, Colombia. This community building could offer shadow and protection from rain for activities like market selling, community meetings, social kitchens, children centres, religious gatherings, etc.





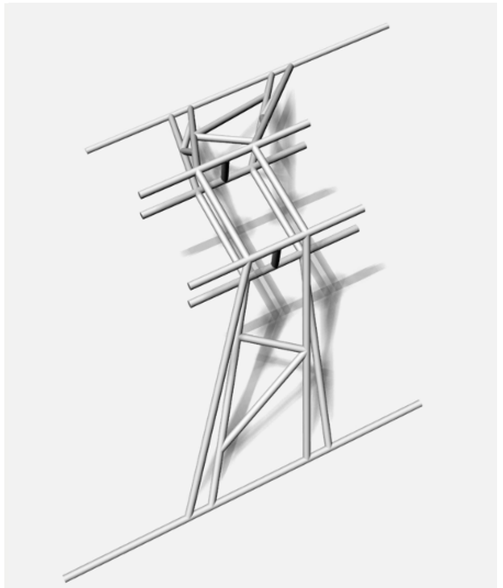
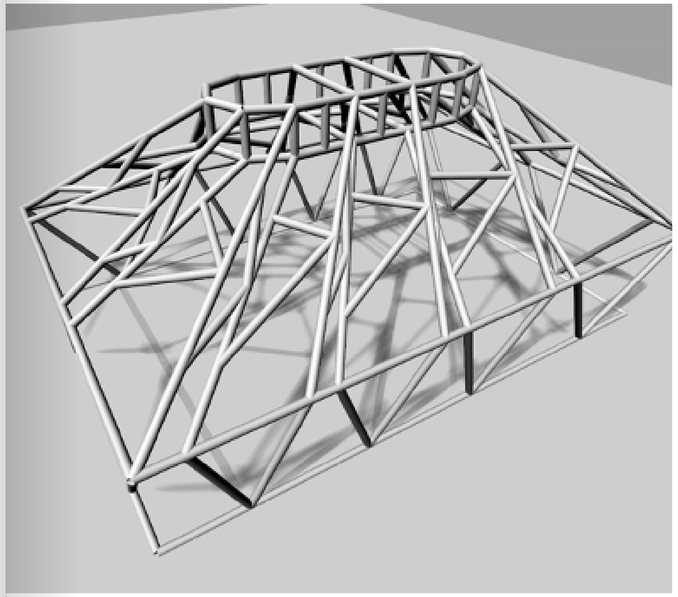


Image 8.16 - 8.23 Design proposal developed on the basis of triangulated reciprocal relationships. The top image is a truss which can be successively placed to create a longer or shorted building. This model was further developed and built as part of the research fieldwork in Colombia 2017

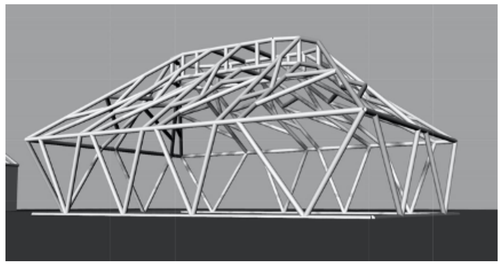




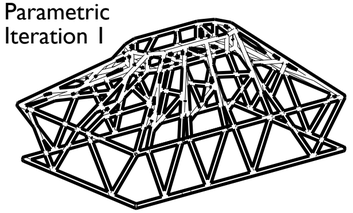


From a construction perspective, the focus is more on the craftsmen-makers who utilises the CNC machine on the construction site. Following a design, the builder cuts each bamboo element in accordance with the design instructions. As the build progresses, there are opportunities to input real-time data back into the computational system. This updates the digital model and adjusts the component data for fabrication.

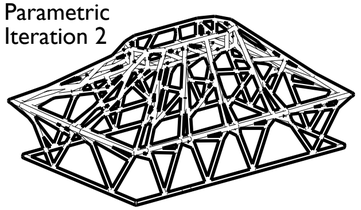




Parametric Iteration 1



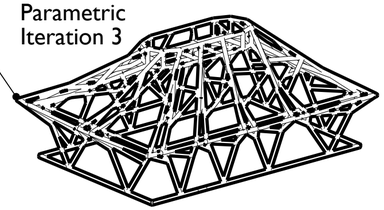
Parametric Iteration 2



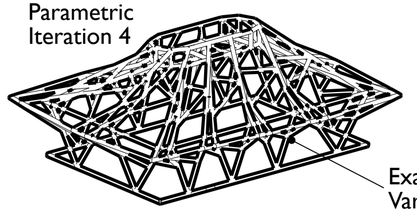
Example Variable x:

Eaves overhang length

Parametric Iteration 3



Parametric Iteration 4



Example Variable y:

Point of connection between eaves structure and columns

Parametric Iteration 5

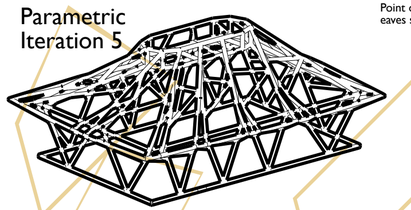


Image 8.24 Parametric design space to articulate variations in form (eaves overhanging - shading & rain protection). This space of design automatically changes the whole model and data correlating all the complexities of the joint connections and lengths of bamboo culms. The computational principles are aiding to the richness and flexibility required to find the right balance of parameters in searching for the appropriate spatial solution.

Utilising the CNC machine in this context permits the craftsman more flexibility in their articulation of what is required from the construction. The machine also works without 3D modelling and can aid the maker in simply cutting the required flute tip/fish mouth joint.

Through the utilisation of parametric modelling, the digital model can have inbuilt variables as shown in the graphic, which can adjust and suit the requirements of the project. For instance, a longer or shorter eaves canopy to adjust to the solar exposure. Equally, this data can be managed as shown in the diagram above to indicate maximum and minimum cutting angles or lengths of bamboo. This is a parametric space where the designer, computer and craftsman can interact with the overall geometry and node connections. This type of dynamic modelling is one of the great advantages of parametric systems.

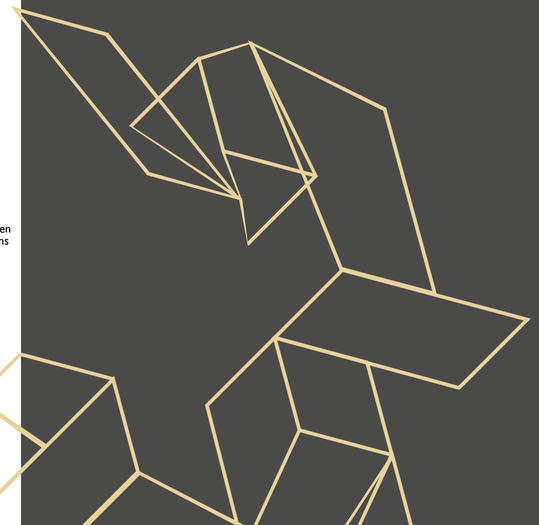
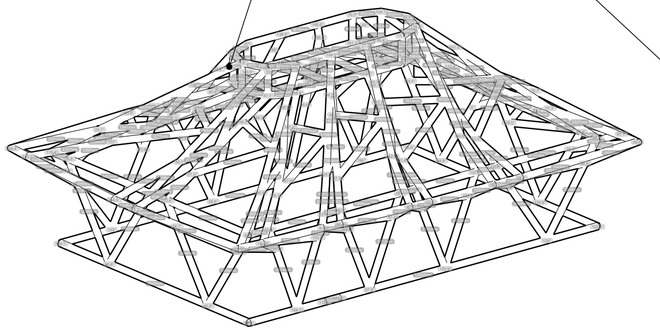


Image 8.25 Parametric design space correlating the range of angles possible with the CNC machine. The data table highlights the limitations set as a constraint and this is directly identified in the 3D model. Many other parameters can be set and managed thought these computational methods which, if seeking innovation in design and material application, can be outside of the scope of human thinking and complexity management.

Culm 13

Error identified:

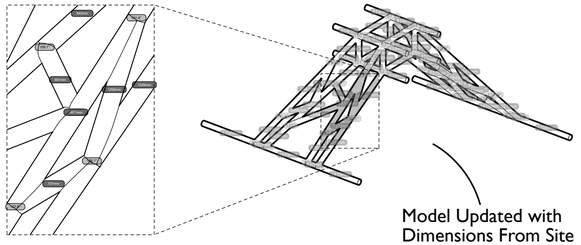
Intersection angle is beyond maximum cut angle



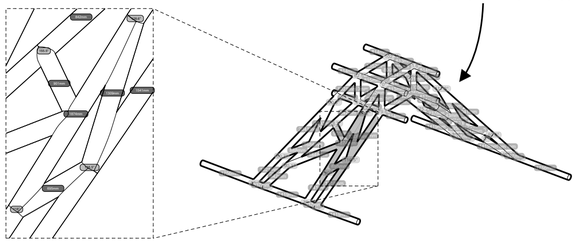
Bamboo Identifier	Length	Culm Diameter	Culm Thickness	Intersects with...	Intersection Angle	Diameter of Intersec
Culm 1	3048mm	80mm	23mm	Culm 4	55.1°	67mm
Culm 2	3073mm	73mm	19mm	Culm 23	55.1°	80mm
Culm 3	3073mm	68mm	17mm	Culm 26	87.8°	78mm
Culm 4	4000mm	85mm	25mm	Culm 152	124.9°	70mm
Culm 5	4503mm	67mm	16mm	Culm 153	66.9°	79mm
Culm 6	4500mm	71mm	18mm	Culm 168	138.6°	66mm
Culm 7	3000mm	81mm	23mm	Culm 191	140.6°	81mm
Culm 8	6037mm	74mm	19mm	Culm 2	69.2°	69mm
Culm 9	4632mm	68mm	17mm	Culm 3	56.4°	95mm
Culm 10	6037mm	65mm	15mm	Culm 59	108.1°	71mm
Culm 11	4632mm	80mm	23mm	Culm 97	124.6°	80mm
Culm 12	800mm	69mm	15mm	Culm 138	124.6°	79mm
Culm 13	800mm	65mm	15mm	Culm 158	138.3°	66mm
Culm 14	800mm	75mm	20mm	Culm 181	129.3°	73mm
Culm 15	800mm	73mm	19mm	Culm 3	124.6°	85mm
Culm 16	802mm	71mm	18mm	Culm 60	92.9°	78mm
Culm 17	802mm	79mm	22mm	Culm 73	91.3°	78mm
Culm 18	802mm	70mm	17mm	Culm 97	55.4°	80mm
Culm 19	802mm	69mm	23mm	Culm 138	55.4°	79mm
Culm 20	802mm	67mm	16mm	Culm 157	70.7°	66mm
Culm 21	802mm	67mm	16mm	Culm 180	141.3°	80mm
Culm 22	802mm	72mm	18mm	Culm 4	90°	67mm
Culm 23	802mm	72mm	18mm	Culm 6	90°	81mm
Culm 24	4382mm	85mm	22mm	Culm 140	67.4°	70mm
Culm 25	4191mm	83mm	24mm	Culm 141	112.6°	74mm
Culm 26	4062mm	81mm	23mm	Culm 143	67.4°	78mm
Culm 27	5186mm	79mm	22mm	Culm 144	112.6°	76mm
Culm 28	5186mm	84mm	24mm	Culm 146	69.4°	77mm
Culm 29	4062mm	67mm	16mm	Culm 147	110.6°	83mm
Culm 30	1447mm	79mm	22mm	Culm 5	90°	71mm
Culm 31	1558mm	84mm	24mm	Culm 150	55.1°	82mm
Culm 32	1447mm	85mm	25mm	Culm 151	124.9°	69mm
Culm 33	1558mm	67mm	16mm	Culm 153	124.9°	79mm
Culm 34	1073mm	65mm	15mm	Culm 6	90°	81mm
Culm 35	1641mm	72mm	18mm	Culm 119	180°	81mm
Culm 36	1073mm	83mm	23mm	Culm 119	180°	81mm
Culm 37	1641mm	79mm	22mm	Culm 121	112.8°	79mm
Culm 38	1958mm	80mm	22mm	Culm 122	67.2°	76mm
Culm 39	1403mm	79mm	22mm	Culm 124	69.1°	80mm
Culm 40	1958mm	67mm	16mm	Culm 125	110.9°	72mm
Culm 41	2464mm	66mm	15mm	Culm 127	67.2°	69mm
Culm 42	3275mm	70mm	18mm	Culm 128	112.8°	69mm
...	...	...	...	...	...	...

3D Model with Integrated Fabrication Data

Data from 3d Model



Model Updated with Dimensions From Site



Model updated to respond to site dimensions

3D Model with Integrated Fabrication Data - Axo

Output Data for Fabrication

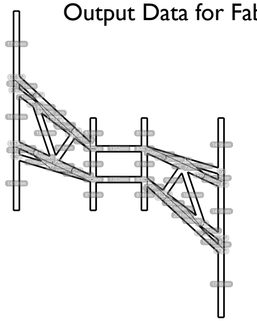
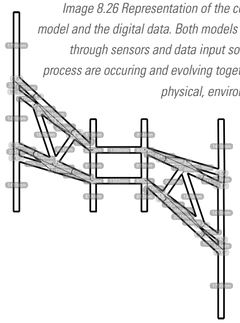
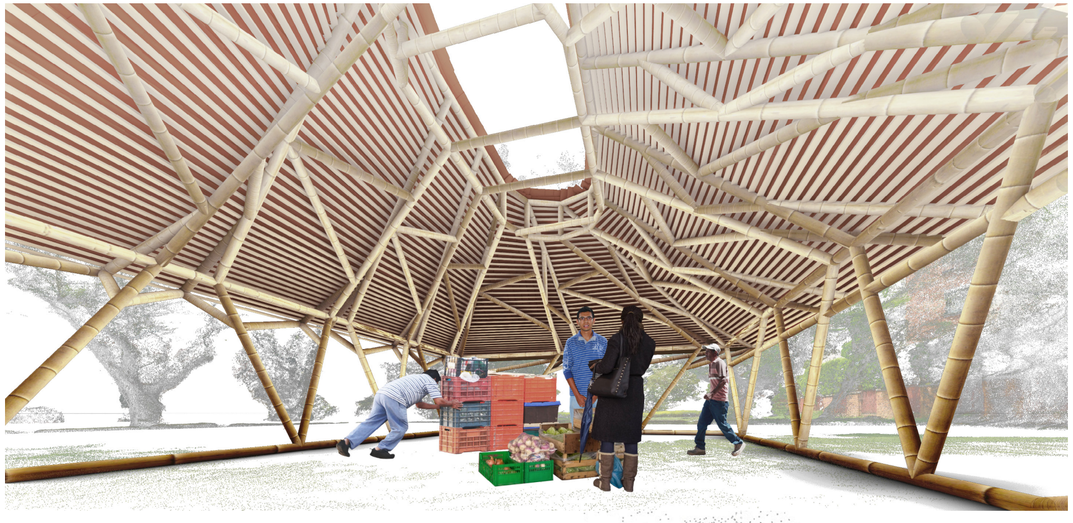


Image 8.26 Representation of the correlation between the physical model and the digital data. Both models can be updated simultaneously through sensors and data input so that the design and fabrication process are occuring and evolving together according to the technical, physical, enviromental and material conditions.





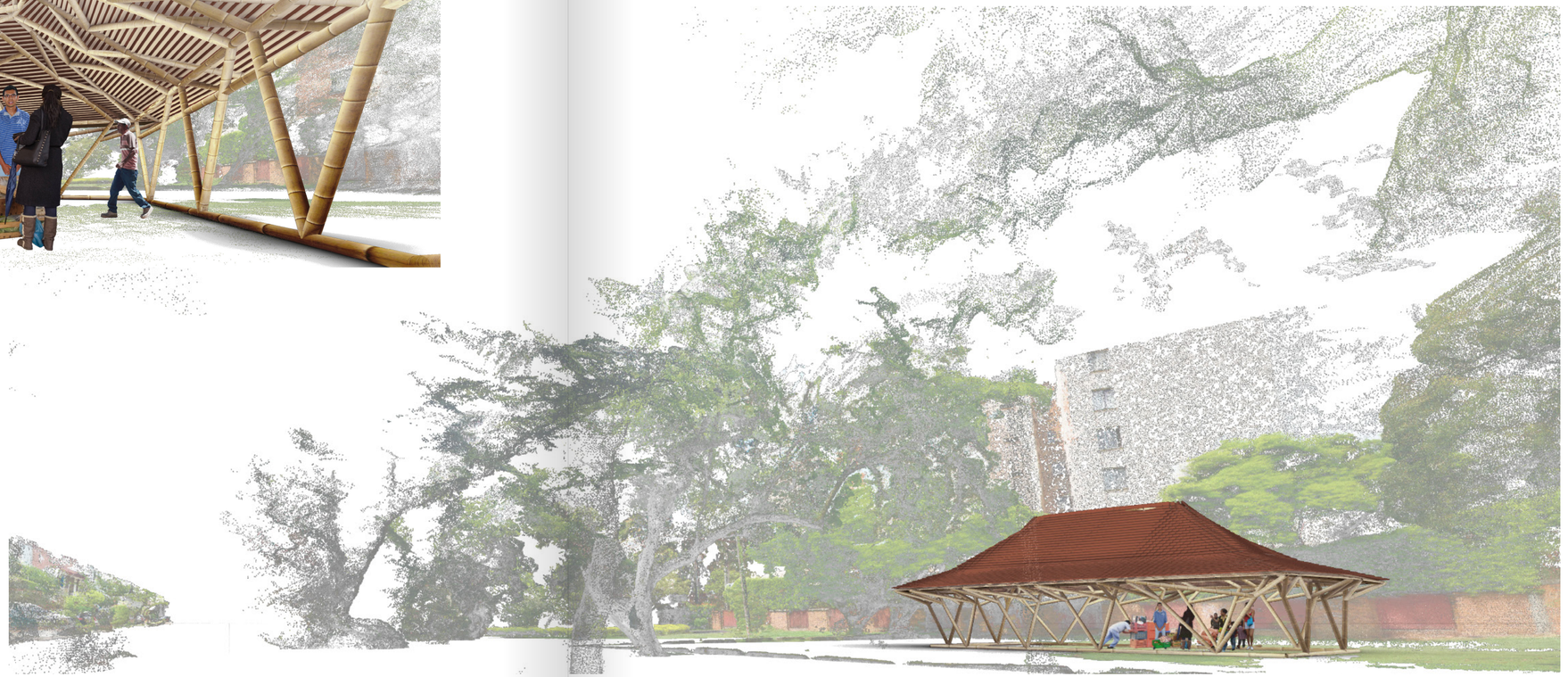


Image 8.27, 8.28 Visual renders for the Cali Community Centre. This project exemplifies the use of bamboo structures for everyday use in an urban environment . This public building demonstrates a principle of applied use of bamboo as a local resource to enhance the social and environmental requirements .

PROJECT 3: GRIDSHELL

This project produces speculative design propositions to determine the orientation, positioning, grouping and connectivity of bamboo elements in relation to an overall geometry. These iterations offer opportunities for analysis and refinement that are fed back into the system until a suitable form is selected.

Through the use of geometry, architects and designers have historically been able to advance the possible ways of describing complex form. “Geometry looks for generalities and, once established, offers them up for use; architecture employs these general relationships constructively to underpin and create specific spatial relationships” (Burry, 2012, p. 9). Digital computation since the last two decades is offering new possibilities of spatial and temporal engagement without tedious manual calculation beyond the limitations of Euclidean geometry and Cartesian planes. Through parametric algorithms, the design is a topological system capable of defining a range of geometrical possibilities (as described in the previous project). This is a mathematically based system of geometrical hierarchies and relationships defined to describe topological possibilities through algorithms that enable the emergence of forms resulting from principles established in the design of the topology rather than the (visual) geometrical form itself. As described by Jane Burry, solid modelling programs place no demand on the modeller to engage closely with the abstract symbolic geometrical descriptions of surface. In this way designers can move conceptually to the more general geometrical world of topology, foregrounding connectivity and continuity, a familiar starting point for space planning but not a traditional metaphorical starting point on design of form (Burry, 2007, p. 613). Designers are generally intensely concerned with the formal (shape) output and not with a more genuine topological space concealed within the design of mathematical algorithms and spatial relationships of these geometrical objects.

To summarise, the design space is (a) composed of the Euclidean descriptive and projective geometry, (b) topological space of the relationships between geometrical objects and (c) a space of infinite possible spatial variations or iterations.

The algorithmic principles to be established in this design project have to do with the already mentioned characteristics of bamboo’s inherent anatomical morphology. Under the principle of continuous fibre, (1) segments of bamboo fibres (culms) are to be connected to other linear fibres (culms) in a continuous way so as to provide for a morphological change in geometry. (2) The longitudinal direction of forces should prevail through the connectivity of bamboo culms where members meet at oblique angles distributing forces along each segment rather than at right angles, where too much force is imposed on individual elements (culms). (3) The typology of nodes throughout the form is variable dependent on the geometrical composition of the form in its locality and the stresses imposed. In this way, the geometry cannot be described at the outset of the project but only a set of rules and relationships. Traditional design approaches involve designing using geometry first, and iteratively re-working this design within specified design constraints (e.g. material usage, structural integrity, spatial conditions, construction time and cost, etc). Computational and algorithmic approaches involve mathematically modelling or defining a chosen set of design constraints first, and either searching for, or iteratively generating, geometries that perform (measurably) against those constraints. The computational system can offer models for analysis to determine the physical, spatial and material conditions for a possible form and further technical realisation. Through analysis of modelled iterations of the design, the relationship between the geometrical pattern’s rules and the overall form develop in a dynamic process. These movements disrupt existing patterns and initiate the emergence of new ones, finding equilibrium between the form and its context (Weinstock & Menges, 2006).





Image 8.29 Examples of joint connections of multiple end pieces

Geometrical principles

The geometrical principles are based on the hypothesis that the joining of bamboo components should be staggered and that no end piece of bamboo should meet another. This is a variation from the current typical typology in which nodes are formed with a mechanical connector as it is not possible to manage the physical and technical union of the parts (see image on the right).

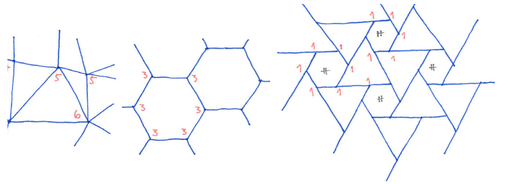
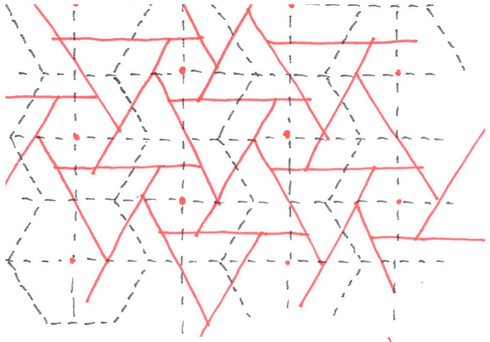
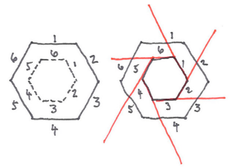


Image 8.30 - 8.32 Geometrical variations with multiple end pieces to singular. This is a search for a geometrical condition where and end piece of bamboo meets the side of another rather than end pieces meeting end pieces.

To create a fluid continuity between members, the staggering of joints entails one end piece meeting the side section of a culm. In geometrical terms, this raises an interesting problem because most three-dimensional forms are described through a network of lines and grids. Multiple edges meet at points forming clusters of multiple end pieces. The image below describes three types of grids: an irregular triangulated surface with varying numbers of nodes; a regular hexagonal grid with constant dimensions, angles and numbers of edges per vertices; and the proposed solution to the geometrical problem: an hexagonal reciprocal shifted pattern in which each node is made of one end piece meeting the side of an edge.



The design process to find this solution was based on a regular hexagonal pattern as shown in the image below. The algorithm essentially instructs a parallel offset from the edges of the hexagonal. Each edge is given a number based on a rotation of 1 from the original object. The lines are then extended 1-1 prime, 2-2 prime, etc. Because of the regularity of the geometrical grid, if the offset is equal to all hexagonals, the extended lines will meet the neighbouring hexagonal and the overall geometry will function.



This same mathematical equation can be applied to other geometrical grids as shown in the computational image below. This is a triangulated surface where we would have observed that each edge meets at a node of 6 which would not satisfy our bamboo design application. Applying the same algorithm, we can create a condition in which, based on a computational 3-dimensional surface, the end pieces of bamboo meet the side of another culm (edge).A potential design limitation here would be the requirement of the geometry to be regular throughout. This would imply regularity to each node and to each intersection, resulting in an overall regular and symmetrical shape, like a dome or a vault. Subtle variations are possible, but this research project aims to find a wider scope in form finding, not pre-imposed by geometrical limitations.

In search for irregular geometries, the Voronoi method contains characteristics which are ideal for this design project. Voronoi geometry is an organisational description that sometimes is named "nature's rule" (Kumar, 2018). Voronoi diagrams describe the tessellation of irregular forms into one overall body – as found in, for example, soap bubbles. To construct these diagrams, one identifies different points in space (the theory is applicable for both 2D and 3D structures, but the following explanation will focus on 2D). As drawn below, once the points are identified, lines are drawn connecting these (dotted grey). At the centre point of these vectors drawn perpendicular are the edges to the Voronoi cells. As the datum of the points changes so do the regions of the cells and their edges.

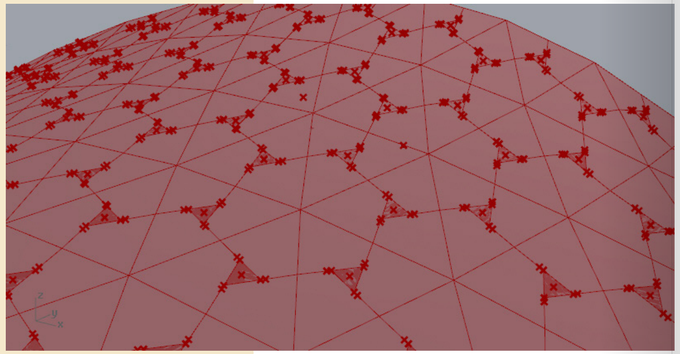


Image 8.33 Application of the reciprocal grid on a curved surface

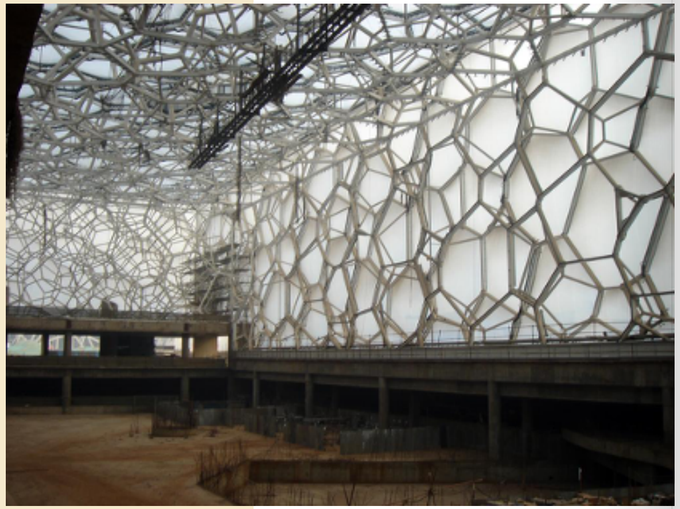


Image 8.34 of the Voronoi 'bubbles' at the construction of the Beijing National Aquatic Centre.

The below diagram was sketched based on the image of the National Aquatic Centre. Even through the dimensions, angles and faces of the Voronoi cells vary, all nodes receive three vectors. In this situation we can apply a geometrical algorithm to change this condition, as shown in the diagram. This algorithm instructs each node point to change i geometrical relationship – for example, at a point where three vecto meet, change condition from P1 – P4 = P1 – R1 (X distance from P4 Extend vector P3 – P4 to R2.

This demonstrates the possibility of constructing an irregular geometric form based on points located in space as an input, providing therefor a specific logic in form finding based on: typology and characteristics bamboo, and site specific data which can be both physical (heights, contour and environmental (solar exposure, wind direction, water management The creation of form becomes interrelated with multiple data criter developed from the material conditions, environmental and technic abilities specific to each project.

Image 8.35 Diagram of Voronoi cells (traced from the National Aquatic Centre) demonstrating the possibility of constructing similar structures in bamboo through different joint methodologies.

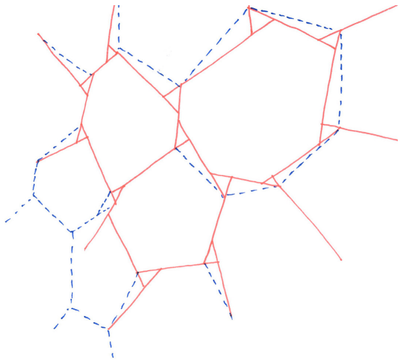


Image 8.36 Example of a Voronoi diagram

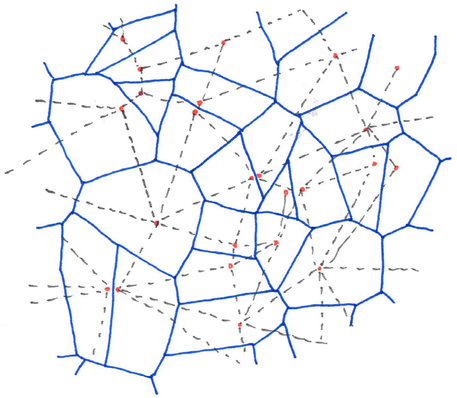
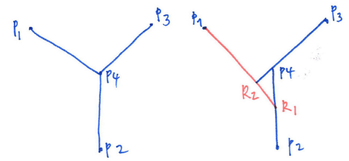


Image 8.37 Representation of the geometrical change in applying the vertex change algorithm



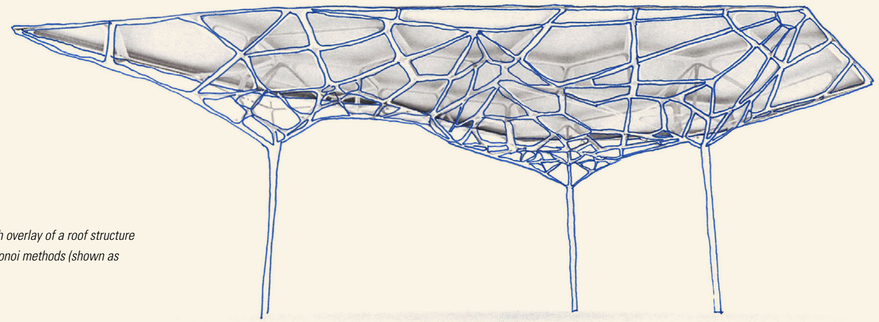


Image 8.38 Design sketch overlay of a roof structure designed through 3D Voronoi methods (shown as design development)



Image 8.39 ZCB pavilion joints

Following this study, it seemed natural to explore gridshells which are excellent structures and have been used quite successfully in architecture. Generally, gridshell principles are quite flexible and offer a range of geometrical possibilities. In this project, the research investigated the possibility of working with short sections of bamboo rather than long continual members. There are successful bamboo gridshells which layer long lengths of thin to medium bamboo to utilise the bending properties of the material. These are then joined by bracing, such as with the ZCB pavilion, rather than joined by cutting. An advantage of using shorter lengths is the control over the variability of the culm dimensions, which therefore gives more control over the structural strength, less movement and elasticity in the overall structure and thus a more rigid system.

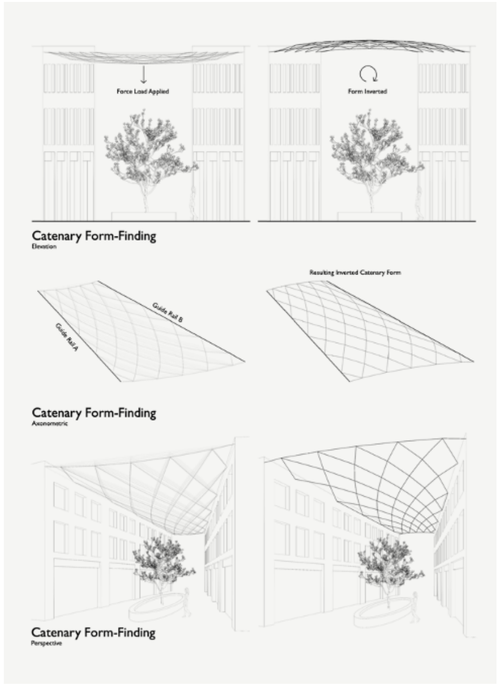
This is possible to achieve with the CNC fabrication system described in Chapter 7, as the joints and lengths can be cut to match the computational model, designed and structurally calculated before construction. The fabrication can be executed in a workshop or onsite and offers an overall methodology which can encourage the use of bamboo for mainstream construction.

The gridshell design proposition has developed based on the principles of a catenary form finding methods used by designers from Gaudi to Frei Otto. Catenary form-finding is a fairly straightforward utilisation of the kind of rules-based ('algorithmic') design process described above. Instead of beginning with geometry, one begins with a set of constraints and rules, and allows the action of those rules to lead to a geometry as an output. The constraints in this case are two fixed "guide rails", A and B, defined as the edges of existing buildings, which do not move. Then, attached to these is a diagonal structure made up of straight members (simple lines) and their joints, which are allowed to swing freely and are modelled as having both a weight under gravity and a factor by which they are allowed to stretch along their length. Each joint is modelled at this stage as a fixed point, from which members are not allowed to break away. Other parameters can then also iteratively be adjusted, for example the density of diagonal members (and therefore the expected lengths of each member – either many short ones under less structural stress, or fewer longer members under greater stress).

The usefulness of the catenary approach is that the action of gravity (either modelled digitally, or in the case of Otto and Gaudi done so with physical fabric, chains and weights) very quickly pulls each member into a form which is the most structurally sound for its given parameters. The gridshell starts as a flat surface between the two guide rails, and then relaxes (for a given 'elasticity' of its members) quite quickly into a shape which one can be sure (mathematically) will perform best structurally when inverted. Modelling this digitally, where each member has its own self-weight and elasticity coefficient, allows this 'relaxing' to happen in only a few thousand iterations, which can be run quite quickly on a moderately powerful computer and gives exact geometry from which a highly-performing structural shell can be easily generated.

Image 8.40 The comparison of design and construction of the Mannheim Multihalle (Frei Otto) and Wood structure Theme Pavilion in Hiansu Province Horticulture Exposition (UNStudio) Source (Jin 2018),

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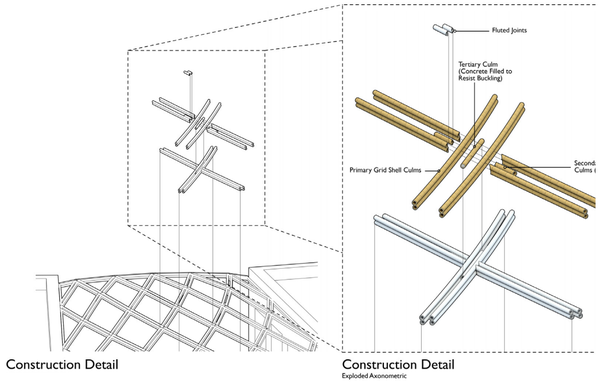


Image 8.41 (left) Description of the process of catenary form-finding.

Image 8.42 (above) Exploded axonometric view of the proposed joint methodology

A joint fabrication methodology developed from the triangulated reciprocal joint discussed earlier. An evolution of this principle was also found in the work of Fredrick Zollinger who in the early twentieth century developed a method of constructing roofs using short planks put together in a diamond grid also described as the lamella roof.



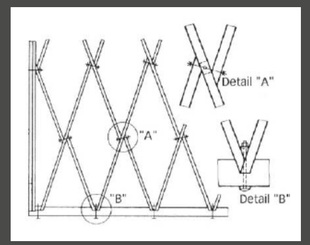


Image 8.43 Zollinger method detail

It was further based on the lightweight steel-timber composite gridshell for the West Bund World AI Conference (Jin, 2018), here they developed a joint connection optimised from the Lamella system.

These precedents informed the design of an innovative bamboo connection using the same principles but adapted to the properties and characteristics of bamboo.

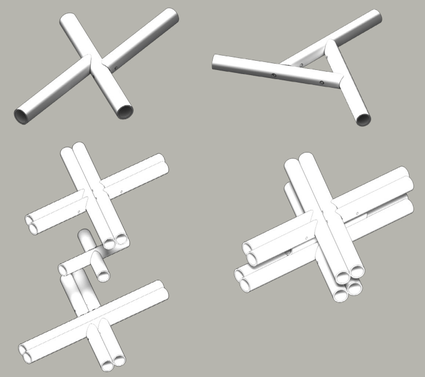
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Image 8.44 Precedent study: Lightweight steel-timber composite gridshell of Vunue B for West Bund World AI Conference (Jin et al, 2018).

Image 8.45 Optimization of the Zollinger construction system by Jin et al, (2018)

Image 8.46 Through combining the Zollinger, the reciprocal method and the design process from Jin et al (2018) the proposed joint methodology optimises the limitations of the joint connections and provides a geometrical and structural logic which is truely innovative in the context of bamboo design.



In addition to the simplistic iterative nature of the 'relaxing' process of generating gridshell geometry (which, of course, could be done either digitally or through careful physical modelling), the advantage of the digital workspace comes into its own in providing a second layer of parameterisation and iterative generation of geometries.

The base constraints (the two immovable guide rails) remain in place. The main parameters that can be adjusted are the divisions of the diagonal structure in both U- and V- directions (where U and V directions are equivalent to Cartesian x- and y-axes, but relative to a non-Euclidean surface). Along with the number of U and V divisions, what results is also a change in the lengths of the members between each joint, and the number of members and joints themselves.

For a given base constraint, then, by adjusting these parameters, a large number of potential geometries can be generated – each of which (after the iterative 'relaxing' process described above) may be the highest-performing structural geometry for that particular set of parameters, but which can now be evaluated for fitness measured by a number of other factors – for example, they can be analysed against one another using a digital structural analysis tool to measure deflection and shear stresses, and they can be costed and analysed in terms of construction time and labour.

This process produces a visualisable 'parameter space' – through which it becomes possible, as a designer, to understand and see the changes in geometric output as parameters are changed, and to judge these outputs against one another.

Below is a representation of this parameter space, in which members that are longer than a desired length are shown in red (perhaps defined by local constraints on bamboo stock and quality of material available), and those close to a desired length are shown in green. A further sub-set of the parameter space is also shown, comparing the structural performance of a number of the generated geometries based on the properties of bamboo. The design process here becomes a high-level executive decision-making process – for example, is the slightly increased structural integrity of a highly-dense gridshell necessary when compared with the increased labour and time involved in its construction?

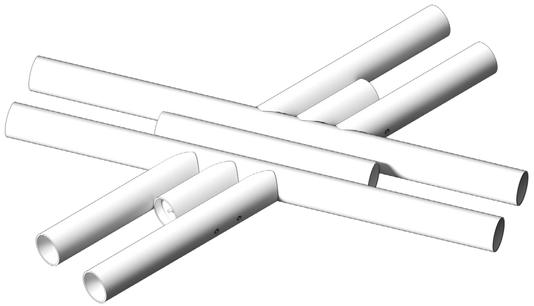
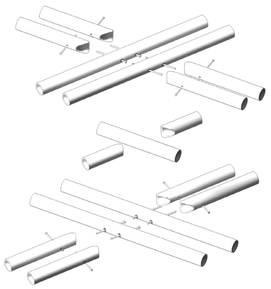


Image 8.47 View of the bamboo node connection



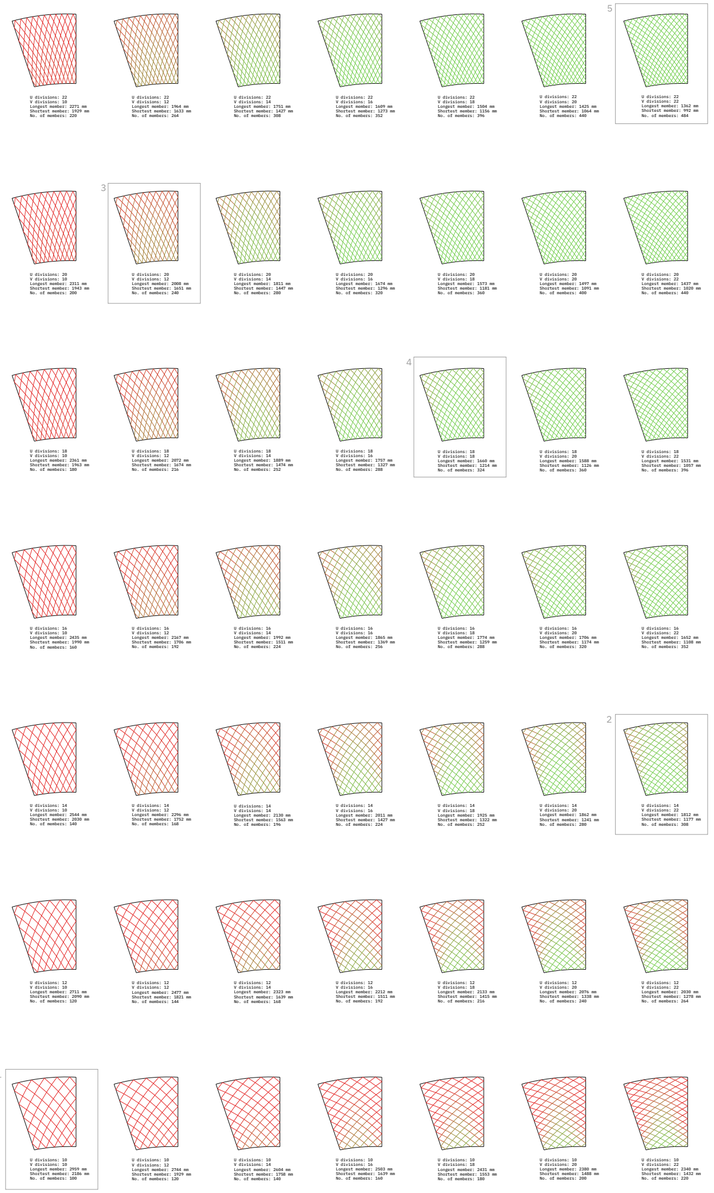


Image 8.48 visualisation of the parameter space to determine the fitness criteria set according an optimisation of the structural curvature, lenght and number of members in relation to the grid density. The colour-coding helps to visually understand the data.

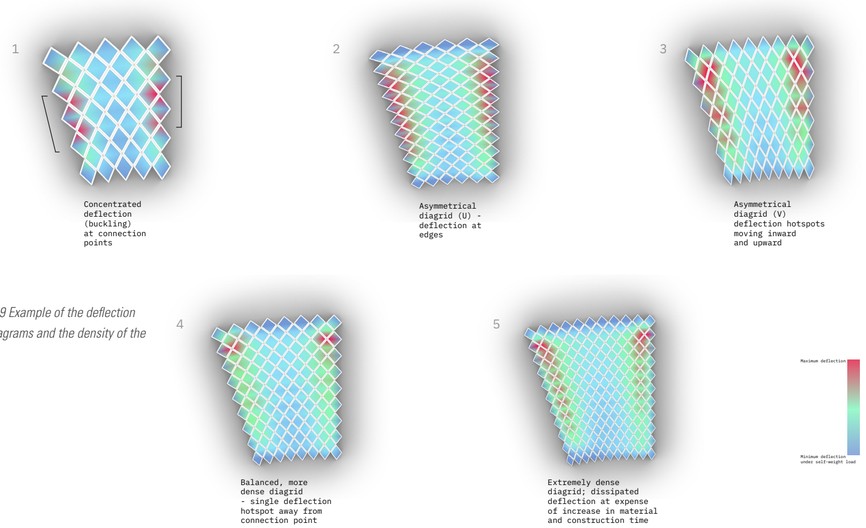


Image 8.49 Example of the deflection testing diagrams and the density of the diagrid.



Image 8.50 Internal view of the proposed roof structure.

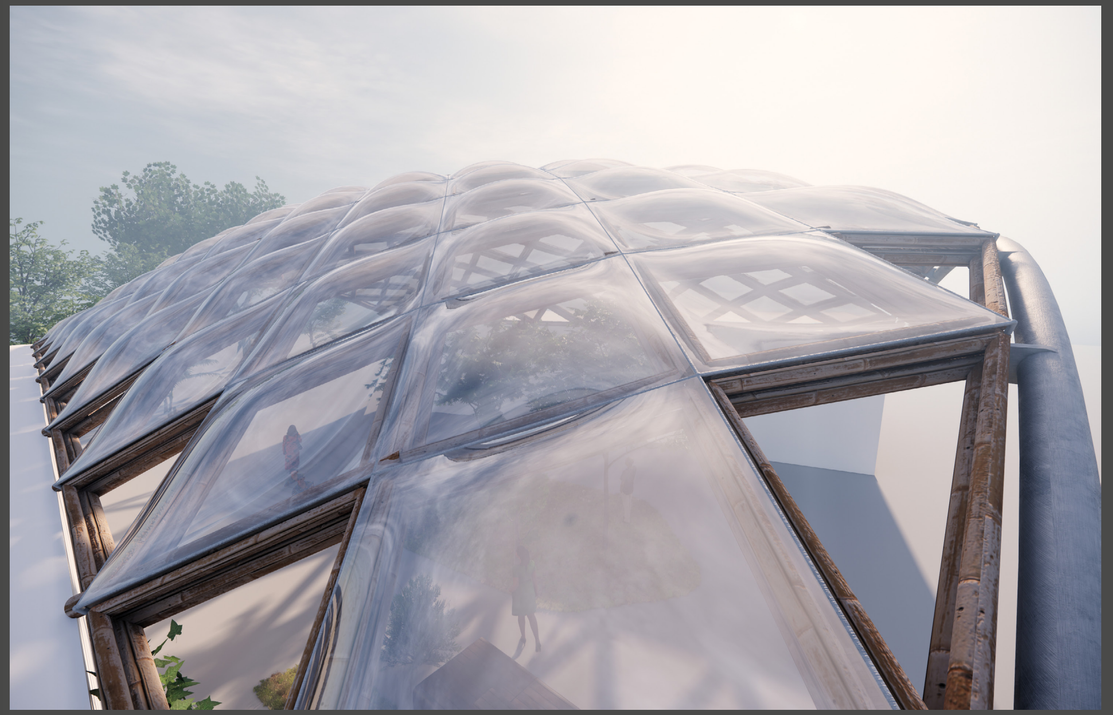


Image 8.51 Rendered view of the roof structure showing the bamboo and ETFE panels

PROJECT 4: ENVIRONMENTAL FAÇADE SYSTEM – BOGOTA

This final project demonstrates the applicability of this system at a different scale. With the intention of proposing design solutions to contemporary urban challenges, this project looks at providing an environmental layer onto an existing building in Bogota. Characteristic of an urban environment, tower blocks are visually harsh volumes standing exposed to solar radiation. In this project a proposal is made to add an additional façade utilising the existing structure of the building. The outcome is to provide the building with shading to prevent solar overheating and to enhance the aesthetic appeal by bringing into the urban setting more vegetation and natural materials – encouraging a material language inspired by the way the canopies of tress provide layers to filter light, wind and sound.



Image 8.52 Athens Inspired urban layering which offers shading and interstitial spaces to enhance the environmental delight and comfort



Image 8.53 Chosen site in Bogota

INSPIRED URBAN LAYERING WHICH OFFERS SHADING AND INTERSTITIAL SPACES TO ENHANCE THE ENVIRONMENTAL DELIGHT AND COMFORT

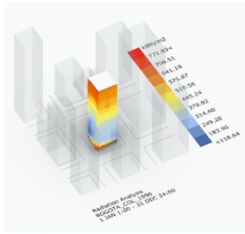
The design process was carried out utilising computational design as an aid to the development of the proposal. The first step was to define a set of constraint rules that would anchor the project and set the scope of parameters in exploration for the final design output.

A solar gain study was carried out for this specific location across the year. The mapping of this is shown in the images. Through this study, it became clear that the top of the building had much more exposure than the bottom and therefore this gave the design process a set of data to which one could respond.

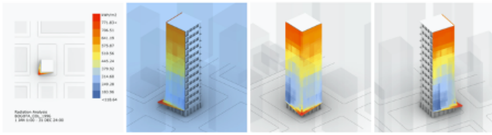
A geometrical principle, a hexagonal mesh, was overlaid onto this data and values were imposed onto the geometry where a tighter grid on areas of higher solar exposure was applied and larger openings to areas of lesser exposure. This resulted in the study shown below. The conclusions drawn from this exercise indicated that the construction process was too complicated with an excessive number of joints and the aesthetics of the overall building were not so pleasing. Whilst other design studies were carried out, this example is described here to demonstrate the applicability of computation parameters on the determination of form.



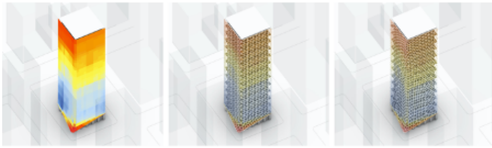
Example Urban Context



Solar Radiation Analysis



Cumulative Annual Solar Radiation
(Using example context geometry and historic EPW data from Bogota)

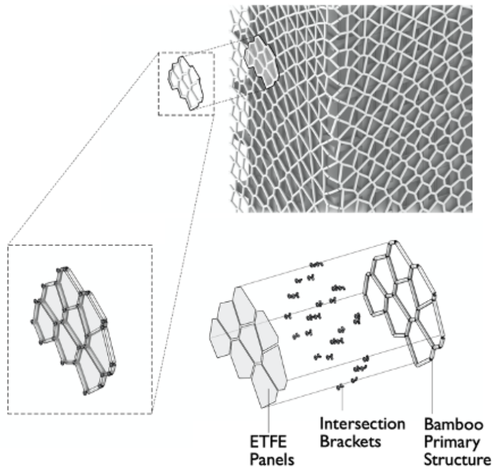


Input Analysis Result

Base Structure

Structure Responds to Solar Analysis to Adjust Opening Parameters

Image 8.54 Solar radiation analysis



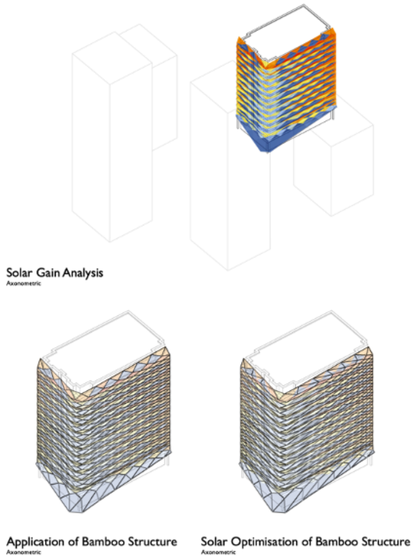
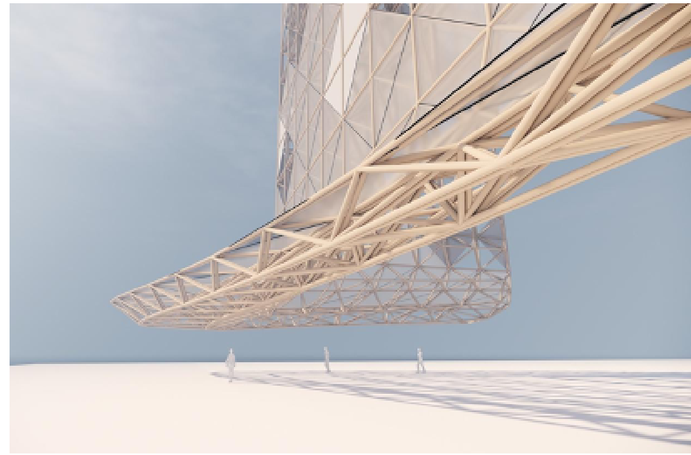


Image 8.59 - 8.61 Study of the façade to determe the construction and structural logic. Solution not chosen due to the irregularity and increased complexity of the joints and panels.



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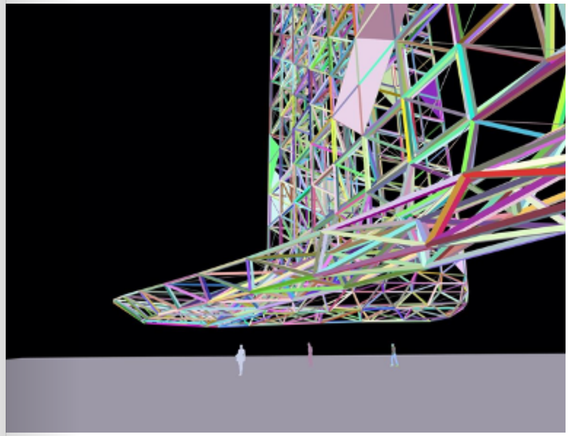
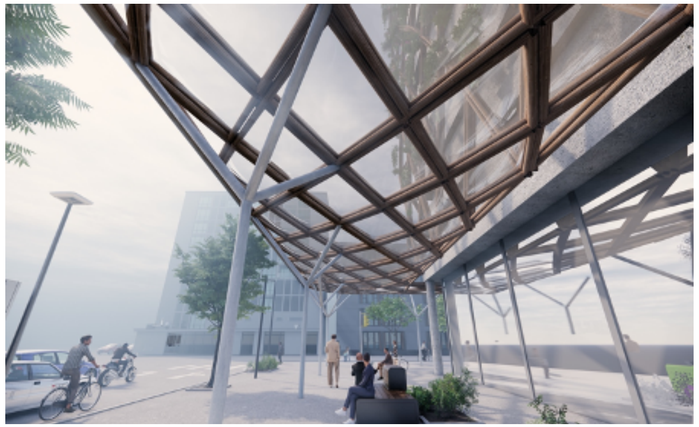


Image 8.62 (top left) Precedent case study (Agkathidis, 2018) of a roof canopy and the base of a tower block.

Image 8.63 & 8.64 Design study of a structural grid system. In conclusion it resembles a steel structure where sections of tubes meet at nodes making the connections in bamboo too dificult to manage.



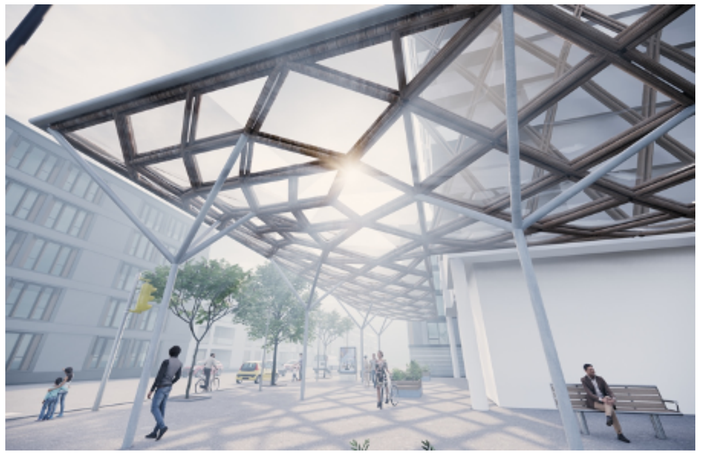


Image 8.65 & 8.66 Rendered view of the proposed canopy using the same joint technology discussed in project 3.

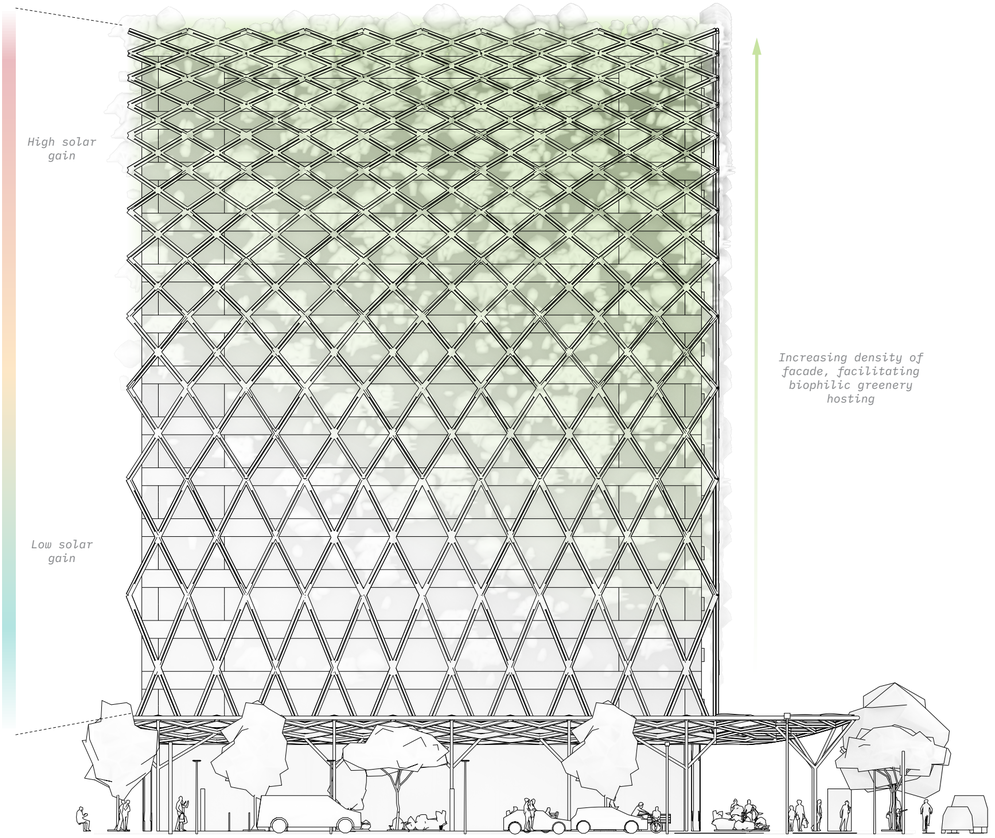


Image 8.67 Applied diagrid system to the facade of the building in response to the solar radiation analysis. Offering higher density at the top than at the bottom of the building.

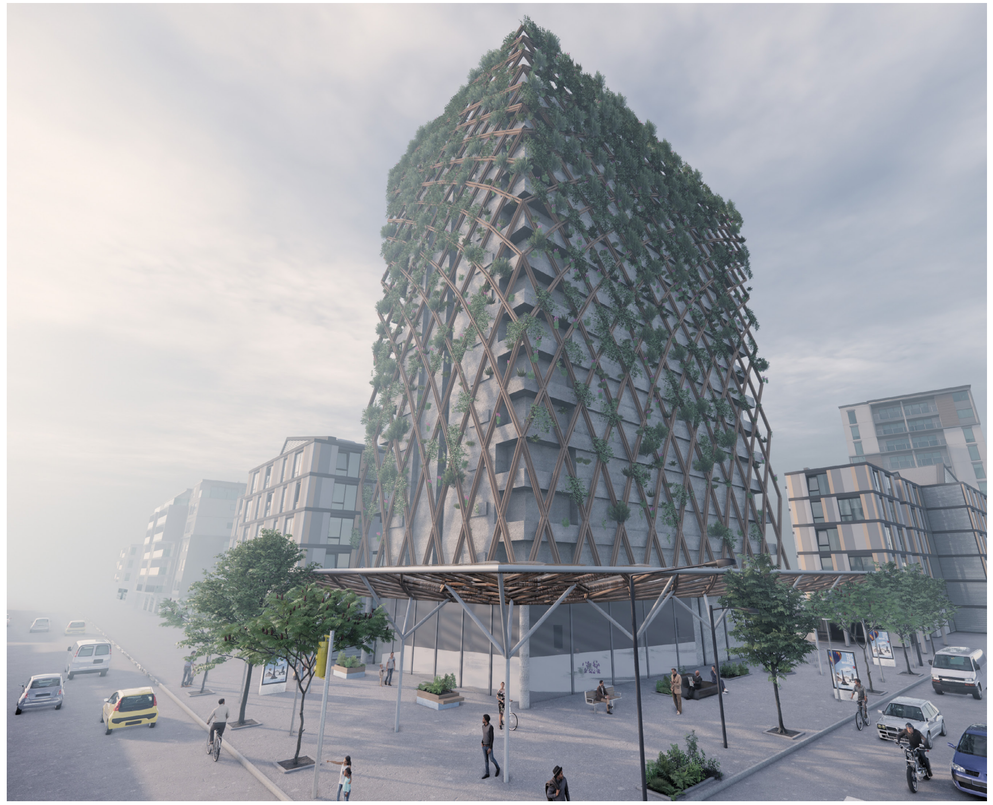


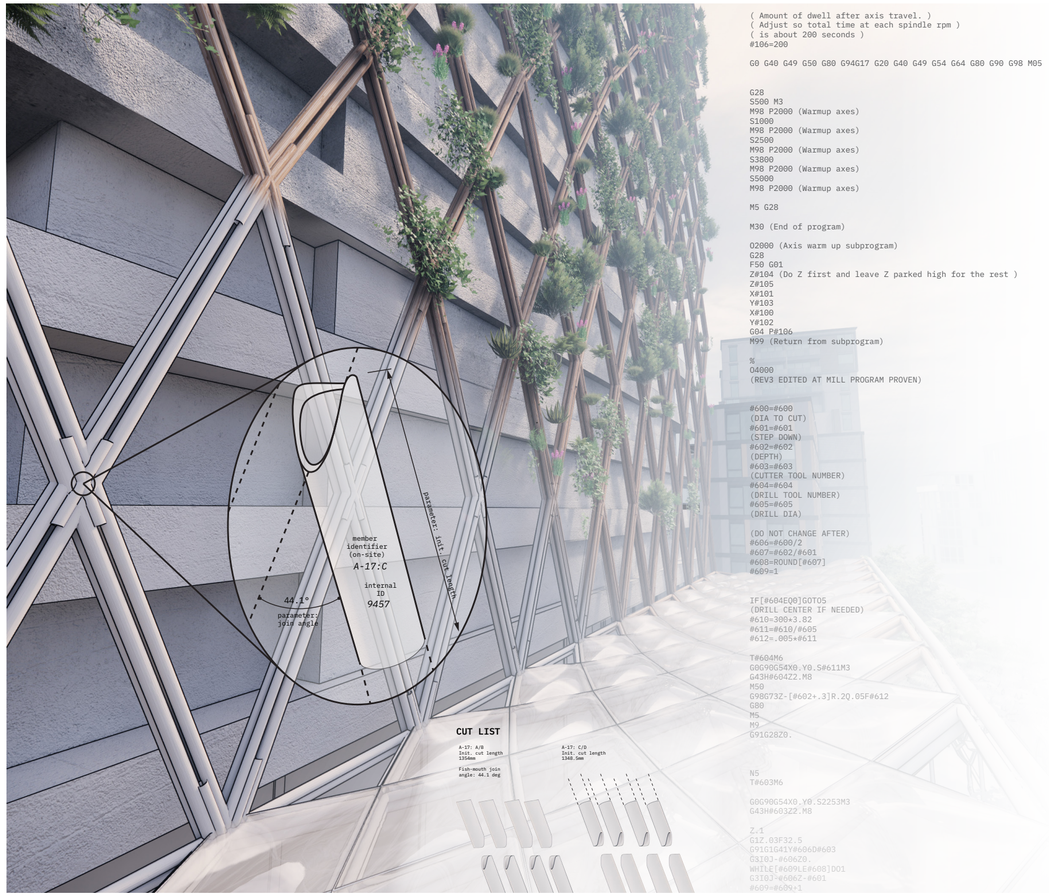
Image 8.68 Visual render of the proposal incorporating the naturally growing plants to aid in environmental cooling and visual delight. The nature of this proposal demonstrates the applicability of bamboo into urban environments, expressing a language resembling nature, breaking down the hashness of the urban environment.



Image 8.69 Conceptual visual renders expressing the principles of BIM (Building Information Modelling). This exemplifies how projects of this nature can be incorporated into contemporary large scale construction projects. As the design process is managed through a series of intelligent computational methods the necessary data for procurement, fabrication and assembly can be stored in the model. This further offers much potential for bamboo to join the mainstram construction industry.

The design presented took the same data from the solar analysis to inform the layout of a diagrid, equally maintaining more density at the top for more shading and less density lower down. The diagrid is therefore distributed proportionally across the building producing an attractive series of arches. The selected version was the result of a study in the parameter space with a more or less dense grid and the maximum length of a bamboo member. Here rather than just the computer determining the outcome, it resides in the design aesthetics and technical decision of the designer.

This project also demonstrates the scope of possible integration into contemporary management methods like BIM (Building Information Modelling) which is a digital model containing all the necessary data to manage both the design and construction process. This would permit designs of this nature to be integrated into the work flow of large construction projects which require a much more refined management of data, material specification and construction information.




```
( Amount of dwell after axis travel. )
( Adjust so total time at each spindle rpm )
( is about 200 seconds )
#106=200

G0 G40 G49 G50 G80 G94G17 G20 G40 G49 G54 G64 G80 G90 G98 M05


G28
S500 M3
M98 P2000 (Warmup axes)
S1000
M98 P2000 (Warmup axes)
S2500
M98 P2000 (Warmup axes)
S3800
M98 P2000 (Warmup axes)
S5000
M98 P2000 (Warmup axes)

M5 G28

M30 (End of program)

O2000 (Axis warm up subprogram)
G28
F50 G01
Z#104 (Do Z first and leave Z parked high for the rest )
Z#105
X#101
Y#103
X#100
Y#102
G04 P#106
M99 (Return from subprogram)

%
O4000
(REV3 EDITED AT MILL PROGRAM PROVEN)


#600=#600
(DIA TO CUT)
#601=#601
(STEP DOWN)
#602=#602
(DEPTH)
#603=#603
(CUTTER TOOL NUMBER)
#604=#604
(DRILL TOOL NUMBER)
#605=#605
(DRILL DIA)

(DO NOT CHANGE AFTER)
#606=#600/2
#607=#602/#601
#608=ROUND[#607]
#609=1


IF[#604EQ0]GOTO5
(DRILL CENTER IF NEEDED)
#610=309+3.82
#611=#610/#605
#612=.005+#611

T#604M6
G0G90G54X0.Y0.S#611M3
G43H#604Z2.M8
M50
G98G73Z-[#602+.3]R.2Q.05F#612
G80
M5
M9
G91G28Z0.


N5
T#603M6

G0G90G54X0.Y0.S2253M3
G43H#603Z2.M8

Z.1
G1Z.03F32.5
G91G141Y#606D#603
G3I0J-#606Z0.
WHILE[#609LE#608]DO1
G3I0J-#606Z-#601
#609=#609+1
```

Image 8.70 Graphical demonstration of the type of data which can be stored on the digital 3D model to be incorporated in Building Information Management (BIM)

CONCLUSION

Across the four design projects, it is exciting to see the prospect of bamboo in contemporary design and fabrication. Through the use of digital design and fabrication methods it is clear that bamboo can raise current standards and that the challenges inherent in the material and in the perception of specifiers and users can be overcome. By using a feedback loop in the design-to-fabrication system to assess the technical design performance and identify areas for improvement, this enables the designer and craftsperson to respond to set conditions, the action of those conditions on the material, the tools and design itself, and factor of tolerances for craftsmen and construction workers' skills. The design itself thus becomes interconnected, creating flow between the original design, the adjustments and the end function. Moreover, the concept of the structure performing to function by working in concert with its environment touches upon principles of the Circular Economy. Without the people, their skills and abilities, the design would not come to fruition; without the original design, the on-site craftsmen would have no structure to work upon; and without the variables being fed back into the design loop, the design itself would be less responsive to all factors. Craftsman, designer and material work together in a continuous loop. The result is a symbiosis of the mind of designer-craftsperson, the mathematics of the computation, the agility and sharpness of the tool, the dexterity of the maker and the play and resistance of the material.



9.

SUMMARY AND CONCLUSIONS

This thesis has focused on three main areas: one, the mind and how it is involved in the development of architectural design, both culturally and technically; two, the tools used in conceptualisation, fabrication and workflow, and three, the matter with has its own properties and characteristics which we reciprocally respond to in the process of design and fabrication.

9.
SUMMARY AND CONCLUSIONS

MIND

Whilst viewed and analysed independently, the successful translation of basic materials into new architectural paradigms requires the interconnection of all three of the area mentioned above. Without the mind to manipulate tools and matter, we cannot transcend the basic stilt hut with bahareque walls and grass roof of the eighteenth-century Colombian Antioquenos. But nor can we create a path forward, responding and adapting to new needs, new technologies, and new philosophies, without those initial beginnings. We have needed the hundreds of years intervening, filled with experimentation, self-examination and new challenges, to move from the simplistic forms of crafting to the sophisticated forms of design we now seek to move beyond with each new structure. Furthermore, our needs have become more complex and diverse as those centuries have rolled by. The craftsman of three hundred years ago is still present and vital in the craftsmen of today but we have refined our understanding of what crafting and making is (Marchand, 2003;Ingold, 2013). We can weave together the intricate strands that meld the mind by practicing, communicating and positioning knowledge so that each relate to the other and to the action itself – the process of designing and fabricating (Marchand, 2003).



THE CRAFTSMAN OF THREE HUNDRED YEARS AGO IS STILL PRESENT AND VITAL IN THE CRAFTSMEN OF TODAY BUT WE HAVE REFINED OUR UNDERSTANDING OF WHAT CRAFTING AND MAKING IS

The anthropological processes of making and designing have been slowly but rigorously integrated into the whole process of seeing what we want to design, using the new technologies that are developing in the twenty-first century – parametricism, computer-aided design and the computerised manipulation of materials to achieve far more than their outward form would otherwise enable us to conceive. We no longer view construction as a simple means to a solid form using available materials. Our designing has become multi-faceted, needing to meet far subtler needs than mere shelter. The Zeri Pavilion brought with it a wave of new thought that was melded with age-old truths: the idea of journeymen craftsmen learning on the job and passing their own innate skills onto others as they did so, the idea of creating a structure that both responded to its use and to its environment, and, perhaps most exciting in terms of this thesis, the use of bamboo, a material hitherto historically regarded as useful only for simple structures.



TOOL

Global warming, environmental crises, growing populations, political and economic needs all now feed into the network of issues that must be indexed and responded to in order to craft a building that meets the needs of today. Increasing support for the circular economy and the need to recycle and re-use – rather than use up – our resources requires us to apply existing understanding to create new ways of dealing with old problems. We are learning to automate fabrication, to create factory processes that can replicate quickly and easily to respond to global crises, and to use our digital skills to push materials and designs beyond boundaries we previously thought to be set in stone. Parametrics provide us with new means of interrogating materials to construct in the most innovative, structurally efficient, resource-conserving ways. We can literally bend materials to our needs using modern software. We can adapt buildings to optimise environmental conditions and utilise the resources to with renewed intelligence and performance. And as with the projects discussed in chapter 8, we can test parameters, feeding them back into the design loop so that we formulate a digital design model that evolves as the building does, enabling individual craftsmen to work with their hand tools alongside more complex fabrication processes in a holistic way.

And yet, a large proportion of the world still struggles to access complex technical equipment and tooling. Craftsmen still rely on the basic construction tools and techniques their forefathers used – knives, hammers and chisels – to enable joints to be made and structures to be built with this limiting technology, particularly when using bamboo as a construction material. Whilst the digital age is slowly filtering into countries with less resources, it is still operating at a high level and is not within the reach of the majority of the population. Parametric design is an exciting design concept, but without a means of translating it down-scale, it will remain the domain of the elite.

The possibility of extracting the basics of parametrics and translating them into an easily manufactured and usable digital cutting tool for bamboo was an exciting one. Basic construction methods could still be used – and by the many that knew them – but with greater speed, precision, volume, efficiency and less waste. Not only could cultural and environmental needs be met – using locally sourced material and craftsmen – but global needs too. Bamboo is readily available, easily resourced, and sustainable. The materials used to create the digital fabrication machine are all low-end technical supplies, sourced easily and cheaply. With the plans shared at creative commons, online and accessible to all, the machine tool becomes a global resource to meet global needs.

MATTER

Bamboo has a long history of use as a construction material for the peoples of Asia, Central Africa and South and Central America. Over the past century, modern materials like steel, concrete and brick have taken over the construction industry, while bamboo has kept its status as a 'poor man's material'(Manandhar, Kim & Kim, 2019). However, bamboo offers incredible solutions to many of the environmental, technical, social and cultural issues present in our built environment. The inherent strength of high-quality bamboo due to its strong fibres and the lightness from the hollow cylindrical shape of the culm provide this material with unique properties for structural design. Bamboo is also excellent in dealing with high seismic activity as the elasticity to weight ratio reduces inertial forces from earthquakes.

It is clear that this natural material could replace certain uses of steel, timber and wood in buildings, yet bamboo is not established as a mainstream material. The intrinsic variability of the material, which complicates performance analysis, construction methods, and dimensional coordination, amongst other factors are impeding its wider use amongst in construction. Many bamboo structures therefore have relatively high levels of redundancy with a consequent loss of efficiency and elegance because of the inefficiency of the spatial and structural design. More sophisticated architectural uses of bamboo have compromised cost or performance advantages over equivalent structures produced using more established engineering materials.

As a construction material of the future, bamboo lends itself to geometrical and mathematical logic therefore ideal for computational, parametric design. Form here, develops through a symbiotic relationship of intrinsic material qualities determined by material knowledge (Hensel, 2004, 2008; Menges, 2006; Oxman, 2010; Ingold, 2013).

Indeed, as well as being an innovative construction material, bamboo also represents a unique solution to ecological shortfalls and pressing environmental issues. Bamboo fits perfectly within the principles of the circular economy and this is undoubtedly an area for further research.

Many architectural research centres – both academic and industry have similarly recognized the importance of advancing digital fabrication specific to material properties to offer innovative solution to the construction industry. ETH Zurich, Bartlett School of Architecture, Architectural Association, Institut d'Arquitectura Avançada de Catalunya, Universidade do Porto, RMIT in Melbourne, University of Sydney, Stuttgart/ ITKE, Universität für Angewandte Kunst Vienna/IOA, Virgina Tech, others) and leading industry partners (Foster + Partners, White Arkitekter, BIG, HENN, ROK, Cloud 9, Buro Happold, str.ucture, designtoproduction, Smith Innovation, Blumer-Lehmann, S-Form, Factum Arte Desarrollos Digitales, McNeel Europe and others) are developing new knowledge focused on understanding materials not as static, inanimate or inert but as active agents engaged in specific behaviours.



BAMBOO LENDS ITSELF TO GEOMETRICAL AND MATHEMATICAL LOGIC THEREFORE IDEAL FOR COMPUTATIONAL, PARAMETRIC DESIGN

9.
SUMMARY AND CONCLUSIONS

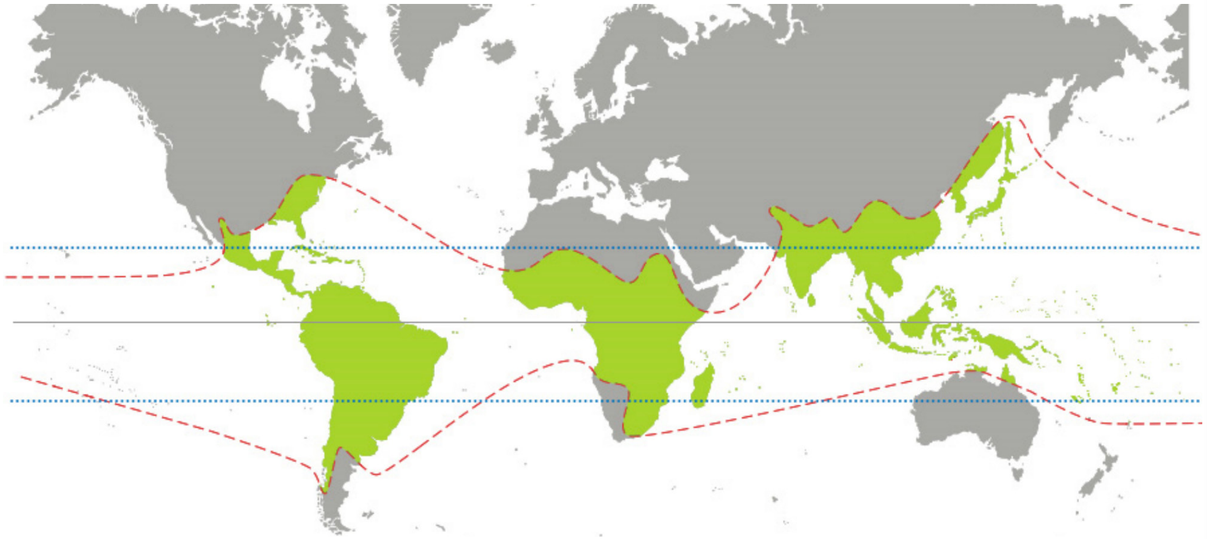


Image 9.1 Global natural bamboo habitat. Source: (national geographic 1980)

There is much potential in continuing this research project as the impact could reach many regions across the globe (image 9.2). Whilst Guadua essentially growns in South and central America, other bamboo species suitable for construction like Dendrocalamus, Bambusa and Phyllostachys grow in other continents. In continuing with this research theme, to improve, with digital technologies, existing methods of fabrication and architectural applications, the impact on a local-global scale is quite evident. The replicability of the methods used in this research project has a transferable nature as it was based on a flexible framework which could adapt to a different context. In principle, this low-cost intermediate technology could be adapted for different geographical, social, cultural and economic contexts; further enhancing the applicability of bamboo in construction and reducing the use of less sustainable materials.

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Image 9.2 A farmer measuring the thickness of a bamboo tree in Madagascar. Photo: INBAR/Lou Yiping



Image 9.3 James Palmer, Ricardo Assis Rosa and Roger Martinez in front of the pavilion structure at the end of the research fieldwork in Colombia (2017)

CONCLUSION

By own work researching the strengths, weaknesses and applications of bamboo whilst developing the digital fabrication tool has led me to the following conclusions:

- Bamboo is indeed versatile, flexible and inherently strong, making it an ideal material to consider for mainstream construction.
- Bamboo is environmentally sustainable, fast-growing and easy to source in many regions of the world where access to raw, useable construction materials is in demand.
- Bamboo works well within the concept of the circular economy, with a low carbon footprint and can re-cycle back to nature with little processing energy.
- Whilst it can respond to sophisticated parametric design, it can also be used simply but effectively based on its own obvious strengths and weaknesses and utilising local craftsmen's knowledge.
- It can be used even more efficiently – small or large scale – by facilitating faster and more accurate joint cutting with digital technologies in both design and fabrication.
- The digital fabrication cutting tool built in this project responded in a logical manner to the precision cuts required. This system developed synchronously to the strengths of traditional craftsmanship, contributing effectively to the culture of bamboo design and making.
- Computational methods clearly enhanced the ability to develop advanced architectural designs, raising the perception and possibilities of this material in contemporary architectural design.

The digital fabrication tool was designed not to impose itself upon its users or the material but to work with both and enable the craft and the material to flourish, offering solutions to our built environment which touch us by their beauty, our connection to nature and our communities.



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