Algorithmic thinking to promote full-culm bamboo durability in architectural design

John Osmond Naylor

Doctor of Philosophy

Civil & Geospatial Engineering

School of Engineering, Faculty of Science, Agriculture & Engineering

September 2023

Abstract

Full-culm bamboo is a fast growing, strong, environmentally sustainable construction material. Inappropriate use of bamboo in buildings results in physical degradation. This leads to negative societal perceptions and an underutilisation of this construction material. Design professionals have a role in changing attitudes to bamboo through the exemplar and appropriate specification in their designs. Bamboo-growing, tropical low- and middle-income countries (LMICs) are some of the poorest and most vulnerable societies to natural disasters, and by 2050 the tropics will be home to one half of humanity. In order to build the required buildings without negative environmental impact, a diversification of materials will be required, and locally available bio-based materials can supplement existing practice.

This research identifies the poor natural durability of bamboo as a key reason for negative societal perceptions and argues that many mainstream architectural design methods and tools pose limitations to design for full-culm bamboo. Quantitative surveys with construction industry professionals and students working in bamboo growing regions were employed, followed by qualitative interviews with Interpretive Phenomenological Analysis. Case study research in Colombia, paired with a literature review, examined best practices and revealed how poor natural durability can manifest.

Design guidance for durability in ISO 22156 (2021) is synthesised in this research along with the methods and tools used by design professionals, including algorithmic design tools, in a novel design approach for bamboo structures. Using algorithmic thinking for *protection by design*, this design approach can be applied to analogue design methods or scripted digitally. A symposium set evaluation criteria for this design approach, identifying Haiti's construction sector as a tropical LMIC context. The research proposes that supporting design professionals to make durability a key consideration in early design stages, can increase the service-life and status of bamboo structures, and promote greater use of locally available bio-based materials in construction.

Acknowledgements

This endeavour would not be possible without so many people letting me into their worlds and sharing their time and insights with me. I would like to thank my supervisors, Dr Ben Bridgens and Dr Sarah Dunn at Newcastle University and Dr Kent Harries at the University of Pittsburgh who have supported this research in so many ways.

I would like to thank Jane and Franck who first introduced me to bamboo and whom I have collaborated with in Section 1 of this thesis; Andry who has been such a support throughout; Sebastian who came to Haiti in 2015 and has remained a guidance since; Mia who supported all the work in Panama; Beatriz, Jolene, Andrea at the Architectural Association as well as Javier, Brett, and Chris who in 2013 got the AA Haiti Visiting School up and running; Doria, Laguerre and Ti Coq for teaching me how to construct with bamboo in Haiti; Neill, Jolyon, Karen and Elyse at Grimshaw for making it possible study a PhD part time while having a full-time job; Thomas, Chase, Cesar, and Rakhmat for their wise advice and insight into the use of digital tools; Diego, Aditya and Rose who all made the AA Haiti Visiting School what it became and have blessed me with their time and guidance ever since; Reenal for all her love and support; Jacqui for always looking out for me on every trip to Haiti; Xavier and Ximena for making my time in Colombia so memorable; Marian and Ruth at Newcastle University for their kindness; Nancy, Ginette, Rose-May, Isabelle, Farah, Christine, Nathalie, Elrica, and Jupille who have opened up Haiti to me; my parents for their proof reading and constant love; and Jörg who has provided frank, honest and invaluable advice and motivation. I have collaborated with Jörg Stamm, Diego Perez Espitia and Cesar Cheng, in Section 4.5.3 of this thesis. The extent of this collaboration is recorded in the relevant thesis section and documented as a peer reviewed conference paper as Naylor et al. (2022) and recorded in Appendix C.

The final acknowledgement is to Marisa Diyana, whose humour, intelligence and critical eye sowed the seeds of so many of the research questions and in whose memory this work and subsequent contributions to knowledge are dedicated.

The views expressed in this PhD research are that of the author alone and do not necessarily reflect the views of those acknowledged, or employers past and present. In acknowledging the advice and inspiration of those who have supported this research, all interpretations, conclusions and any errors in this thesis are the author's own.

General notes

Funding

This research was majority self-funded with additional support from the University of Pittsburgh Chancellor's Distinguished Public Service Award and the Newcastle University Global Partnership Fund which is administered through Newcastle University's International Relations and Partnerships team.

Software platforms used

Inclusion of software in this research should not be construed as commercial endorsement by the author. Names of software platforms have been italicised where it has been deemed appropriate within the thesis.

Disclaimer

Although the design approach and decision tree for *protection by design* has been developed and tested, no assumption should be made that following this design approach or decision tree in isolation without the input of qualified professionals will ensure durability in full-culm bamboo structures. Structures must be designed by appropriately qualified and experienced design professionals; construction is to be overseen be personnel having appropriate skills and experience; and adequate supervision and quality control are to be provided in factories, treatment plants and on site. Relevant standards, codes and competent persons in the region where a bamboo project is to be designed for, should be consulted for advice at all stages of design and construction with full-culm bamboo. A design approach should be used in conjunction with such advice.

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Symbols and abbreviated terms

Abbreviation, acronym, or symbol	**Description**
A	Cross sectional area of a single culm
AA	Architectural Association School of Architecture
ABACUS	The Architecture and Building Aids Computer Unit, Strathclyde
ACD	Allowable load-bearing capacity design
AD	Algorithmic design
AEC	Architecture, engineering, and construction
AI	Artificial intelligence
AJ	The Architects' Journal [UK]
ARB	Architects Registration Board [UK]
ASD	Allowable stress design
AAVS Haiti	Architectural Association School of Architecture Visiting School workshops in Haiti, 2014-2017
BIM	Building information modelling
BS EN	British Standard European Norm
BS EN 350 (2016)	BS EN 350:2016 - Durability of wood and wood-based products. Testing and classification of the durability to biological agents of wood and wood-based materials
CAD	Computer aided design

C_{DE}	Modification factor for Service Class and load duration for modulus (a term used in ISO 22156, 2021)
C_{DF}	Modification factor for Service Class and load duration for capacity and strength (a term used in ISO 22156, 2021)
CFD	Computational fluid dynamics
CH_4	Methane
CLT	Cross-laminated timber
CMU	Concrete masonry unit
CNBH (2012)	Le Code National du Bâtiment d'Haïti (2012) [Haiti]
CNIAH	Collège National des Ingénieurs et Architectes Haïtiens [Haiti]
CO_2	Carbon dioxide
CROSS-UK	Collaborative Reporting for Safer Structures UK
D	Nominal culm diameter
DfMA	Design for Manufacture and Assembly
DPM	Damp proof membrane
EBP	Engineered bamboo product
EMC	Equilibrium moisture content ("*W*EMC" is the term used in ISO 22156, 2021)
EN 338 (2016)	EN 338:2016 - Structural timber - Strength classes
EPW	EnergyPlus Weather
DWG	DraWinG [AutoCAD file format]
FAO	Food and Agriculture Organisation of the United Nations

FEA	Finite element analysis
FONDDIM	Foundation for Sustainable Integrated Development of Marmelade [Haiti]
FSC	Forest Stewardship Council
FSP	Fibre saturation point ("*W*FSP" is the term used in ISO 22156, 2021)
FOKAL	Fondasyon Konesans Ak Libète (Foundation for Knowledge and Liberty) [Haiti]
FRP	Fibre-reinforced polymer
GHG	Greenhouse gas
GSAPP	[Columbia University] Graduate School of Architecture, Planning and Preservation
H-H	Hailwood-Horrobin sorption model
HKBD	Hong Kong Building Department
ICBO ES	International Conference of Building Officials Evaluation Service
IEA	International Energy Agency
IL	Institut für Leichte Flächentragwerke (Institute for Lightweight Structures) [University of Stuttgart, Germany]
INBAR	International Network of Bamboo and Rattan
IPA	Interpretative phenomenological analysis
IPCC	Intergovernmental Panel on Climate Change [United Nations]
IRP	International Resource Panel
ISO	International Organisation for Standardisation

ISO/CD 7567 (2023)	ISO - Committee draft 7567: Bamboo structures—Glued laminated bamboo—Product specifications
ISO 22156 (2021)	ISO 22156:2021 - Bamboo culms — Structural design
ISO 22157 (2019)	ISO 22157:2019 - Bamboo structures [Test procedures]
ISO 19624 (2018)	ISO 19624:2018 - Bamboo structures [Grading procedures]
ISO 21887 (2007)	ISO 21887:2007 - Durability of wood and wood-based products — Use classes
ISO TC 165	International Organisation for Standardisation Technical Committee 165 – Timber structures
LBL	Laminated bamboo lumber
LCBF	Light cement bamboo frame
NGO	Non-governmental organisation
LMIC	Low- and middle-income country
MC	Moisture content ("*W*MC" is the term used in ISO 22156, 2021)
MCBI	Ministry of Construction and Building Industry [China]
NMX	Norma Mexicana [Mexico]
NBS	National Building Specification [UK]
ND-GAIN	Notre Dame Global Adaptation Initiative
NFI	Non-Food Items
NGO	Non-governmental organisation
NIOSH	National Institute for Occupational Safety and Health [USA]
NSR (2010)	Norma Sismo Resistente (2010) [Colombia]

NURBS	Non-Uniform Rational B-Splines
OECD	Organisation for Economic Co-operation and Development
OHCHR	Office of the United Nations High Commissioner for Human Rights
OpenFOAM	Open Field Operation and Manipulation
OSArc	Open-Source Architecture
PACE	Package for Architectural Computer Evaluation
PD	Parametric design
PEFC	Programme for the Endorsement of Forest Certification
PGA	Peak ground acceleration
QA	Quality assurance
RH	Relative humidity
RIBA	Royal Institute of British Architects
SWB	Strand woven bamboo
t	Nominal [bamboo culm] wall thickness* *δ is the symbol used in ISO 22156:2021, ISO 22157:2019 and ISO 19624:2018, however literature in this field more commonly notates wall thickness as t. In this PhD research, the symbol t will be used to align with a wider array of literature in this field.
T	Temperature
TEEB	The Economics of Ecosystems and Biodiversity
UN	United Nations

UNCCD	United Nations Convention to Combat Desertification
UNEP	United Nations Environment Programme
UN-Habitat	United Nations Human Settlements Programme
UNISDR	United Nations Office for Disaster Risk Reduction
[UN] SDG	[United Nations] Sustainable Development Goal
USGS	United States Geological Survey
UTP	Universidad Tecnológica Pereira
UV	Ultraviolet
WHO	World Health Organisation [United Nations]
WIS	Wood Information Sheet
ZCB	Zero Carbon Building
ZERI	Zero Emissions Research and Initiatives

1 Chapter 1. Introduction

1.1 Thesis structure

This thesis develops and presents an approach to design for full-culm bamboo. Bamboo is a remarkable building material which is strong, lightweight, versatile, environmentally sustainable (Figure 1), with ecological benefits in growth (Figure 2). This research aims to promote the use of full-culm bamboo (Figure 3b), the most sustainable form of bamboo to use in construction (Harries et al., 2012), by supporting the design professional in their design decision making to increase an awareness of the potential of full-culm bamboo (in construction), wherever the use of full-culm bamboo is—or could be—practical.

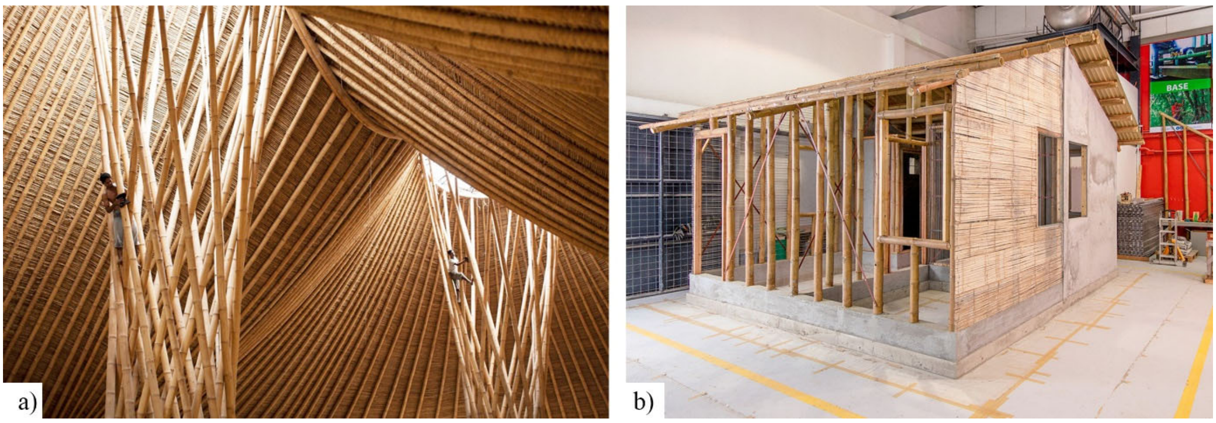


Figure 1: (a) *Three Mountains building*, designed by Jörg Stamm, Bali, Indonesia. Image by Mark Magidson, reproduced from https://www.christies.com, and (b) example of a single storey bamboo home by Base Builds in the Philippines. Image reproduced from https://www.hiltifoundation.org.

1.1.1 Chapter structure

This thesis is structured around six chapters, each focus around sub-questions (Figure 4): (1) Introduction and research context, (2) why bamboo is perceived as a *poor man's timber*, (3) how durability can be addressed in full-culm bamboo structures, (4) what tools and methods do design professionals use in architectural design, and how these could be applied to design for full-culm bamboo, (5) a design approach to durability and a decision tree for considering *protection by design*, and (6) the conclusion and suggested future research.

Figure 2: Bamboo of species *Guadua angustifolia* growing at the *Foundation for Sustainable Integrated Development of Marmelade (FONDDIM)*, Marmelade, Haiti. Photo by author, 2016.

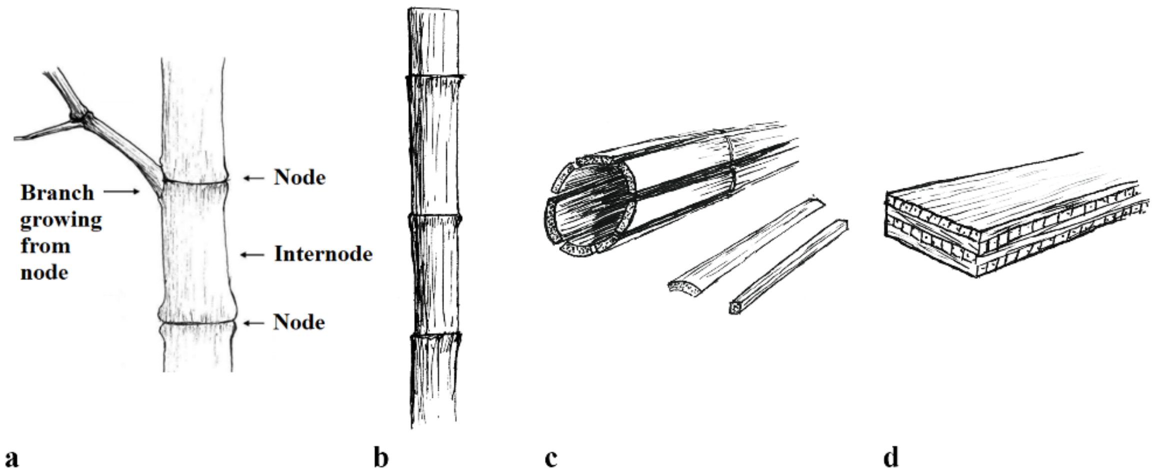


Figure 3: (a) Bamboo culm terminology, (b) the round pole form of bamboo known as full-culm bamboo, (c) bamboo splits, and (d) an example of engineered bamboo, otherwise known as an engineered bamboo product (EBP).

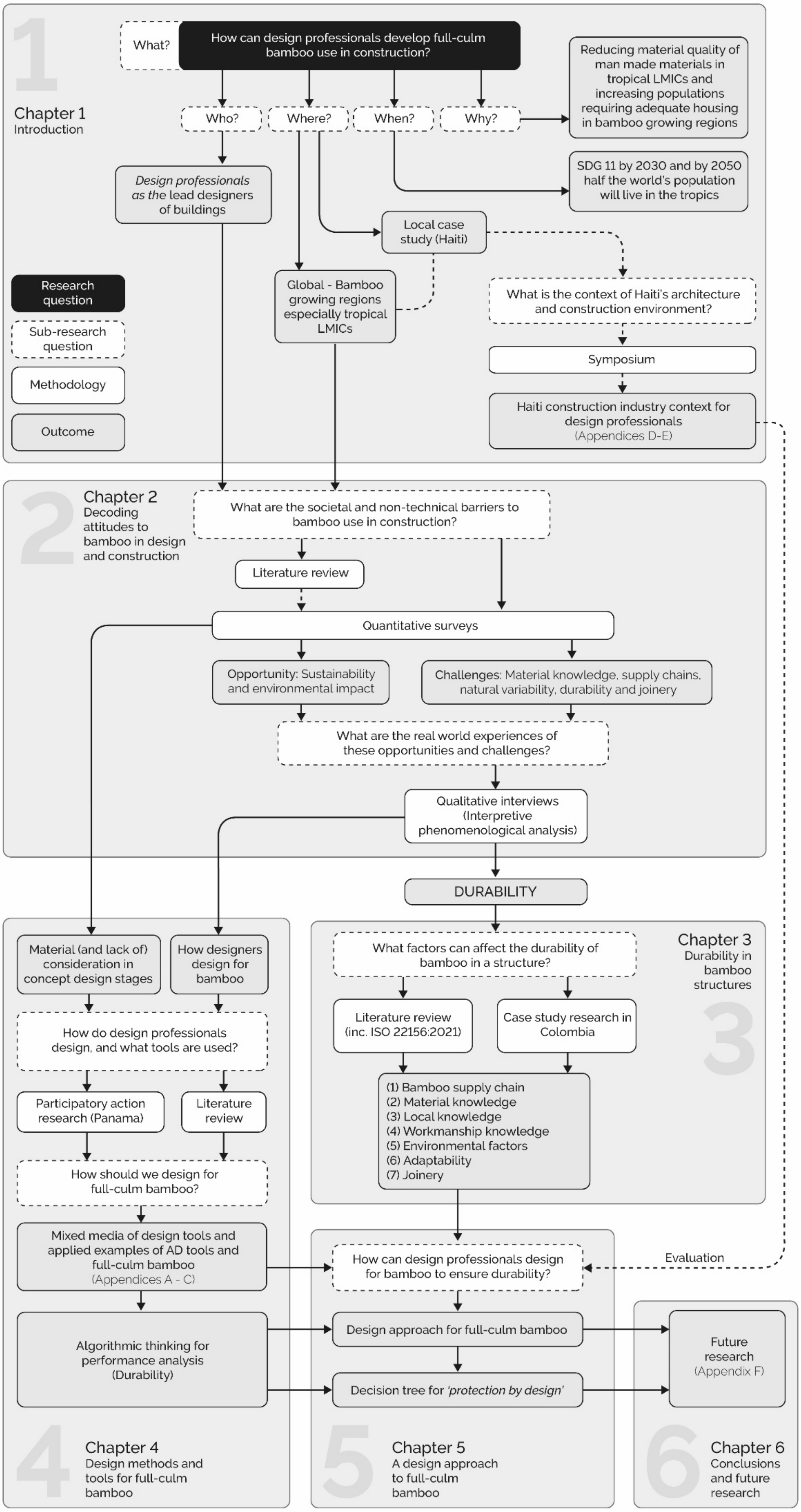


Figure 4: Thesis chapter structure with research sub-questions and methodologies used in each chapter.

1.1.2 Overarching methodologies in this research

A mixture of research methodologies are employed in this research. Each methodology is described in detail in each of the relevant chapters of this thesis (indicated in Figure 4). Below is a summary of how each was used:

- **Literature review:** Within each chapter (other than Chapters 5 and 6), literature reviews have been used to: set the context of this research, assess the role of bamboo in construction, and provide an understanding of a LMIC context (Chapter 1), investigate the non-technical societal barriers to bamboo in construction including a historical undercurrent (Chapter 2), understand what factors affect the durability of bamboo with a focus on the full-culm bamboo design standard ISO 22156 (2021), understand what design decisions can positively affect the longevity of bamboo structures (Chapter 3), and understand the methods and tools design professionals and students use in contemporary design practice including a review of algorithmic design (AD) tools and how they have been applied to the design of bamboo structures (Chapter 4). The reasons for the consistent use of literature reviews have been to establish the background of each of the relevant aspects of this research to inform, validate, and position the unique research contribution.

- **Symposium:** In Chapter 1, a symposium has been the format by which information on the low- and middle-income country (LMIC) context of Haiti has been explored to generate information which can be used to evaluate the application and relevance of this research (Section 1.7). Prior to this symposium a self-administered questionnaire assisted in establishing the themes for the symposium discussion. This questionnaire was written up, peer reviewed and presented as a conference paper (Appendix D). The symposium participants were a range of professionals in the architecture, engineering and construction (AEC) industry who worked in, or had experience of, working in Haiti. The symposium facilitated discussions on the current state of bamboo architecture in the region, the challenges faced, and the potential for future growth and development. Also in Haiti, there is a lack of literature which focuses on the contemporary construction industry and therefore a symposium format could fill this gap whilst providing deeper experiential insights of the participants. More detail on this methodology is discussed in Section 1.7.3.

- **Quantitative surveys:** Surveys gathered insights from architectural design professionals/practitioners, engineers, and students, exploring attitudes to bamboo in construction (Section 2.3), trends in the design processes (Section 4.2.7), and design tools used by design professionals and students (Section 4.6.1). While not explaining *Why?* certain attitudes arose, these offered a systematic quantitative overview and a starting point to efficiently gather data from a larger sample size. This provided a preliminary understanding of prevailing trends to be explored in greater depth using qualitative methods. It was this quantitative framework that provided a priori themes as a foundation for the subsequent qualitative interview coding.

- **Qualitative interviews:** Qualitative interviews were undertaken with architectural design practitioners and engineers with experience of addressing societal attitudes in their experience with bamboo, with a portion of interviewees aware of the Haitian built environment (Section 2.4). This method was chosen as it offered a deeper understanding of the factors influencing decision-making and design processes, revealing invaluable insights that were difficult to capture through quantitative methods alone.

- **Case study research:** This research also delved into case study investigations in Colombia, where bamboo buildings served as examples to examine and analyse successful implementations. The reason for focusing on only one region, was due to the COVID-19 pandemic and the restrictions on travel from 2020-2022 and this visit occurred in the spring of 2022. Case studies of in-use bamboo structures were chosen as they provided practical, contextual insights that go beyond theoretical knowledge from literature reviews. They offer an opportunity to explore specific instances in depth, observing the design, construction, bamboo growing locations, and material behaviour of in use bamboo structures. Such empirical research enabled this research to draw valuable lessons from real-world scenarios broadening the literature review in Chapter 3.

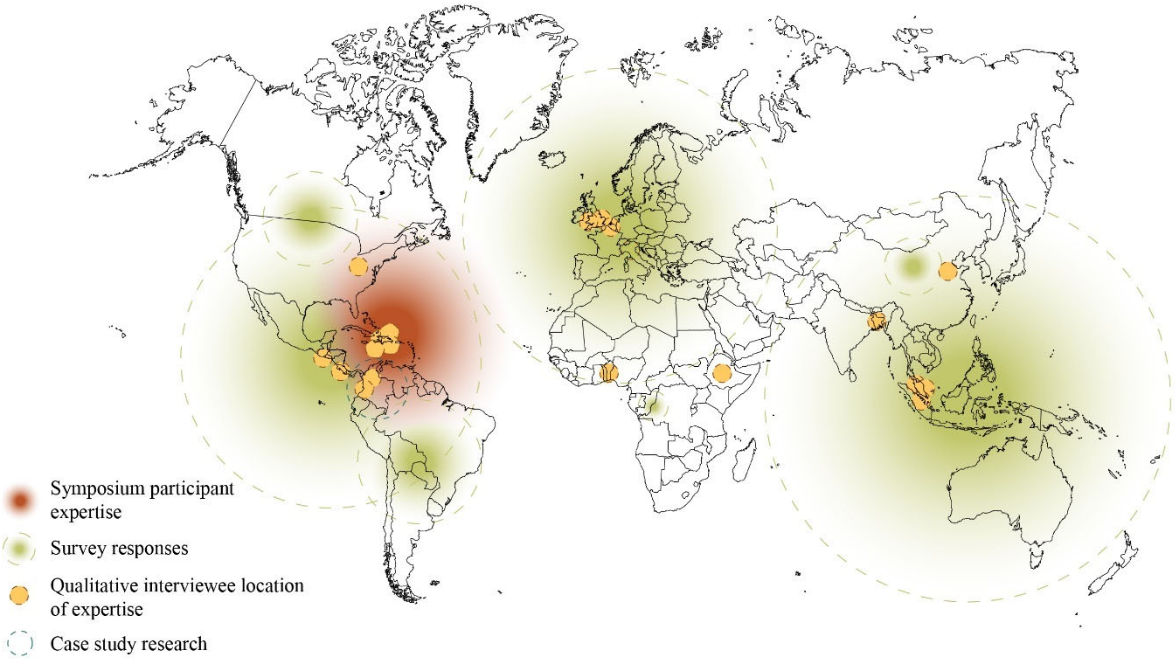


Figure 5: Overarching research methodologies map: Mercator projection world map, with an overlay of where each of the methodologies used in this research were deployed, or where survey responses or interviewee experience was geographically located.

By embracing a mixture of methodologies, the goal of this research is a qualitative study to develop a design approach which can support the design professional in a procedural and systematised manner to promote durability in full-culm bamboo structures. It is important that given the distinct geographic spread of bamboo growing regions (which is introduced in Section 1.3), the locations of where each of these methodologies were deployed is relevant (Figure 5).

1.2 Defining the thesis audience

1.2.1 Defining the role of the design professional and the thesis audience

The design approach proposed within this thesis is intended for design professionals, who may have an interest in using bamboo in their projects. At this stage it is crucial to define the role of the architect as a design professional since a universal definition of the term is elusive (ARB, 2017; Burr & Jones, 2010; Fischer & Tatum, 1997; Sinclair, 2010; Taylor, 2000; Yates & Battersby, 2003). In developed economies (alternatively referred to as the so-called Global North), Fischer and Tatum (1997) observe that design professionals can lack construction and material knowledge which can result in design errors and project delays. This is a consequence of the greater complexity of the built environment in the nineteenth and twentieth centuries when two distinct professionals emerged, the designer (design professional), and the builder (construction professional) (Burr & Jones, 2010). The *architect* as a master builder or craftsperson was transformed and a profession of architecture emerged as one separate from construction. This was one in which the performance of an architect as design professional, is based on "professional judgment, not craft" (Burr & Jones, 2010, p. 124). This has caused an unfortunate cycle in which a lack of construction knowledge in the design stages has resulted in reduced input of the design professional in the construction stage, which has meant less opportunity to gain construction knowledge (Yates & Battersby, 2003). Considering constructability in the early design stages of projects can improve designs and reduce errors (Fischer & Tatum, 1997; Yates & Battersby, 2003).

The design approach in this research targets appropriately qualified and experienced design professionals relevant to the region where the design for a bamboo structure is to be located. This is a description used in ISO 22156 (2021) which is the design standard for full-culm bamboo (which is covered in Section 1.2.5). This role of design professional may not necessarily be an architect in the understood usage in the relevant locale. They may—or may not—have experience working with bamboo. The term design professional will be used throughout this thesis. The design professional can follow this design approach to develop formalised material knowledge, constructability knowledge and wider consciousness of full-culm bamboo. The design approach developed in this thesis supports the evaluation of design output which can be practical to construction professionals, who will detail joinery and build the full-culm bamboo structure, and for an engineering professional who is required for structural calculations. This approach will guide a design professional through the durability considerations when designing with bamboo, referencing established standards and bridging the gap between architecture and engineering disciplines.

1.2.2 A design approach within Open Source Architecture

The term *Open Source Architecture* describes a practice of collaborative architectural design (Dortheimer & Margalit, 2020; Kaspori, 2005). In Haiti open source platforms facilitated the surveying of the built environment following the earthquake of 2010 (Columbia University GSAPP, 2016, p. 20). Sometimes abbreviated to *OSArc*, Open Source Architecture is an "inclusive approach to spatial design, a collaborative use of design software and the transparent operation throughout the course of a building and city's life cycle" (Ratti & Claudel, 2015, p. 122). Those in the architecture profession can use their work to demonstrate and advocate for sustainable, locally sourced, bio-based materials, and their projects can resonate and promote change. The principles established in robust design, if done in a way which is affordable, desirable, and does not clash with social norms, can have a profound effect on even the informal building sector. Contemporary architecture already sees the sharing of project drawings online for others to reference (Aravena, 2016; Frearson, 2014a; OpenStructures, 2019; Seksan, 2019). Projects like *WikiHouse* by 00, are conceived as a platform for design professionals to share designs and design tools that make it possible to download, adapt and "print" parts for a house from standard materials to be built without construction expertise (Parvin, 2013, p. 94). Design professionals can collaborate with local builders and governments around the world using specific projects to transmit experience and knowledge (Aravena, 2011, p. 35). Platforms such as *Collaborative Reporting for Safer Structures UK* (CROSS-UK), show that we can learn more from failures than sharing the newly completed building photographed at completion (CROSS-UK, 2021).

Architectural design for a building is a niche concept for the majority of the global built environment (Easterling, 2012, p. 4). In tropical low- and middle-income countries (LMICs) this is more true. In Ghana, over 90% of the urban housing stock is *informal,* the majority of which is built by individuals (UN-Habitat, 2011, pp. 161-163). Hardoy and Satterthwaite (1989) report that in most cities, 70%-90% of all new housing is built "illegally" (p. 12). In Haiti, Burlotos et al. (2020) observe builders operate on experience rather than drawings or regulations (p. 5). Design decisions are often driven by cost and convenience over structural or performance requirements. In many cases the construction manager or master builder is one person locally who coordinates construction on a community level without any "formal" training, but bases their design decisions on past experience handed down from friends or family (Kijewski-Correa et al., 2012, p. 277). Where design and engineering services are rendered, in cases such as Haiti, design and engineering professionals are merged into the same professional organisation which is effective when communicating between the disciplines (Le Moniteur, 1974). Those architects who work as design professionals in tropical LMICs often have a greater material and construction knowledge than those working in the so-called Global North. This is a result of the marginal field of sole design services, and the wider remit of the design professional in tropical LMICs. Therefore, these design professionals can reimagine and tackle issues in a holistic manner. Design professionals can promote this through their daily work and through the transmission of knowledge from their practice into local marketplaces and communities. Design professionals in this field, such as Alejandro Aravena, contend that it is important to involve the public in building processes rather than relying strictly on government action and the housing market (Thorne & Duran, 2016). A valid question here is still, if architects as design professionals are responsible for no more than 2% of global construction, employed by clients representing 1% of humanity (Parvin, 2013; Ratti & Claudel, 2015), then why is the output from this PhD research not design guidance for self-builders?

Brillembourg and Navarro-Sertich (2011), reason architects (as design professionals) can engage with the political processes, and persuade decision makers who may only be in office for three to five years, by "paring back architecture to its elements, and making it simple and repeatable" (p. 107). To paraphrase Dortheimer and Margalit (2020), design professionals may not be "creators" but can be "conductors" (p. 282). Design professionals, in tropical LMICs, have an opportunity to use the projects they work on, to become examples of best practice, and material advocacy. These trends are discussed in a symposium in Section 1.7. As Aravena (2011) explains in his own practices' work in this field, the built project designed by a design professional can be a demonstrator and education tool, "empowering local builders by giving them the knowledge that allows them to take these same innovations and apply them themselves" (p. 35). The design professional need not design the whole building. When Brillembourg and Navarro-Sertich (2011) use the phrase "simple and repeatable" (p. 107), this could be components of building systems. A first step for integrating bamboo into the construction industry will likely be through hybrid construction with other materials, or smaller building elements. Chaowana et al. (2021) suggest that the roof truss of a building is arguably its most crucial component.

As proposed in Fischer and Tatum (1997), an expert system that provides constructability information in the design stages would assist design professionals on construction projects to avoid costly situations during construction. Given the poor natural durability of full-culm bamboo, a lack of material or construction knowledge, can have a lasting impact on the building, and material perception. The design approach presented in this PhD research should consider how it can facilitate greater awareness of robust design for bamboo, without stipulating the design itself. An approach to design for bamboo should not propose a design, but support the design process, and inform the work of a design professional. Thus, design professionals can innovate and tailor their design for the local context, they can do so in a way to ensure the practical application of the material.

1.2.3 Contemporary design methods, tools, and non-standard materials

Contemporary architectural design practice (predominantly in the so-called Global North) follows a series of spatial explorations and formal manipulations (BIG, 2022; Butler, 2013; Di Mari & Yoo, 2012; FOA, 2003; Holl, 2000; UN Studio, 1998; ZHA, 2006). These involve a prioritisation of form over material and a design practice which operates on "reduced matter-models designed to behave like pristine, controlled numerical milieu" (Kwinter, 1996, p. 70), and as contended by Berkel (2012), "just because something can be modelled on the computer, it can get built, which is what is now happening around the world" (pp. 78-79). Calder (2021) points out that from *Modernism* a culture arose where "if you poured enough energy into it, modern servicing could eliminate the age-old local differences between buildings around the world" (p. 386). Form was not just prioritised over material, but form would dominate local environmental conditions, materials, and culture. As for bio-based materials, the architect Herman Kaufmann states, "Timber construction wasn't appreciated in the modern age but considered retrograde, so it was hardly developed" (Hofmeister et al., 2021, p. 56). An international style, today architecture schools still tend to treat Modernism as a foundation (Calder, 2021). Bio-based materials such as timber and bamboo buildings require a fundamentally different approach to design (Frearson, 2023).

Computational techniques including an algorithmic design (AD) approach, are increasingly used by design professionals in the design process for design exploration and visualisation (Berkel, 2012; Böke, 2018; Burger, 2012; Caetano et al., 2020; Deutsch, 2019; Hemmerling & de Falco, 2018; Senske, 2017). The engineering professions have long used software for design optimisation and recent advances that connect geometric design environments with analysis programs have made simulation more accessible to design professionals, even early in the design process (Brown & Mueller, 2018, p. 36). However, as Koyré (1948) contends (as cited in Carpo, 2003, p. 448), modern technology has created a "universe of precision", in contrast to the previous "world of approximation", and such precision means computational techniques in architecture today do not fully allow for the incorporation of materials with natural variabilities such as bamboo (Willis & Woodward, 2005, pp. 75-76). Therefore, the tools design professionals are using can promote the use of manufactured materials over bio-based materials. This means both design methods and computational tools in architecture are marginalising the use of bio-based materials at a time when the opposite is needed. Ensuring a way digital design tools can be applicable in a design approach for full-culm bamboo also provides an opportunity for efficiencies and reduce the cost of design. Chapter 4 will explore a range of these design tools that design professionals use, to design for bamboo.

The malleability of manufactured materials such as concrete and steel enable abstract forms to be constructed. As discussed in Crolla (2018b), “precision can be expected in controlled industrial manufacturing contexts, but inevitable higher levels of tolerance will creep in when manual labour drives the materialisation process” (p. 38). For bio-based materials such as bamboo and timber there are constraints including strength and stiffness—therefore requiring an efficient structure—and available sizes of elements. The precision which emerges from the use of digital design tools can only then be achieved by the comparable precision of standardised materials. Materials with natural variability or long-term dimensional variances—such as the creep behaviours of bamboo and timber—struggle to fit into this design environment. When material is considered it is often as a mapped texture which, as asserted by Moloney and Issa (2003), simply alludes to the material with little reference to the weight, ductility, or the constraints of fabrication. It also creates a platform where environmental factors are not considered. Concrete as an external surface could be a practical application of concrete. Applying bamboo in the same way can situate bamboo elements in a vulnerable position due to exposure to excess moisture and other environmental factors.

Digital tools, however, lend themselves to Open Source Architecture. Ratti and Claudel (2015) remarks “Open-source codes and scripts enable design communities to share and compare information and collectively optimize production through modular components, accelerating the historical accumulation of shared knowledge” (p. 125). Software and files containing 3D models or algorithms can be downloaded across borders. Digital architectural design tools become a platform for global innovation, to be applied locally. If digital tools in the architectural design process save time, provide efficiencies, and can implement standards, then there can arguably be no more relevant application for this process than in tropical LMICs.

1.2.4 Relevant policy, standards, and codes for design for full-culm bamboo

Since the year 2000 and the recognition of structural bamboo in an ICBO ES evaluation report (ICBO ES, 2000), the engineering profession has made great advances in understanding how bamboo can be used in construction (Trujillo, 2020). However the knowledge gap lies in how these recent advancements can be incorporated into the design methodologies for design professionals. Peters and Building Arts Forum/New York (1991), as cited in Holzer et al. (2007), note that the progressive specialisation of each field and the divergence between them has created a growing gap between architects and engineers exacerbated by the different theories, objectives, measures, and tools. Information has not automatically entered the domain of architecture practice and education and design professionals have not benefitted from the increase in engineering knowledge for bamboo. Within this vacuum, those with even the best of intentions, can promote applications for bamboo which Archila et al. (2018) and Harries, Rogers and Silva (2022) advise against (Walker, 2014), present vague generalisations of bamboo's strength performance (Newsweek, 2010), or present buildings where it is unclear how the principles of durability (as outlined in Janssen 2000, p. 55), have been incorporated (ArchDaily, 2023; Davis, 2013; designboom, 2019).

Appropriate design for full-culm bamboo can change attitudes to the material. Embedding guidance for durability as outlined in ISO 22156 (2021) into a design approach for full-culm bamboo for design professionals, can better align design, engineering and construction professionals around a common framework to follow. This in turn can develop better knowledge of bamboo in design professionals, which in turn, can produce new built examples innovating full-culm bamboo use, and in turn, change attitudes to bamboo and increase the available information for engineers to update code documents. As Mottram (2017) states when discussing this situation with Fibre-reinforced polymers (FRPs):

> To be able to write a codified standard (say for a Eurocode) the FRP R & D community needs (matured) practice to learn lessons from, and to have practice at this level we need the standard to overcome cost and an inherent reluctance to choose FRP as the structural material.

In short, good practice to inform standards requires standards to inform the good practice. Design professionals can be instrumental in creating projects, that with good awareness of design principles for bamboo, can inform others to institutionalise good practice. Through testing and the institutionalisation of new knowledge which remains situated in the *vernacular*, this field can move forward. The term *vernacular knowledge* is applied in this context and is a key discussion throughout this PhD thesis. This is defined and discussed in Section 1.2.6.

A design approach for full-culm bamboo for design professionals can only ever be just one element of a wider series of government policies and codified standards. When looking at the advances in the use of timber in construction in Europe and North America timber has benefitted from policies stipulating a proportion of timber to be used (YM, 2023), or in the case of British Columbia, Canada, publicly funded projects should consider *wood first* (FAO, 2016). In locations with a weak state apparatus such as those found in bamboo growing regions, policies and their enforcement would not be possible. Though policies are outside the scope of the design professional, good practice, and the demonstration of quality, functional, and inspirational bamboo structures can inform policy. This can change the minds of those in the government to invest resource, particularly if a locally sourced material offers economic growth.

1.2.5 Research in this field and the novel contribution

The publication of three international standards by the ISO Technical Committee 165 since 2018 has provided a suite of documents focusing on the structural use of full-culm bamboo, a design professional should be aware of (TC 165 has also produced and continues to work on new standards for engineered bamboo). ISO 22156 (2021) provides structural design criteria, ISO 22157 (2019) prescribes test procedures to determine physical and mechanical properties of full-culm bamboo, and ISO 19624 (2018) provides guidance for grading bamboo resources. However, for design professionals working in the concept design stages of a project that involves bamboo, these are not appropriate contemporary documents. In parallel with the development of standards by the engineering community, the task of presenting the information in these standards into clear design steps a design professional could use to interrogate and evaluate their emerging design is lacking. Before even the first—intent signifying—edition of ISO 22156 was published in 2004, there were a series of guides available to design professionals looking to work with full-culm bamboo which remain today a library of influential and important documents. These include books such as: *IL 31* by Dunkelberg et al. (1985), *Bamboo: Gift of Gods* by Hidalgo-López (2003), and a series of documents by Dr Jules Janssen (Janssen, 1979; Janssen, 1981, 2000). Other books are less compendiums of information but rather aimed at providing sequential guidance to designers such as: *Building with bamboo: A handbook* by Janssen (1995), *Guia para la construccion de puentes en guadua* by Stamm (2001), and *Building with Bamboo* by Minke (2012), which has been recently revised (Minke, 2023). Minke (2012, 2023) provides a series of detailed case studies as do books such as *Bamboo Architecture and Design* by van Uffelen (2014). These are all examples of books with information a design professional can gather inspiration from and find precedents relevant to their own project. This PhD research aspires to reconcile a gap for design professionals between design guidance and code requirements. The *International Organisation for Bamboo and Rattan* (INBAR) has published reports and guides on a range of bamboo applications including construction (Gutiérrez, 2000; Janssen, 2000; Ubidia, 2015). There have also been influential research publications that provide additional guidance to building with bamboo such as the re-classification of bamboo joinery by Widyowijatnoko (2012). There have been a series of works aimed at understanding the durability of full-culm bamboo (Kumar et al., 1994; Liese, 1998, 2019; Liese et al., 2003; Liese & Tang, 2015a) and in recent years there have been a series of reports to provide guidance on bamboo construction particularly durability, written by some members of the team who ultimately drafted the 2021 update to ISO 22156 (2021) (Kaminski, Lawrence, & Trujillo, 2016a, 2016b; Kaminski, Lawrence, Trujillo, Feltham, et al., 2016; Kaminski et al., 2017; Kaminski, Lawrence, Trujillo, & King, 2016). Since the publication in 2021 of ISO 22156 (2021), there have been publications that provide more details and illustrate how these standards can be applied (Harries, Rogers, & Brancaccio, 2022; Harries, Trujillo, et al., 2022; Kaminski et al., 2022).

Without clear guidance, some technologies or practices have emerged which the engineering community advises against. An example of this is bamboo as a reinforcing (bar) material for concrete (Archila et al., 2018; Harries, Rogers, & Silva, 2022). Many myths about bamboo—both its strengths and weaknesses—remain in the vernacular. That is, they are held within local isolated clusters of knowledge formulated by experience to local materials within a local context. In Section 1.2.6, the discussion and definition on knowledge in the vernacular is defined in greater detail. Formal codes and standards and peer-reviewed literature is critical to the responsible (and myth-free) adoption of bamboo as a building material. When considering design principles for durability in timber there is guidance such as WIS 4-28 (2019) – *Durability by design* which design professionals can use when designing and specifying timber. Equivalent guidance for bamboo is contained within wider literature on bamboo (e.g., Janssen, 2000), research documents (e.g., Kaminski, Lawrence, Trujillo and King, 2016) and conference papers (e.g., Kaminski et al., 2022). A next step developed through this PhD research is to synthesise this guidance into a format which can be used by design professionals to evaluate emerging designs, in the early design stages.

The format of a design approach for a full-culm bamboo structure which provides support to a design professional was presented in Mardjono (2002). Here a *decision support tool* for the design of bamboo structures was developed to be applied in “the early design stages of a bamboo building”, so it can “be applied to support the bamboo design” (Mardjono, 2002, p. 2). This provides structured guidance for a design professional to follow from the initial steps of a project with a catalogue of building elements which could be varied. This was developed as a standalone piece of software with a user interface for the design professional to answer questions posed by the tool. These questions would relate to aspects of the design from site (which would link to a database of bamboo species availability, growing environments such as altitude, earthquake vulnerabilities, etc.) and information on the constructional elements, with the wall system developed for the prototype of the tool. This was an impressive endeavour, especially given that it predated even the initial 2004 versions of the ISO design suite.

Computational tools have developed greatly over the past two decades with the paradigm of AD now providing opportunities to inform the design process. Crolla (2018b) has demonstrated the opportunity for digital tools in the design for non-standard materials and notes their latent opportunity to accommodate and leverage on-site realities—such as material properties and construction practices—as part of the design process (p. 41). Aligning with this advocacy, it is apparent through this PhD research, that to design for full-culm bamboo requires a greater emphasis on physical models and understanding of construction logic than with manufactured materials such as concrete and steel. This is also influenced by physical models being potentially a more useful communication tool for bamboo construction professionals than conventional architectural drawings. Though computers are widely used in the design of bamboo structures, they are used for structural testing by engineers or creating representational 2D and 3D material for drawings or renders. In recent years there have been more examples of AD tools being used in the design of bamboo structures, mostly experimental bamboo structures which are temporary, prototypical, or unbuilt (Chen & Hou, 2016; Crolla & Garvin, 2020; EPFL, 2022; Kamath, 2013; Lorenzo, Mimendi, et al., 2020; Ma et al., 2021; MacDonald et al., 2019; Mimendi et al., 2022; Qi, Zhong, Kaiser, Nguyen, et al., 2021; Sun et al., 2022; Suzuki et al., 2020; Wang et al., 2017). In most cases AD has been applied to find form, whether through live physics simulations such as Kangaroo (Piker, 2013), or using finite element analysis (FEA) with programmes such as Karamba 3D (Preisinger, 2013). However, there are notable exceptions which also demonstrate design processes for bamboo with both digital and analogue tools (Crolla & Fingrut, 2016).

1.2.6 Knowledge of bamboo in the vernacular and non-codified experience

There are also pockets of knowledge on bamboo in construction, supply chain information, and local environmental contexts which are important. This PhD research explores how local, experiential knowledge—spanning generations and contemporary construction practices—intersects with formalised standards, such as ISO 22156 (2021). This process is conceptualised in Figure 6.

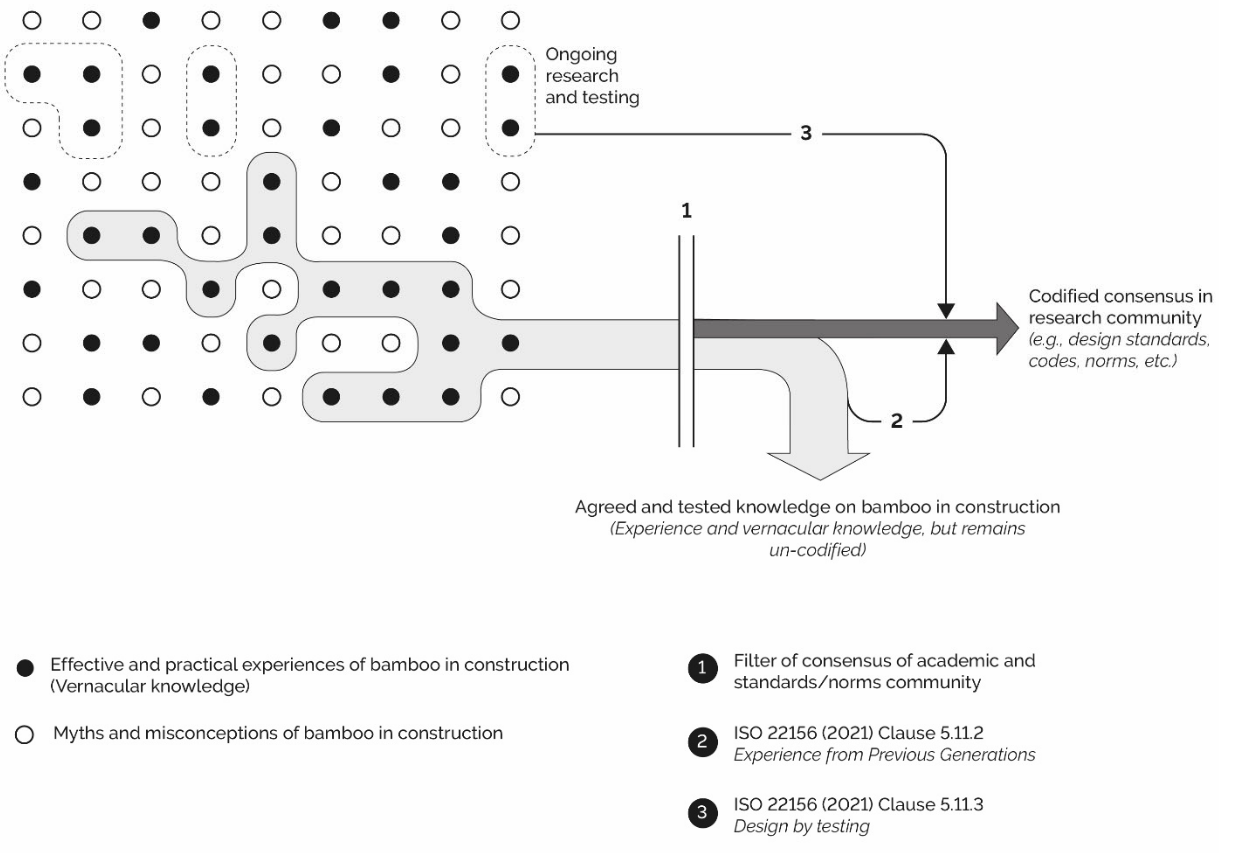


Figure 6: Conceptual diagram of knowledge in the vernacular for bamboo in construction and the challenge of testing to identify relevant experiential knowledge and differentiate these from myths of bamboo in construction. Through the testing of vernacular knowledge information can input into, and inform new code documents.

This research defines vernacular knowledge as both historical knowledge passed down from generation to generation (also described as "tried and tested"), and contemporary practices and experiences not yet included in formal codes. These can inform and challenge existing building codes, leading to their refinement and evolution. This occurs in two ways:

- **Input information:** The provision of information which can be input into a code (e.g., material information, site conditions, proximity to sea or other water bodies, site microclimates, etc.)

- **Code development:** Opportunities to challenge and develop code documents which lead to new information codified in subsequent revisions. This does not just extend to the technical information within a code, but also covers the usefulness and accessibility of the document to those who need to use these most. Feedback from those in the field on how the code is used will ensure this document is accessible (e.g., full-scale testing and acceptance of three-storey structures, greater information of fire performance, etc.).

Vernacular and traditional knowledge in architecture provides—as described by Anthony Reid in May (2010)—a “mirror” reflecting construction experiences (p. 6), and Schittich (2019) points out that vernacular architecture is also informed by permanent development, a process subject to technological change over time. Codes themselves are “living” documents, suggesting that insights from localised practices and testing can dispel myths and contribute to more relevant standards. For example, Minke (2023) begins by stating a “proviso that data can vary depending on local conditions” (p. 7). An aim within this research is also to decolonise this term, as highlighted by Oliver (2006), the emergence of the term vernacular architecture has largely been developed in the so-called Global North and often applied to building traditions of former European colonies. This term should simply mean knowledge from local experiences which may not be formalised. By integrating vernacular practices with engineering principles, this PhD research seeks to bridge the gap between traditional and formal design methodologies, advocating for a design approach that values local knowledge as much as codified standards. The investigation into ISO 22156 (2021) clauses related to *Experience from previous generations* (ISO 22156, 2021, Clause 5.11.2) and *Design by testing* (ISO 22156, 2021, Clause 5.11.3) exemplifies the potential for vernacular knowledge to enhance and complement formal codes (this relationship is shown in Figure 6).

The use of qualitative interviews as a methodology in Section 2.4, and action research in Section 4.5.3, was in part influenced by this phenomena. So much lived experience is undocumented in this field that engaging those who hold this knowledge is critically important to inform the development of a design approach which has practical relevance.

Bamboo is most sustainable when used locally (Harries et al., 2012; van der Lugt, 2008), therefore cultivating, rather than discarding, local vernacular knowledge is critical to ensure local supply chains and local skills are developed to avoid the imposition of impractical knowledge and species. “Parachuting in” knowledge, risks jeopardising the localised benefits of using full-culm bamboo which are local economic development through local supply chains, and environmental sustainability. This PhD research advocates for a holistic approach to bamboo construction, emphasising that no building code, such as ISO 22156 (2021), can operate effectively in isolation without considering the tacit and vernacular knowledge alongside formalised standards. Drawing inspiration from Frei Otto’s philosophy, “you feed them good grass and you get good milk” (Goldsmith, 2016, p. 29), this research illustrates that a successful design approach for bamboo construction necessitates the inclusion of relevant, localised information, as well as the intuitive understanding of materials and conditions. This is a discussion threaded through the thesis. In Section 3.8.1 and throughout

Chapter 3, vernacular knowledge is discussed in parallel to the information in ISO 22156 (2021) as well as in Sections 5.3 and 5.4 to highlight where vernacular knowledge can—and should—fit into a design approach for full-culm bamboo.

1.2.7 The objectives of the design approach developed in this research

This research identifies durability as the key factor that negatively impacts the societal perceptions of full-culm bamboo use in architectural design (Chapter 2), and this is also recorded as a main challenge faced by design professionals and students (Section 2.3). Through an understanding of the factors which can impact the durability of full-culm bamboo (Chapter 3), this research structures design guidance for full-culm bamboo in ISO 22156 (2021) as a series of questions a design professional can ask of their emerging design (Section 5.2 and 5.3). The difference to Mardjono (2002), is that the design decision support developed in this research, could be applied to a design already conceived through other design tools or processes (analogue or digital). A design may emerge through physical modelling, sketching or 3D explicit modelling. This research applies algorithmic thinking to develop a decision tree of sequential and related questions a design professional can use to interrogate their design. These questions are structured to align with the design guidance in ISO 22156 (2021) and evaluate the design with the *Use class* and *Service class* information in this document (which is discussed in Chapter 3). Digital AD tools can then be applied following this same series of questions for durability to automate this process. However, at the outset of this research and throughout, consideration is given to how this would be applied in a LMIC context, in the case of this research this context is the Haitian built environment. The design approach in this research therefore endeavours to perform the following (Figure 7):

- Develop a design approach to address the primary reason behind negative perceptions of bamboo, which is identified as durability in Chapter 2.

- Follow the design guidance for ISO 22156 (2021) to provide a bridge between the design and engineering disciplines, with a standard approach to classifying durability risk, and communicating this to clients or end users.

- The design approach should present itself so that a design professional can evaluate their emerging design ideas though the early design stages.

- The design approach should take advantage of AD tools but be applicable with or without the use of digital tools.

- The design approach should be applicable in a LMIC context (Haiti).

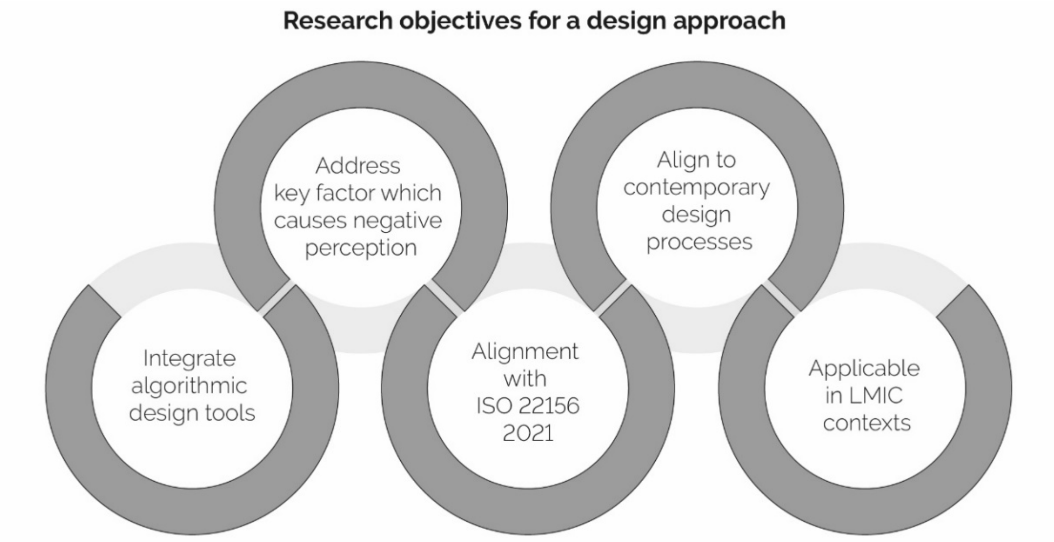


Figure 7: The five research goals in this PhD which endeavours to provide a unique contribution to this field.

1.3 Characterising bamboo growing regions

Tropical low- and middle-income countries (LMICs) (World Bank, 2023), are some of the most vulnerable societies to natural disasters (Bündnis Entwicklung Hilft, 2022). By 2050 half the world population will live in the tropics (State of the Tropics, 2020). The tropics are a region in which tropical woody bamboo grows (Figure 8) and the vast majority of countries in this region are LMICs (Lobovikov et al., 2007; Zhao et al., 2017). LMICs face population increase and rapid urbanisation which puts pressure on the current critical shortage of *adequate housing*, that which is structurally sound and durable (OHCHR, 2014; UN-Habitat, 2015, 2016b).

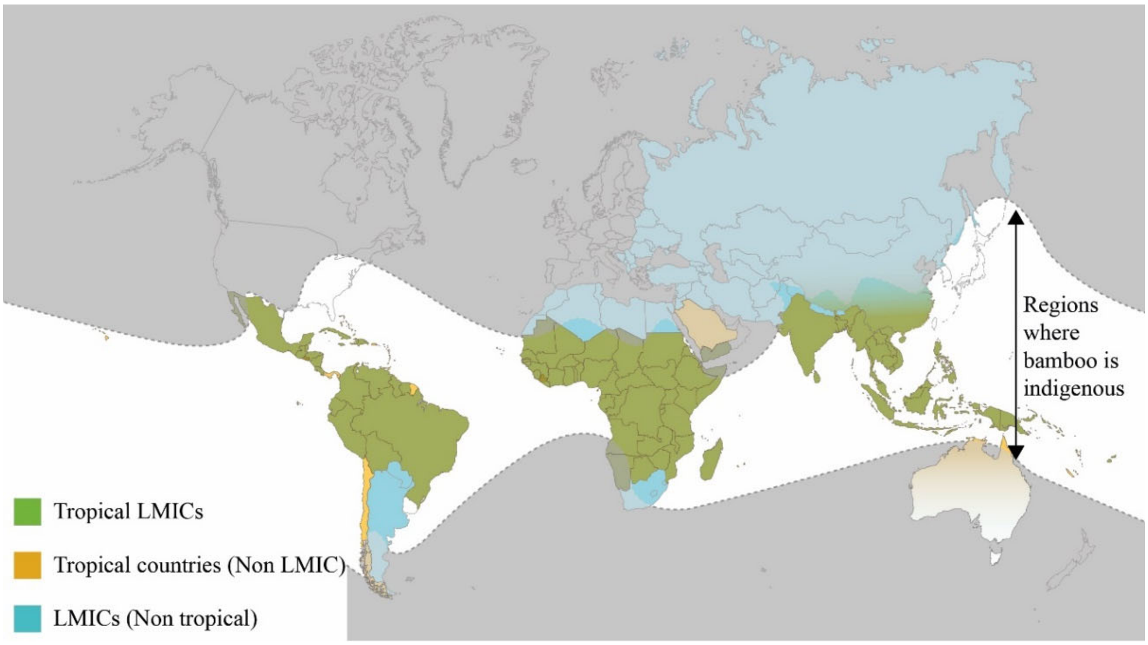


Figure 8. A definition of tropical LMICs: Mercator projection world map with an overlay of tropical countries[1] (State of the Tropics, 2020); low- and middle-income countries (LMICs) (World Bank, 2023); and bamboo growing region (light colour) (Lobovikov et al., 2007; Zhao et al., 2017).

In short, bamboo grows where people are the poorest, where there are the highest rates of inadequate housing, the urban population is set to increase the most, deforestation is the highest and where there is severe threat from natural disasters.

1.4 UN Sustainable Development Goals

The UN Sustainable Development Goal (SDG) 11.1 and 11.C target by 2030, the access for all to adequate, safe, and affordable housing, and the suggestion that the building of sustainable and resilient buildings utilising local materials can become a catalyst to support the least developed countries (UN-Habitat, 2016a). The Sendai Framework also proposes by 2030 to substantially reduce the number of people affected by disasters globally prioritising investment in disaster risk prevention and reduction to enhance the economic, social, health,

[1] Though only the north of Australia and the south of China is included in the tropical zone, these countries are included within this zone based on the criteria in the State of the Tropics Report (2020) that the proportion of the population living in the Tropics is 5% or more of the region's population living in the Tropics. Therefore, China is also included within this definition of a Tropical LMIC for this research.

and cultural resilience of persons, communities, countries, and their assets, as well as the environment (UNISDR, 2015). Using locally available bio-based materials does not just provide a means of supplying an adequate, safe, and affordable built environment, but one which can also provide adequate financial incentives to tropical LMICs, to advance forest management though their supply. If design professionals have the tools to design practically with bamboo, then a greater awareness and specification of bamboo on projects can encourage greater use of bamboo in the construction sector. In effect, in the long term, this can increase the number of jobs involved in the manufacture of local building materials, out of the total number of jobs in the construction industry (SDG 11.C), whilst catalysing the management of forest resources to supply these materials, protecting local forest habitats and ecologies (UN SDG 15.B), and reducing global GHG emissions (SDG 13). UN SDGs which can be impacted by wider use of bamboo in the construction industry are outlined in Table 1.

Table 1: Selected SDGs from the *UN 2030 Agenda for Sustainable Development* (United Nations, 2015), for which this research identifies potential impact, with commentary from relevant UN source.

SDG Target		**Proposed indicator**
11.1	By 2030, ensure access for all to adequate, safe and affordable housing and basic services and upgrade slums (United Nations, 2015).	Proportion of urban population living in slums, informal settlements, or inadequate housing (UN-Habitat, 2016a).
11.C	Support least developed countries, including through financial and technical assistance, in building sustainable and resilient buildings utilising local materials (United Nations, 2015).	Number of jobs in the construction industry of least developed countries (LDCs) involved in the manufacture of local building materials, out of the total number of jobs in the construction industry (UN-Habitat, 2016a).
13.1	Strengthen resilience and adaptive capacity to climate-related hazards and natural disasters in all countries (UN, 2021a).	Number of deaths, missing persons and persons affected by disaster per 100,000 people; number of countries with national and local disaster risk reduction strategies; and the proportion of local governments that adopt and implement local disaster risk reduction strategies in line with national disaster risk reduction strategies (UN, 2021a).

13.2	Integrate climate change measures into national policies, strategies and planning (UN, 2021a).	Number of countries that have communicated the establishment or operationalisation of an integrated policy/strategy/plan which increases their ability to adapt to the adverse impacts of climate change, and foster climate resilience and low greenhouse gas emissions development in a manner that does not threaten food production (including a national adaptation plan, nationally determined contribution, national communication, biennial update report or other) (UN, 2021a).
13.3	Improve education, awareness-raising and human and institutional capacity on climate change mitigation, adaptation, impact reduction and early warning (UN, 2021a).	Number of countries that have integrated mitigation, adaptation, impact reduction and early warning into primary, secondary and tertiary curricula; and the number of countries that have communicated the strengthening of institutional, systemic and individual capacity-building to implement adaptation, mitigation and technology transfer, and development actions (UN, 2021a).
15.B	Mobilise significant resources from all sources and at all levels to finance sustainable forest management and provide adequate incentives to developing countries to advance such management, including for conservation and reforestation (United Nations, 2015).	Official development assistance and public expenditure on conservation and sustainable use of biodiversity and ecosystems (UN, 2021b).

1.5 Anthropogenic impacts of the contemporary construction industry

1.5.1 The impacts of manufactured materials such as steel and concrete

In 2020, the global anthropogenic mass (the mass of all objects made by humans) outweighed all of Earth's living biomass, a result of a 23-fold increase in natural resource use for construction over the twentieth century (Elhacham et al., 2020; Schandl & Krausmann, 2017). Over half of humanity now lives in towns and cities and from 2010 to 2030, it is predicted that another one and a half billion people will be added to the urban population (Elmqvist et al., 2013). As the urban population continues to grow in the coming decades, the world's building stock is expected to double by 2060 (Gates & Gates, 2019). The floor area per capita is expected to double from 2017 to 2060 (IEA, 2017), as is overall material use over the next 50 years (OECD, 2019). As populations and incomes rise, without a change in current material use for construction, large amounts of concrete will be needed (Miller et al., 2016; Monteiro et al., 2017). If LMICs reach building stock levels similar to those of developed economies, the production of raw construction minerals alone could consume up to 60% of the remaining carbon budget (Müller et al., 2013). This is the remaining amount of CO_2 emissions possible by 2050, to hold the increase in the global average temperature to 2 °C above pre-industrial levels. The iron and steel industry alone accounts for 7.2% of global greenhouse gas emissions, of which 55% goes into the built environment (UNEP, 2022), with the impacts from iron ore mining harmful to the environment (Carmo et al., 2017; Hk & Hossiney, 2022; Kossoff et al., 2014; Neves et al., 2016; Segura et al., 2016; Vergilio et al., 2020).

Concrete is the most widely used construction material on the planet (Lehne & Preston, 2018) and, to quote Welland (2009), each year, each human "consumes" around forty times their own weight in concrete (p. 325). Concrete has been described as the most important man-made material in terms of both the amount produced each year and the total mass laid down (Smil, 2013). It has also played a factor in reducing extreme poverty by half since 1990 (Beiser, 2018; Smil, 2013; Torres et al., 2021). Production of concrete is responsible for approximately 3% of global energy demand (Monteiro et al., 2017), and by 2050, 75% of the water demand for concrete production will likely occur in regions that are expected to experience water stress (Miller et al., 2018). It is unfair to expect developing regions of LMICs to forego the materials which have facilitated the health and wealth of the so-called Global North. Where practicable, alternatives to cementitious materials and other manufactured materials, such as steel and aluminium, can be a positive means of creating the same growth in the built environment, without the depletion of the ecologies, and production of GHGs.

Concrete is formed from cement, water, granular rocks (aggregates) and admixtures where appropriate. In the production of cement, CO_2 is generated and the annual production of more than four billion tonnes of cement account for around 8% of global anthropogenic CO_2 emissions (Andrew, 2018; Lehne & Preston, 2018; Olivier et al., 2016). The quantity of cement produced has tripled in two decades (UNEP, 2019), and current production could increase by as much as 23% by 2050 (Harvey, 2018). It is imperative however that global net-zero CO_2 emissions are achieved (IPCC, 2021), and the production of cement has been identified as one of the most difficult sources of emissions to decarbonise (Davis et al., 2018). There have been developments to make concrete faster curing, lighter weight, stronger, resistant to corrosion, self-cleaning, and potentially able to clean up air pollution (Welland, 2009), but recycling concrete can be difficult (Allwood et al., 2010). Many of these steps would still consume resources of both aggregates and water. Technical solutions should not just be sought as Lehne and Preston (2018) recognise, concrete demand can be reduced by taking steps such as a new approach to how buildings are designed and substituting concrete for other materials that do not emit CO_2 during manufacture, such as bamboo (Davis et al., 2018; Lehne & Preston, 2018).

As well as water, sand is also consumed in huge quantities as an aggregate for concrete (Beiser, 2018; Leal Filho et al., 2021; Torres et al., 2017; UNEP, 2014, 2019). As sand becomes scarcer, and without locally available alternatives, the quality of construction in tropical LMICs get worse. Today, as shown in Figure 9, sand, gravel, and crushed rock, together referred to as construction aggregates, constitute the largest share of the anthropogenic mass (Torres et al., 2021; UNEP, 2022).

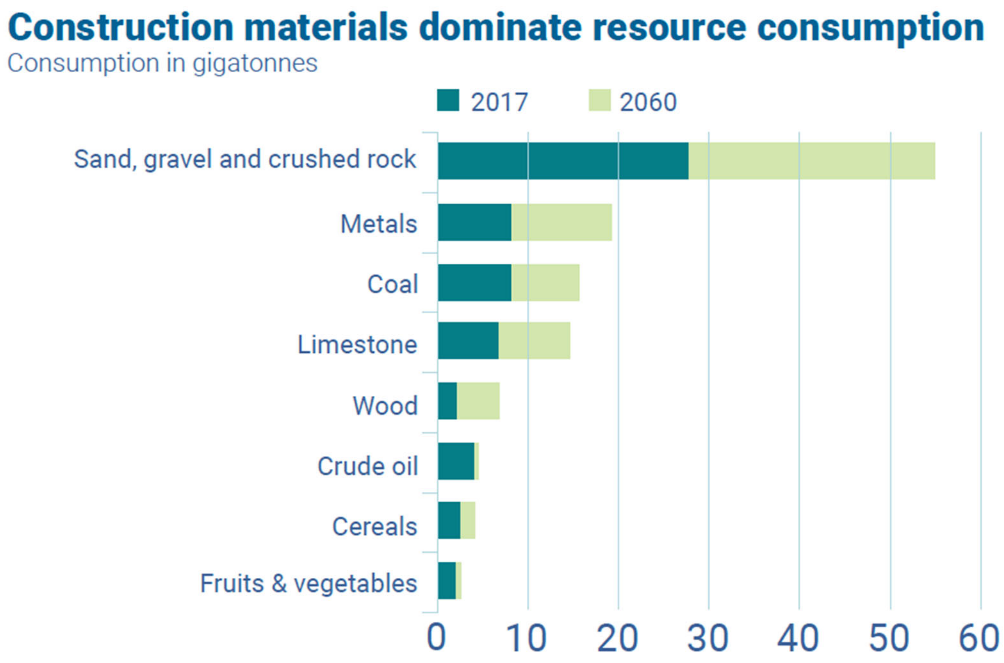


Figure 9: The resource consumption of construction materials and their projected increase by 2060 due to fast-growing developing economies. Chart reproduced from UNEP (2022), which was originally adapted from *Global Material Resources Outlook to 2060: Economic Drivers and Environmental Consequences* (OECD 2019).

Mineral extraction rates are exceeding natural sand replenishment rates (UNEP, 2019), whilst having a major impact on rivers, deltas, and coastal areas. This extraction is the most significant global geomorphological shaping force of the twenty-first century and a major contributor to climate change (IRP, 2020; Müller et al., 2013). Sand and gravel is one of the largest extracted resources by volume, possibly one of the most profitable illegal trades, while also being one of the least regulated (UNEP, 2019). Due to a lack of regulation for sand, the cement industry has been used as a proxy to derive an estimate (Krausmann et al., 2009). For every tonne of cement, six to ten tonnes of sand and gravel are used (Leal Filho et al., 2021; Torres et al., 2021; UNEP, 2019). Sand for concrete can only come from a select range of places. Desert sand is of no use for concrete (Beiser, 2018), and sand is essentially a non-renewable resource (Pereira, 2020). Additionally, the worldwide average retention of sediment by dams is 20% which causes shrinkage of beaches, and the availability of sand and gravel for construction (De La Rocha & Conley, 2017). China—a country which used more cement between 2011 and 2013 than the United States used in the entire twentieth century—now has only one remaining free-flowing river depositing sand and gravel (Leavenworth, 2020; Swanson, 2015).

Sand and gravel at the quantities required for an increasing population cannot be produced from terrestrial, riverine and marine environments without effective policy, planning, regulation and management (UNEP, 2019). Unregulated sand mining has catastrophic impacts on ecosystems, economies, and resilience to natural disasters which are exacerbated in their impacts by climate change (Ashraf et al., 2011; Farahani & Bayazidi, 2018; Koehnken & Rintoul, 2018; Kondolf et al., 2018; Padmalal & Maya, 2014; Park et al., 2020; Pereira, 2020). Torres et al. (2021) contend that the primary substitute for mining natural sand is crushed rock, for which there are abundant geological resources (USGS, 2020a), but regional sand scarcity is an emerging issue (Ioannidou et al., 2020; Torres et al., 2021). Therefore, the regional availability of sand in LMICs with proximity to more developed economies demanding sand can have a disastrous effect on the local price of sand for their own construction needs. Such a case is Haiti where the increased price of sand gives the builder a stark choice of aggregate between mineral rich river sand, or sand crushed from limestone, which is inappropriate for concrete, particularly in a seismic zone, such as Haiti.

The increasing cost of quality construction materials such as sand has increasingly devastating effects on material quality in LMICs, but there are alternatives for buildings which do not require so much concrete use (IRP, 2020). As the UNEP (2019) report highlights, one solution is in substituting traditional concrete where possible in building design with traditional bio-based materials like timber and bamboo, especially for low- and mid-rise buildings (Brownell, 2019; Churkina et al., 2020; UNEP, 2019). This will decouple the built environment in LMICs from the price increases of sand and imported construction materials, but will also produce one which is less carbon-intensive, less ecologically destructive, and design professionals have a significant role to play in this transition (Torres et al., 2021; UNEP, 2019).

This research is not about challenging manufactured materials such as concrete and steel directly. In El Salvador for example, the current construction industry infrastructure denotes that the best option for permanent low-cost housing is widely considered to be reinforced hollow blockwork. This is due to its durability, seismic resistance, availability, and simplicity of construction (Kaminski, Lawrence, Coates, et al., 2016). However, as more buildings are required and quality construction materials become more expensive in LMICs, alternative locally available construction materials will be needed. Many tropical LMICs will find it hard to reduce their construction mineral consumption, partly because alternatives such as the use of wood are limited to avoid further deforestation (IRP, 2020). Bamboo can play a significant role in providing a built environment which protects local ecologies yet ensures structural integrity at a time of rising construction material prices.

In 2015 the largest sectoral consumer of cement in the USA was residential, with the largest component of this being single family housing which is masonry cement, and brick and block intensive (USGS, 2018). Low-rise buildings up to 7 m in height, comprise the vast majority of the building stock of urban areas in the so-called Global South, especially outside dense urban areas (Zhou et al., 2022). SDG 11.3 suggests a more efficient use of land is required by evaluating urban population growth to the growth of urban land consumption, but this does not necessarily always mean high-rise residential typologies are the only way to address this (UN-Habitat, 2016a). ISO 22156 (2021) limits the document scope to bamboo structures of one- and two-storey residential, small commercial or institutional and light industrial buildings not exceeding 7 m in height. The contemporary discourse with timber suggests similar cellulose materials are more suited for low-rise construction (Crook, 2023), a typology that Lawrence (2021) additionally suggests is globally the most prevalent. Use in low-rise buildings of 7 m in height, or less, is a significant typology where full-culm bamboo can make a significant impact. The design approach developed in this research also considers low-rise buildings (one- and two-storey or 7 m in height).

1.5.2 Deforestation and the pressure on tropical forest ecosystems

Bamboo has an important role to play in reducing pressure on forestry resources. Forests are defined as land area greater than 0.5 ha with trees higher than 5 m and a canopy cover of more than 10% (FAO, 2020b). It does not include land that is predominantly under agricultural or urban land use, but includes flora such as rubber, mangroves in tidal zones, and bamboo (FAO, 2020b). The tropics are home to 45% of all these forests (FAO, 2020a), however, 58% of all deforestation occurred in this domain between 2000 and 2012 (Hansen et al., 2013; Runyan & Dodorico, 2016a). Deforestation has reduced in temperate forests, but increased in tropical regions (Runyan & Dodorico, 2016a). This is through urbanisation, increased demand for agricultural products, and required space for crops and livestock (DeFries et al., 2010). One factor driving this is that a unit of cleared land in the tropics produces less than half the crop yield of temperate regions, which leads to further cutting of forest in a repeated cycle of deforestation (Harmon, 2005; West et al., 2010).

Deforestation causes hydrological changes and negatively impacts the plants, animals, fungi, microorganisms and ecosystems of which they are a part (Brook et al., 2006; Brook et al., 2003; Dirzo & Raven, 2003; Helmore, 2008; Runyan & Dodorico, 2016c; Seymour & Busch, 2016; Sodhi et al., 2004). The removal of vegetation reduces precipitation which in turn hinders future vegetation growth, increases evaporation from the soil surface (D'Odorico et al., 2007; Runyan & Dodorico, 2016b; Vetaas, 1992), and removes the means to bring the condensed water down to the ground, by channelling of moisture or rainwater from the canopy to the ground by stem flow (Greene, 1992; Greene et al., 1994; Martinez-Meza & Whitford, 1996; Whitford et al., 1997; Wilson & Agnew, 1992). Given the magnitude of deforested land given over to agriculture, finding a forest resource, which can match the economic capacity of crops (such as palm oil), but perform many of the hydrological and ecosystem functions of tropical forests (such as some species of bamboo), is crucial.

Deforestation in tropical areas accounts for an estimated 10% of man-made CO_2 emissions (Harris et al., 2012), but it is not just the capacity to remove CO_2 from the atmosphere through photosynthesis which is affected by vegetation removal. These removals raise the water table in areas with relatively shallow groundwater (Runyan & Dodorico, 2016b), and expose vegetation to anaerobic conditions which will either result in their death, or hinder the ability of seedlings to re-establish (Jones et al., 2006). Upland soils incubated anaerobically begin producing methane (CH_4), a gas which in the first 20 years after release, is around 80 times more powerful than CO_2 at trapping heat in Earth's atmosphere (Mayer & Conrad, 1990; Megraw & Knowles, 1987; Nature, 2021; Wang & Bettany, 1997; Zachariah et al., 2016). Replacing standardised cementitious materials with bio-based materials such as timber and bamboo that sequester CO_2 can be one solution to help reduce overconsumption of resources to manufacture materials for construction (Pomponi et al., 2020; UNEP, 2019; van der Lugt, 2017). Bamboo is less susceptible to clear-cutting than trees, therefore has an important role to play in reducing pressure on forestry resources (van der Lugt, 2017).

In China, since nationwide logging bans of certain tree species came into effect in 1998, bamboo has increasingly been seen as a substitute to timber and has entered many markets traditionally dominated by timber (Lou et al., 2010). Timber and bamboo have similarities including their: chemical composition, possible uses, strength to weight ratio, and natural variability. Gottron et al. (2014) point out that the strengths of wood and bamboo are affected by similar variables such as: species, direction of loading in relation to the fibres, growth characteristics, environmental conditions, and duration of load. Sustainable exploitation of tropical forests to produce certified timber (FSC/PEFC) can be part of the solution as it provides an economic incentive (van der Lugt, 2017). However, in many regions of the world, timber will most likely never be able to provide the sustainable alternative at the quantity of material needed given the speed of growth and long rotation cycles of hardwoods (van der Lugt, 2017). This means timber extraction could have a deleterious effect on ecosystems (Pomponi et al., 2020). Supply is often lower than demand, which is why additional hardwood alternatives such as high-yield cultivated building materials such as bamboo are required (van der Lugt, 2017).

1.5.3 The climate crisis and the role of bamboo

The poorest of humanity will be hardest hit by the effects of climate change (OHCHR, 2019), and this is highlighted in Figure 10 showing counties ranked by their vulnerability to the effects of climate change based on *Notre Dame Global Adaptation Initiative (ND-GAIN)* data (Chen et al., 2015). Bamboo can mitigate the effects of climate change by sequestering CO_2 and restoring ecosystem services (Bystriakova et al., 2004), whilst providing a resource base, and significant pathway out of poverty (Belcher, 1995a). Bamboo can represent a symbiotic relationship between humans and the natural world, though one challenge for bamboo plantations is genetic diversity, which is arguably the most important component of biodiversity (C. Liu et al., 2018).

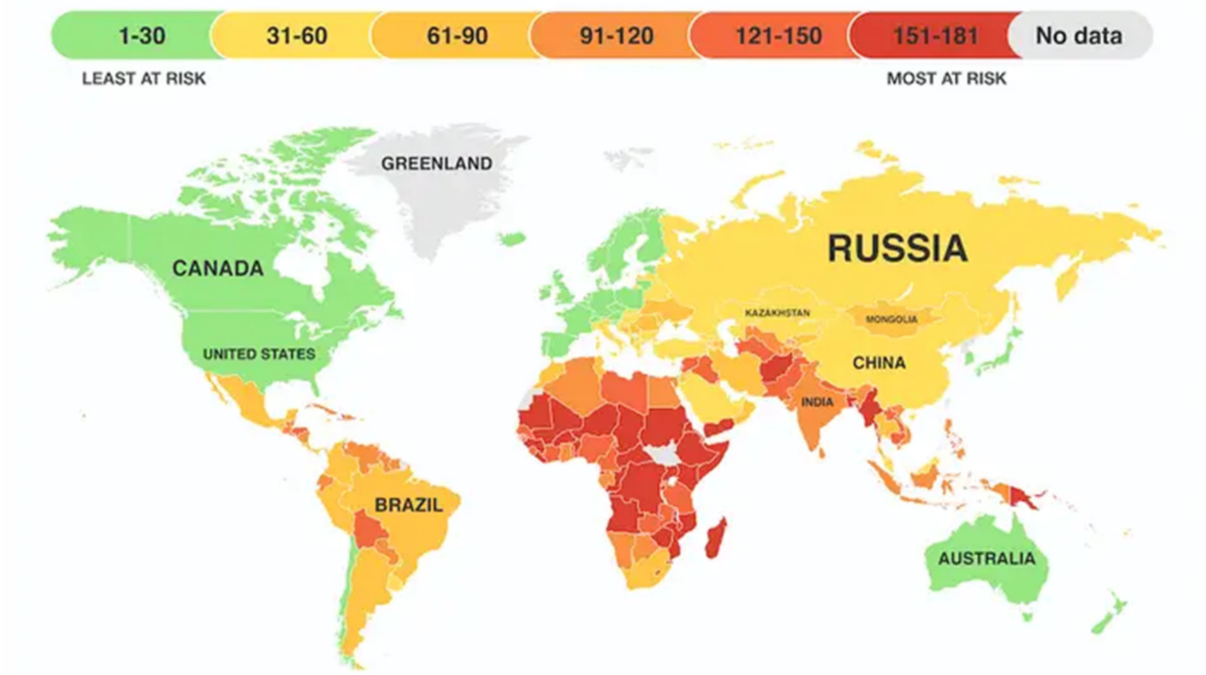


Figure 10: Countries ranked in order of those most at risk from the effects of climate change. Image reproduced from Whiting (2022), based on ND-GAIN data.

Most monoculture crop species plantations consist of a single particular variety representing the same genotype with almost no variation (Liu et al., 2018). With some species, producers must rely on cloning for propagation (Poppens et al., 2013). Consideration of this low level of genetic diversity in prevailing bamboo species will be important for suitable long-term management (Isagi et al., 2016). Accepting this as a consideration, by afforesting with bamboo, more atmospheric CO_2 can be sequestered (Lou et al., 2010). A bamboo plantation of the species *Phyllostachys edulis* (also known as *Moso* bamboo) showed a peak of 5.5 tC/ha sequestration in the fifth year of growth which was more carbon than Chinese Fir in the first five years, but less absorption than Chinese Fir during the subsequent five years (Lou et al., 2010). Bamboo for construction is optimal at an age of three to five years (Lu et al., 1985; Minke, 2012). Understanding the factors which affect carbon sequestration are still under study (Lou et al., 2010; Zachariah et al., 2016). What is clear however, is that in order for the bamboo system to continue to be a net sink, bamboo plantations have to be managed, and the bamboo has to be stored or used long term in other forms (Lou et al., 2010).

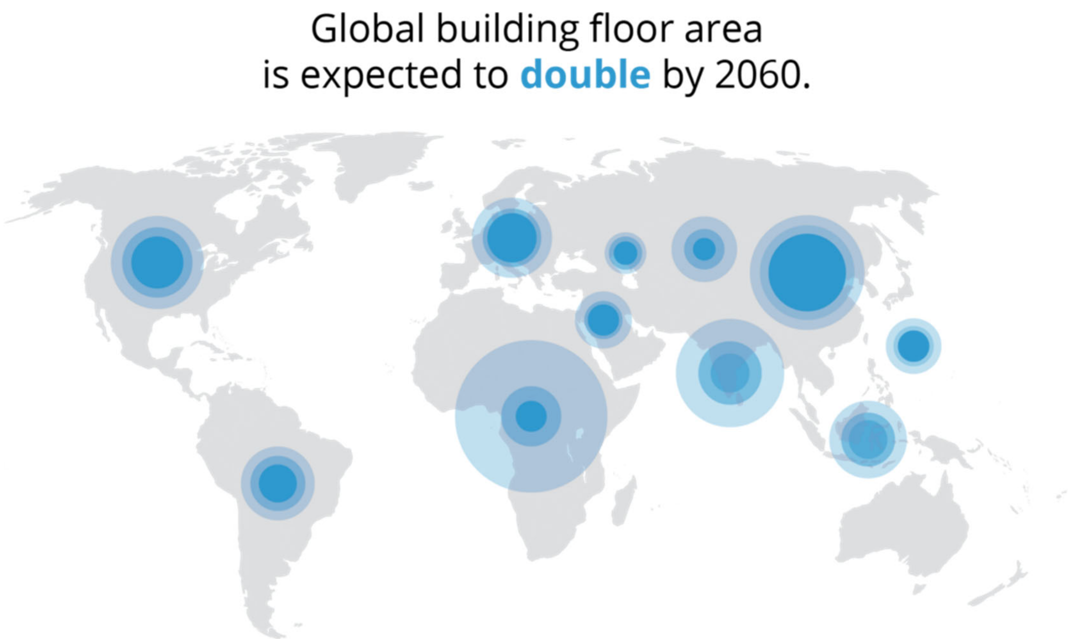


Figure 11: Diagram reproduced from Architecture 2030 (2023) showing that the increase in global building floor area (lighter blue colour surrounding darker blue circle – with darker blue circle representing current building floor area) is expected to double by 2060 globally, but this is not uniform with Africa, India and South East Asia (bamboo growing regions) with the largest expected increases. Original data for this diagram sources from: ABC, Global Status Report (2017).

Almost all of the harvested bamboo can be used in the manufacturing of commercial products, whereas a lower percentage of the timber from felled trees can be used (Lobovikov et al., 2011; Muladi, 1996), with questions over the viability of large-scale timber extraction for construction to reduce GHG emissions, or protect biodiversity loss (Peng et al., 2023; Searchinger et al., 2023). Bamboo plantations may still pose biodiversity risks if not properly considered, and more information on monocarpic events are required (Griscom & Ashton, 2003). However, their crop-like harvesting makes bamboo less susceptible to clear-cutting, bringing ecological, carbon absorption, and economic benefits (van der Lugt, 2017). Often volume or weight is a measure of construction materials used when CO_2 emissions are compared. This is not an appropriate comparison since the performance of a cubic meter or kilogram of concrete, steel, or timber is completely different in strength, stiffness, creep behaviour, fire risk, etc. In the case of timber and bamboo, using the volume of material is arguably more appropriate when comparing. A good method is to compare the GHG emissions of a *functional unit* of a material for a specifical purpose, similar to that in Laleicke et al. (2015).

Using minimally processed raw form bamboo (full-culm bamboo) in a permanent building is one means of locking away carbon with minimal processing. The more durable the design of the bamboo, the longer the bamboo will remain intact storing carbon. The built environment in LMICs could be the incentive to harvest bamboo, creating buildings which store carbon, instead of the contemporary situation where today buildings create about 40% of the world's anthropogenic CO_2 (IEA, 2023), through materials such as steel and cementitious materials.

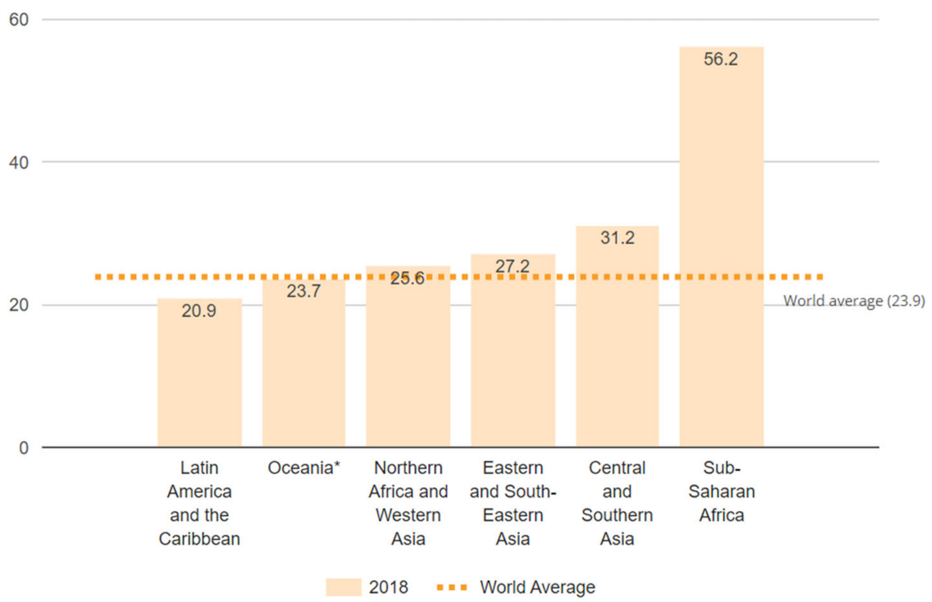


Figure 12: Proportion of the urban population living in "slums" in selected regions, 2018 (percentage). Image reproduced from (UN, 2021c). (* Excludes Australia and New Zealand).

The potential of bamboo drives the primary motivation of this research. Bamboo is a locally available material for construction, available where we need buildings in the future (Figure 11). Even if the so-called Global North has a focus on adaptive reuse as a means of tackling climate change, in the Global South, the current building stock is inadequate in both quantity, and quality (Figure 12), and more new buildings need to be constructed.

1.6 Full-culm bamboo

1.6.1 The benefits of bamboo and use in construction

Bamboos are tall grasses with key differences to trees and timber. The growth rate of bamboo is faster than hardwood as there is no secondary growth with bamboo. A bamboo culm breaks through the ground at the final diameter without any secondary growth (Liese, 1998), whereas trees grow upwards with the diameter of the trunk also increasing in growth. The lifecycle is also different. Trees can live for decades to hundreds of years and more, whereas bamboo culms live for 7-10 years whilst the underground rhizome system ensures continuous growth and regeneration of the plant, producing new culms. Bamboo has a structure composed of culms (Figure 13a) with solid transverse diaphragms or *nodes* separating hollow internodal regions along its height (Figure 13b). The bamboo wall (Figure 13a), can vary in thickness, but will typically have a diameter-to-wall thickness ratio of less than 12 to be used in load bearing structures (ISO 22156, 2021). Some culms of certain bamboo species' wall thickness can sometimes be significantly below this number, making the bamboo culm effectively solid. Countries which have made attempts to embrace bamboo in a codified way in their construction industry, such as Colombia, have many exemplar projects (Figure 14).

Worldwide, roughly 100 so-called *woody* species are suitable for construction, which can maintain regular cropping of around 20%-25% throughout their productive lifecycle (Kaminski, Lawrence, & Trujillo, 2016b). These different harvesting patterns along with faster growth cycles than timber (bamboo of four to five years of age can be cut and used in construction) make this a favourable material source of construction materials (Janssen, 2000; van der Lugt, 2017). Bamboo also provides economic opportunities where there was none before. It can be a freely available resource base, involve both men and women in the economy and provide an economic source (Baral, 2014; Ongugo et al., 2000).

As a construction material, bamboo is strong and versatile, typically with a strength similar to high grade (e.g., D40) hardwood (Kaminski, Lawrence, Trujillo, Feltham, et al., 2016), achieving 100% material utilisation in most cases (Correal, 2016), but can still be cut and split with simple tools (Janssen, 1995). Globally, over 2.5 billion people are linked to a bamboo economy (Bystriakova et al., 2004; INBAR, 1999). Bamboo forests can be biodiverse habitats supporting mammals (Behrens & Barnes, 2016; Fossey & Harcourt, 1977), amphibians (Heying, 2001), reptiles (Pedrono et al., 2001), birds (Areta et al., 2009; Cockle & Areta, 2013), with up to 5% of all bird species in the Amazon relying on bamboo (Pilcher, 2004). However, depending on species, climate, and management, as well as other factors, bamboo forests can be invasive and develop into monocultures (Griscom & Ashton, 2003; Q.-F. Xu et al., 2014). The effect that bamboo species have on biodiversity is discussed in Section 3.6.1 and shown in Figure 56. A whole range of insects and other macrofauna can form a diverse community of aquatic and terrestrial organisms within the internodes (Louton et al., 1996). More than 80% of the bamboo forests in China are located at the source of a river system, playing an important ecological function of soil and water conservation (Banik, 2015; W. Liu et al., 2018). Though bamboo plantations can exacerbate landslides[2] (Yang et al., 2022), with careful consideration of site, species, and other adjacent plants such as deep rooted vetiver grass, some bamboo species can help decrease surface soil erosion and can stabilise river banks (Song et al., 2011; Tardio et al., 2018). The leafy mulch that is common around bamboo clumps protects the topsoil from erosion by the direct impact of rain (Liese, 2009; Song et al., 2011; Zhou et al., 2005). Reducing deforestation and protecting ecosystems can play a critical role in climate change adaptation strategies (TEEB et al., 2009; World Bank, 2009).

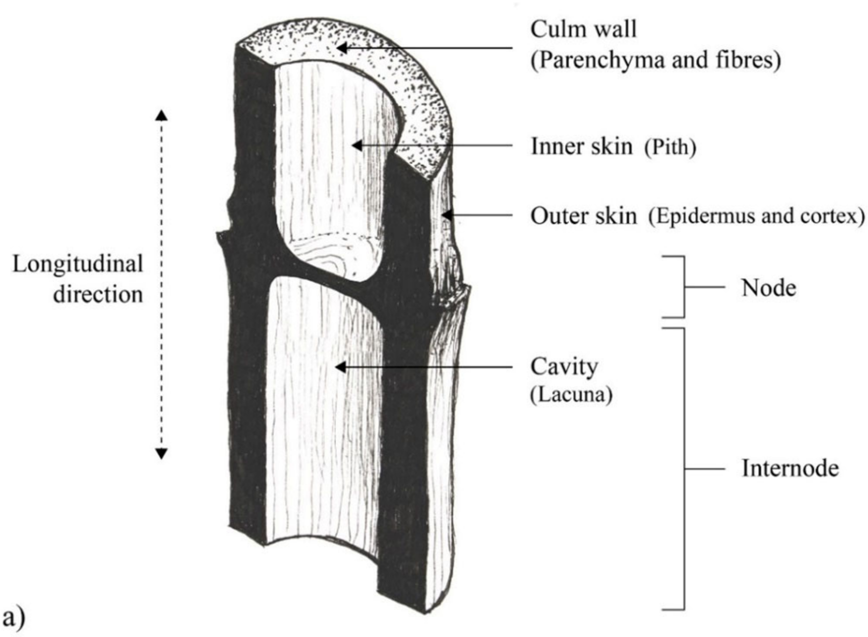
Bamboo is often perceived as *the poor man's timber* (Kaminski, 2013; Vélez et al., 2000). Those who have experience working with bamboo have a long experience of exposure to this attitude and must address these attitudes in their design work. As documented by Appiah-Kubi et al. (2014), there are three typologies of bamboo structures based on the form of bamboo used. Additional titles have been added to the descriptions given by Appiah-Kubi et al. (2014). These are:

- **Full-culm bamboo structures:** Structures built with raw/round bamboo culms.

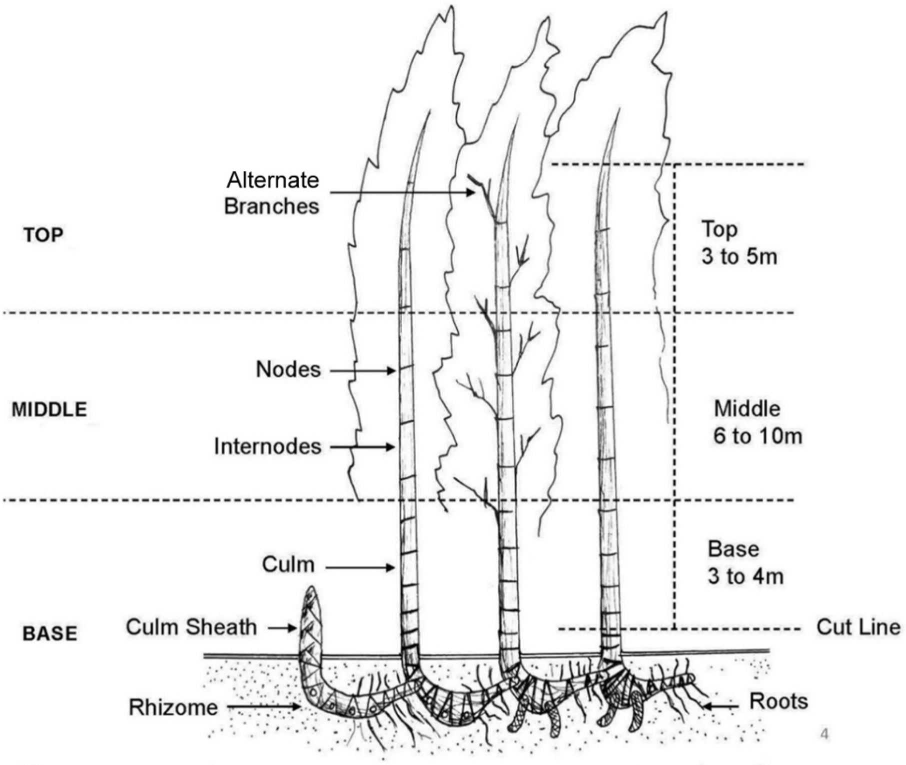
[2] The author cautions that the use of bamboo plantations as a means of mitigating landslides is by no means universal. While the rhizome structure of some species may be appropriate to the purpose, other species may exacerbate the potential for landslides by creating a *weak slip plane* just below the soil surface.

- **Engineered bamboo (EBPs) structures:** Structures built with laminated/processed bamboo.

- **Hybrid bamboo structures:** Structures built with full-culm bamboo, processed/ laminated bamboo in composite with other building materials.



a)



b)

Figure 13: (a) Bamboo culm cross section at the node, and (b) bamboo plant anatomy. Sketch by author.

Figure 14: Examples of full-culm bamboo structures used for infrastructure, education, community and religious uses from Colombia and Indonesia: (a) Aceh Mosque, Tanjung Lombok, Indonesia by Andry Widyowijatnoko, (b) *piaje* [toll gate] outside Manizales, Colombia by Simón Hosie, (c) bridge at the UTP Campus in Pereria, Colombia, by Jörg Stamm, (d) classrooms at the Universidad Gran Colombia, Armenia, Colombia, and (e) corridor between classrooms at the UTP Campus, Pereira, Colombia. Photos by author, Indonesia 2019 and Colombia 2022.

It is important to note that all structures with bamboo will be in some manner hybrid structures whether this is through concrete foundations or metal or plastic roof coverings. Two forms of EBPs (Figure 3d) are laminated bamboo lumber (LBL), made by gluing together strips of bamboo to form rectangular cross sections similar in shape and size to sawn lumber (Sinha et al., 2014), and strand woven bamboo (SWB) or parallel strand bamboo, consisting of crushed fibre bundles saturated in resin and compressed into a dense block (Sharma, Gatóo, Bock, et al., 2015). Such products only utilise 30% in LBL to 80% in SWB of the bamboo culm (van der Lugt, 2008). Though SWB has a higher efficiency of material use, the strands of bamboo leave more space for resin to bind the strips together. SWB can be anywhere between 7%-12% resin content by volume, and as high as 16% (Chen et al., 2019; Lugt et al., 2015). Resin content in laminated bamboo is typically less than 3% of its total mass (Chen et al., 2019; Lugt et al., 2015). Phenol formaldehyde resins, isocyanate resins, and polyurethane resins can be used in the manufacture of engineered bamboo (Chen et al., 2019; Sinha et al., 2014; Xiao, 2016). Phenol formaldehyde is known to have certain toxicity (Xiao, 2016), and is not biodegradable at the end of life. In both cases engineered bamboo selected for use (SWB or LBL) has varying impacts on the material efficiency, the volume of resin used and therefore toxicity, and the energy involved in the manufacture. Finding non-toxic resins was identified as a research priority in 2021[3] (Harries, Mofidi, et al., 2022).

This research is looking at the use of the round, most sustainable form of bamboo when used locally, full-culm bamboo (Harries et al., 2012). There are a few terms for bamboo which appear in literature. Terms such as *non-conventional* (Harries et al., 2020), or *alternative* (Ghavami, 2016; Liese, 2020; Patil & Mutkekar, 2014). In this research the term *non-standardised* (MacDonald et al., 2019), or *non-standard*, is used.

1.6.2 The challenges of full-culm bamboo in construction

There are challenges to incorporating bamboo into contemporary design and construction practices. These challenges are in part due to the natural variability of bamboo across the approximately 1600 species of bamboo (Canavan et al., 2017; Lobovikov et al., 2007; Vorontsova; et al., 2016), the variability between individual plants of the same species due to

[3] This paper was co-authored by the author of this PhD research, peer reviewed, and is included as Appendix F.

growth conditions, and the variability between individual culms of the same plant due to generational growth. Only about 100 species are of dimensions suitable for construction. Within individual culms there is then a non-regular distribution of node locations, a tapered diameter, and a reduced width of the culm wall over the length of the culm (Figure 13b). Within the same species, mechanical properties can differ since bamboo grown at different altitudes, in drier areas and on slopes, may have a differing fibre density and strength properties (Liese & Tang, 2015b; Lu et al., 1985). As well as trying to understand and standardise the calculation of physical and mechanical eccentricities of bamboo, there are other non-technical reasons why full-culm bamboo is not widely used in construction. These are linked to: the history of—often inappropriate—bamboo use, societal attitudes, and the properties of the material. These can be grouped into four areas:

1. Poor natural durability (Janssen, 2000; Kaminski, Lawrence, Trujillo, & King, 2016)

2. Lack of standardisation (Harries et al., 2012; Paraskeva et al., 2019; Trujillo, 2020)

3. Lack or complexity, of connection details (Paraskeva et al., 2019)

4. Negative societal perceptions (INBAR, 2003; Kaminski, 2013)

One response to the natural variability of full-culm bamboo has been to standardise the material through the manufacture of Engineered Bamboo Products (EBPs) (Sharma, Gatoo, et al., 2015), which, since 1989, have grown in application and prevalence (Mahdavi et al., 2011; Sharma, Gatoo, et al., 2015; Sharma, Gatóo, Bock, et al., 2015; Sharma, Gatóo, & Ramage, 2015). Full-culm bamboo on the other hand can be worked with simple tools (Janssen, 1995), and is the most sustainable form of bamboo when used locally (Harries et al., 2012).

Instead of adapting bamboo to fit standardised design practices, this research is based on the objective to expand design practices to design for the requirements of full-culm bamboo, the natural form of bamboo. Through this research it has become apparent that EBPs are more likely to play a significant role, especially in urban settings. This research is developing a design approach for full-culm bamboo since addressing the greater challenges of full-culm bamboo will also be relevant to EBPs, whereas the reverse is not the case.

1.6.3 The opportunities of full-culm bamboo in construction

The suite of three international standards—ISO 22156 (2021); ISO 22157 (2019); and ISO 19624 (2018)—demonstrates full-culm bamboo's contemporary viability as a normative construction material. While there are obstacles to the broader adoption of full-culm bamboo in construction, many of these challenges are not technical but stem from unfounded societal attitudes. Chapter 2 of this thesis explores and attempts to decode these attitudes to then strategise how design professionals can challenge them.

Unfounded negative societal attitudes to bamboo are a barrier to wider use, as are unsubstantiated positive attributes given to bamboo which often sets bamboo up to fail. Bamboo is often described as absorbing more CO_2 than timber, being seismic resilient, or being stronger than steel (Fairs, 2015; Newsweek, 2010). When these claims are accepted uncritically by design professionals, bamboo may be used in an inappropriate manner. When these claims are proven to be false, either by failing structural performance or degradation to the bamboo, then this can also affect the impression of bamboo in society. Therefore, as much as countering negative impressions of bamboo, it is important to address unfounded positive attitudes and myths of bamboo characteristics. As the architect Hermann Kaufmann terms with the parallel challenge with timber construction, the challenge is, "to refute the prejudices…with built projects, facts, and a scientific review…[and] put the 'fake news' into perspective" Hofmeister et al. (2021, p. 53). With bamboo for example, a statement which is widely purported is that bamboo has the tensile strength of steel. This strength comparison is presented in an influential online architectural design magazine (Fairs, 2015). Liu et al. (2022) claims bamboo has twice the strength of concrete and slightly stronger than steel (p. 3) and Liu et al. (2018) alleges bamboo's strength is "higher than that of steel" reasoning that this makes bamboo earthquake-resistant (p. 138). The idea that bamboo is inherently seismic resilient and stronger than steel, has also featured prominently (Newsweek, 2010). A 2012 article in the Financial Times claimed that bamboo has the tensile strength of mild steel (Williams, 2012), and numerous reports and publications have propagated this information (Appiah-Kubi et al., 2014; Daud et al., 2018; DeBoer & Groth, 2010). These isolated notions of the strength of bamboo have also allowed some to postulate that bamboo could be a good reinforcement in concrete (Bakker, 2020; Mondal et al., 2020; Walker, 2014). However, as rebutted by Archila et al. (2018) and Harries et al. (2022), favourable comparison with steel performance for strength and ductility is not valid. While the intermodal tensile strength may indeed approach that of mild steel, beyond specialised laboratory tension tests, it is not remotely possible to develop this strength in situ. As well as bamboo being anisotropic, in a dry state, bamboo characteristic strengths are, at best, comparable to those of high-grade hardwood (Kaminski et al., 2016). *The Pittsburgh Declaration* was a call to action in 2016 at the conclusion of a symposia at the University of Pittsburgh, USA. This was a major step forward to develop the appropriate use of bamboo in construction. The title was *Bamboo as a Construction Material for the 21st Century*. There were a series of eight recommendations (INBAR & University of Pittsburgh, 2017), one of which included the development of what became ISO 22156 (2021).

Today, it has never been more critical to support design professionals to design in a manner which ensures durability, buildability, and can promote bamboo in a way which will appropriately develop its use in the built environment. It is apparent that there will always be a place for concrete, steel, and other manufactured materials. However, particularly in one- to two-storey buildings in bamboo-growing regions, bamboo is a local resource which can be incorporated to reduce the overuse of manufactured materials. As noted by Zea Escamilla (2015), these challenges are "not going to be overcome with a single solution but with a mixture of construction materials and technologies" (p. 154). A design approach to support design professionals to increase the application of minimally processed bio-based materials such as bamboo, has never been more vital if the SDG targets are to be achieved by 2030.

1.7 LMIC context: Haitian construction and symposium

1.7.1 Context of Haiti

Finally in this introduction it is important to introduce a LMIC context which can be used to assess the relevance of a design approach to bamboo. Bamboo is a significant latent resource to the construction industries of tropical LMICs with the Republic of Haiti as the context for this research. Haiti occupies the western portion of the Caribbean Island of Hispaniola with the Dominican Republic to the east. In 1804, Haiti became the first Republic born out of a slave rebellion against European colonial rule, able to oversee grand infrastructure projects (French, 1991), and with a climate enabling exports of coffee and sugar. Today, Haiti has suffered both natural and man-made disasters including earthquakes, hurricanes, deforestation, inept and corrupt governments (Bhatia, 2023; Borger, 2022; Foxx, 2012), and is ranked as the third most susceptible to natural disasters from climatic events (Eckstein et al., 2021), as highlighted in Figure 15.

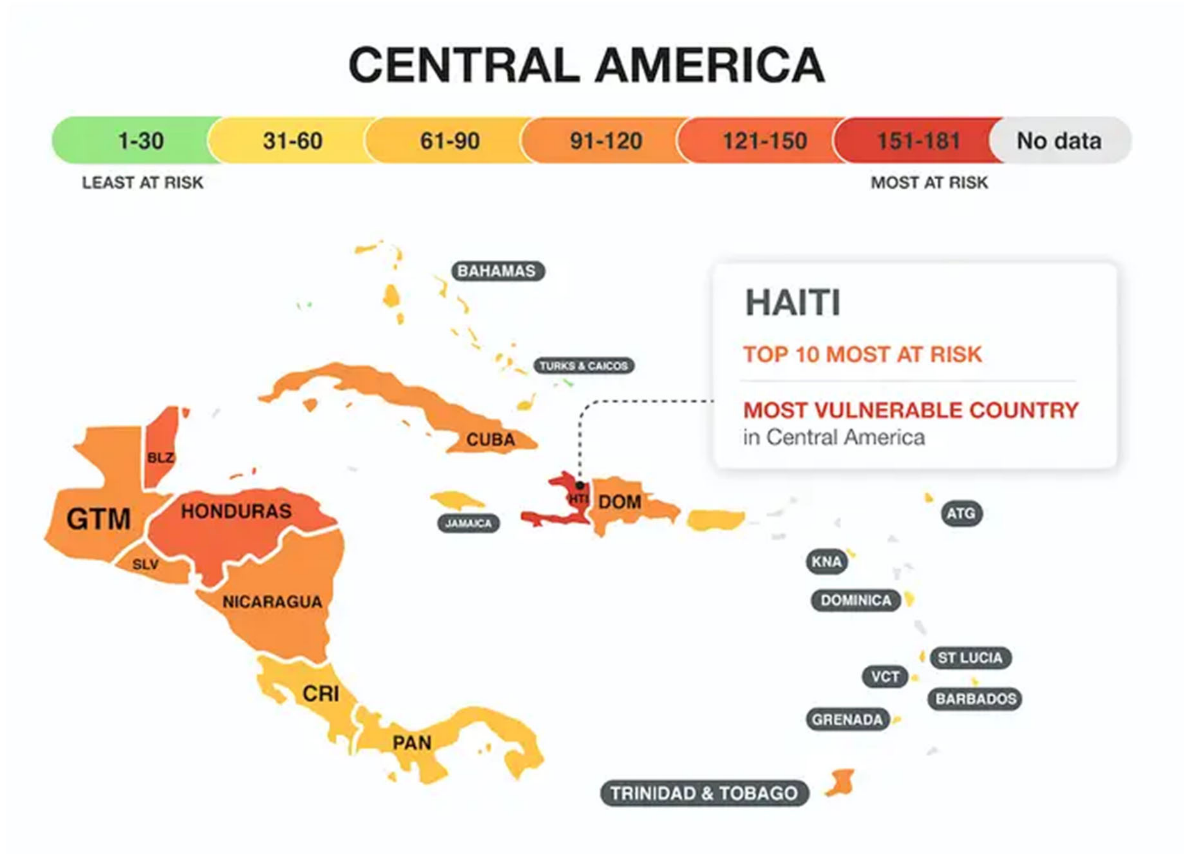


Figure 15: Haiti is the most vulnerable country to the effects of climate change in Central America, and within the top 10 countries most at risk in the world. Image reproduced from Whiting (2022), based on ND-GAIN data.

Haiti has a deforestation problem (Dolisca et al., 2007; Dubois, 2016; Foxx, 2012; Hedges et al., 2018; Lewis & Coffey, 1985; Nature, 2018; Pellek, 1988). Even though it has been suggested that Haiti is almost totally devoid of forests, with figures such as 0.32% in 2016 (Hedges et al., 2018), Pauleus and Aide (2020) analysed land use in Haiti and estimated that forest cover declined from 26% in 2000 to 21% in 2015. Most of Haiti's watersheds are entirely deforested, and much of the soil is highly degraded (Figure 16) (Cohen, 2013).

The loss of forest cover results in the loss of the topsoil through erosion and increases the probability of flooding (Pauleus & Aide, 2020). After the 2010 earthquake, which displaced millions of people from the capital to rural areas, both illegal logging and forest clearing for agriculture occurred (Pauleus & Aide, 2020). A lack of timber due to deforestation is disheartening given Haiti was once a regional pioneer in timber frame construction (Figure 20c), most notably in the Gingerbread architecture of the 19^{th} Century (Columbia University GSAPP, 2016).

Figure 16: The deforested steep hillsides to the southeast of Kenscoff, Haiti, south of Port au Prince. Photo by author, 2016.

Haitians spend more than half their incomes on food with more than half of all food imported (Crane et al., 2010). Soil erosion in Haiti is a significant challenge, and Haiti's ecology and agriculture is in need of drastic support due to soil infertility and the soils of Haiti being intrinsically fragile (Bargout & Raizada, 2013; Jolly et al., 2007). Bamboo presents an opportunity for Haiti. Depending on species and how the bamboo is planted, the strong rhizome-root system has the potential to reduce soil erosion (Shinohara et al., 2019). The name Haiti—or *Ayiti*—comes from the indigenous pre-Columbus inhabitants, the *Taino*, and means "Land of mountains" (Dubois, 2012, p. 18). This name suggests an opportunity for bamboo as bamboo grown on slopes may have higher fibre density and increased strength properties (Liese & Tang, 2015b). More than 60% of the land in Haiti has a slope gradient exceeding 20% (UNCCD, 2006).

Today, the lack of timber means that lightweight bio-based materials are absent from the material palette of AEC professionals in favour of concrete masonry units (CMUs). Kijewski-Correa et al. (2012) document that the lack of timber for formwork means CMU walls can be erected first adjacent to anchored cages of exposed rebar (Figure 17). The blockwork wall becomes the formwork for the columns (Kijewski-Correa et al., 2012).

Figure 17: Images of construction taking place in Port au Prince, Haiti: (a-b) Construction with CMUs in Baillergeau, Port au Prince, Haiti, and (c) reinforced concrete columns under construction, Delmas, Port au Prince. Photo taken in 2012 and 2016 by the author.

On 12th January 2010, an earthquake hit Port-au-Prince, Haiti's capital, causing a catastrophic death toll (Kolbe et al., 2010; Schuller, 2019). A lack of lightweight building materials, and lack of enforcement of standards and codes played a significant role in this disproportionately high death toll (Haas, 2010). As a comparison, between September 2010 and February 2011, the New Zealand region of Canterbury suffered multiple earthquakes and aftershocks of similar magnitudes and proximities to an urban centre. The most deadly of these resulted in 185 fatalities (Bannister & Gledhill, 2012). The February 2011 Christchurch earthquake also had a higher peak ground acceleration (PGA) of around 2g compared to a PGA of around 0.7g in the January 2010 Port au Prince earthquake (Kaiser et al., 2012; USGS, 2020b). Following the 2010 earthquake in Haiti, early assessments of timber-framed Gingerbread houses (Figure 20e) found that traditional construction techniques proved seismically resistant. This prevented many Gingerbread structures from collapsing (Columbia University GSAPP, 2016), while over half of the contemporary built stock of predominantly unreinforced masonry in Port au Prince collapsed or was damaged enough to require repairs (Desroches et al., 2011). Nearly 80% of all schools collapsed in the Port-au-Prince area (Bilham, 2010) and near the epicentre of the earthquake, in the city of Léogâne, it is estimated that 80%-90% of the buildings were critically damaged or destroyed (Desroches et al., 2011). The need for safe and lightweight buildings in Haiti is critical and this is especially true for urban areas which are home to 57% of Haiti's population (UN-Habitat, 2016b). Eroded or poorly compacted soil layers, because of deforestation, can amplify ground motion and make soil more prone to liquefaction (CNBH, 2012, pp. 14-15). It is likely the topsoil from the hillsides around Port au Prince, which has poured down and added more area to the city, amplified the effects of the earthquake. According to the Inter-American Development Bank, the 2010 Port-au-Prince earthquake was the most destructive event any country has experienced in modern times when measured in terms of the people killed as a percentage of the country's population (Bilham, 2010; Cavallo et al., 2010).

Poor quality construction due to expensive building materials in Haiti will only get worse since materials have been increasing at a cost of 10% per annum since 1990 (Huynh et al., 2013). Additionally, most of these materials need to be imported, and the high cost of mineral rich river sand leads most to use calcite sand in the reinforced concrete columns and unreinforced masonry walls, making it unsuitable for use in cement (Huynh et al., 2013; Kijewski-Correa et al., 2012). Certified quality materials are even more costly and enforcement of building codes, such as Haiti's national building code, CNBH (2012), are difficult when most low-income homes are built informally and are unlikely to seek building permission (Huynh et al., 2013). Due to a lack of resources, as shown in Figure 17 and Figure 18, most housing in urban areas in Haiti uses a combination of reinforced concrete columns and unreinforced masonry walls made of CMU (Kijewski-Correa et al., 2012).

Figure 18: Chalky limestone aggregates used in construction in Port au Prince, Haiti, in 2012, two years after the devastating earthquake of 2010. Photograph by author, 2012.

Haiti needs safe buildings, but, for lasting change, these need to be designed in Haiti by local design and construction professionals, and not be “air drop solutions” (Sinclair, 2010). As Merkel and Whitaker (2010) put it, to move away from concrete towards sustainable, lightweight materials, “Haiti would need a new generation of builders adept at pounding nails rather than mixing cement” (p. 133). Haiti grows species of bamboo such as *Guadua angustifolia*, a species widely used in bamboo structures in Colombia. This species has been used to construct in Haiti (Figure 19). The availability of such species makes Haiti an opportune location to apply this lightweight material for construction, restore ecologies and support economic development.

Figure 19: Bamboo structure constructed with the bamboo species *G. angustifolia*. Croix-des-Bouquets, Haiti. Photo by author, 2015.

The context of Haiti is one scenario in immediate need of this global shift away from manufactured materials—such as concrete and steel—where unique vulnerabilities exacerbate global trends into acute local catastrophes. This is where the challenge of bamboo as a construction material may be one of the most challenging (as highlighted in Figure 15) but can be the most impactful. By considering a design approach globally but also addressing the parameters set by Haiti's construction industry, this research aims to develop a practicable design approach whilst filling a knowledge gap in Haiti's bamboo resource. With enough local demand for lightweight natural renewable materials from clients, inevitably those with barren unproductive land in Haiti could see an economic benefit from planting trees and bamboos. If design professionals and other AEC professionals can be successful in promoting non-standard bio-based materials, and demonstrating that these materials are affordable, durable, and provide a functional space, over time, these built projects can influence the informal sector too.

1.7.2 AA Haiti Visiting School workshops 2014-2017 (AAVS Haiti)

Between 2014 and 2017, the author directed a series of five architectural design workshops in Haiti, which provide valuable insights on the relevance of bamboo for the built environment, economy, and ecology of a tropical LMIC. The experience and the questions raised from this praxis in Haiti has been the basis and motivation for this PhD research. These workshops took place to develop skills and awareness of bamboo as a lightweight, sustainable construction material through teaching design and construction for full-culm bamboo. The five workshops were overseen by the UK based Architectural Association School of Architecture (AA) and were known as the *AA Haiti Visiting School* (AAVS Haiti). The AAVS Haiti workshops were coordinated by local involvement from Quisqueya University architecture department in Port au Prince, and the Wynne Farm Ecological Reserve in Kenscoff, Haiti. They were all roughly two weeks in duration. There were four wider objectives established for the workshops: (1) to equip local students with computational design tools to increase their capacity to design for climatic and seismic conditions, (2) to develop a portfolio of student work showcasing the aesthetic potential of bamboo buildings, (3) to engage students, design professionals and builders in a construction course using domestically grown bamboo, demonstrating both construction techniques and existing infrastructure so skills can be disseminated, and (4) to create a platform linking bamboo growers, landowners, and the construction industry together in Haiti, while showcasing skills of those in Haiti, internationally.

Over the five workshops there were 37 Haitian participants, some of whom attended more than one workshop. The co-operative learning approach to active learning noted in Keyser (2000) was employed as the means of delivering the curriculum. Tutors acted as design coaches to drop into student groups over the course to provoke and stimulate the emerging design and offer technical support. Participants would work in groups of three and would develop one design project over the course of each workshop. Groups were configured to ensure there would always be a mix of Haitian and overseas participants. Upon receiving the brief, participants were to follow an iterative problem-solving process based on one documented by Mitchell and Bevan (1992). Participants were encouraged to identify the problem in the brief from multiple stakeholder perspectives and identify the economic, social and material constraints in which they can design (Mitchell & Bevan, 1992), with the prescription of bamboo material as the exception to this. In proposing bamboo, participants had to argue how this project would be a catalyst to develop a future bamboo infrastructure. Secondly, a method of design, build, test and assess was followed to inform design decisions in an iterative process (Mitchell & Bevan, 1992).

Figure 20: (a-c) Examples of student work produced during the 2015 and 2016 workshops, (d) a Fishmouth joint with full-culm bamboo constructed during the October 2016 workshop, (e) Maison Dufort Gingerbread House in Port au Prince restored by the *Fondasyon Konesans Ak Libète (Foundation for Knowledge and Liberty)* (FOKAL) visited during the summer 2016 workshop, (f) construction exercises during the 2017 workshop, and (g) bamboo harvesting at FONDDIM in Marmelade, Haiti, during the summer 2016 workshop. Images reproduced from the AA, photos taken in 2016 and 2017 by the author.

The design process taught on the workshops began with physical model making with bamboo sticks to conceptualise initial design responses to the brief. This was supported with parallel site visits, and lectures on bamboo growth, selection, harvesting, processing, and joinery. Following this, 3D modelling software was taught so participants could build their physical models digitally and then thinking algorithmically, identifying input parameters, to efficiently produce new versions using AD software, which could respond to changing parameters such as a changing site or alternative bamboo species selection.

From 2016 onwards participants undertook bamboo harvesting and one-to-one scale bamboo construction (Figure 20 d, f, g) which allowed participants to learn more about the buildability of their designs and then use this construction experience to develop the practicality of their design. Throughout this process, local and international architects and ecologists would give lectures to the participants presenting a vast palette of issues and ideas from which they could cultivate their design work. This provided the input of outside ideas from other bamboo growing regions of the world and provided networking opportunities for participants. At the end of the course the designs (Figure 20 a-c), were presented to stakeholders, tutors, and peers in the course.

The last of these workshops concluded in 2017 and in 2020 a self-administered online survey was shared with the participants. The results of this survey were documented in a peer reviewed conference paper co-authored with Nancy Leconte and Franck Vendryes and presented as Naylor et al. (2020). This is included in this thesis as Appendix D. The response rate was only 41%, however, it did provide some insights and clear trends. From this evaluation survey the strengths of the course were learning about bamboo, the different design methodology the participants learnt, and the networking opportunities. The last two were also shown to be the most useful to participants' professional work following the workshops. There was unanimous agreement from respondents that bamboo could play an important role in Haitian construction. An apparent weakness from the responses appears to be the subsequent use of the software taught as part of the curriculum. The 3D modelling software which was taught had been used by two-thirds of respondents, but subsequent use of AD software (specifically *Grasshopper*) showed this not to be relevant with 85% stating no subsequent use. Reasons for this could be cost, complexity of the software, and relevance to everyday software requirements of a design and engineering professional in the Haitian construction industry. Key messages from this evaluation were used to plan a symposium which would investigate these issues in more detail and provide a context in which this PhD research should be applicable.

1.7.3 Symposium: Methodology

On the 27th of May 2022, a symposium was held as a joint event by Newcastle University, UK, the University of Pittsburgh, USA and the Wynne Farm Ecological Reserve, Haiti. The symposium took place in a hybrid format at the Swanson School of Engineering, Benedum Hall, University of Pittsburgh, Pittsburgh, USA. The author led the organisation of this symposium, aimed to bring those with knowledge and an interest in bamboo together to provide a platform for voices from the Haitian built environment to discuss the real-world challenges and identify the opportunities for alternative materials to concrete and steel. One of three sessions which looked at the ways bamboo can be applied to the built environment and construction industry context in Haiti is documented for this research as this pertains to the context of a LMIC built environment in which a design approach will be applicable. The other two sessions were an interview with Jane Wynne of the Wynne Farm Ecological Reserve in Haiti, and a session to discuss a series of questions pertaining specifically to the AAVS Haiti. The participants in the symposium are outlined in Table 2. Consent was sought from participants at the symposium to transcribe the event and transcripts were shared with attendees for confirmation.

There were 86 registrations for the symposium session, with 28 attendees attending the symposium session documented in this research. Most registrees for the symposium were from the Americas. Within this region the main source of attendees were from Haiti, the USA, Canada, Mexico, and Colombia. This session lasted roughly one hour with 30 minutes following the session for questions from audience members. The choice of this symposium methodology was informed by Kewei et al. (2022) and Harries, Mofidi, et al. (2022) both of which the author was involved with the organisation, or as a speaker. In both cases the discussion topics and information are concisely presented. This is the aim here, to set the context of the construction industry in Haiti. Appendix E contains more information on this session.

Table 2: Profile of symposium participants.

Participant	**Profile**
Jupille Facile	A former alumnus of the AAVS Haiti, structural engineer and founder of *Bambou Facile*, a bamboo contractor and advocacy organisation.

Isabelle Jolicoeur	Haitian architect, educator, and founder of *Aetypik*, a media platform that worked closely with the AAVS Haiti throughout the later workshops.
Nancy Leconte	Haitian architect and course tutor on three AAVS Haiti workshops in 2016 and 2017.
Rose Di Sarno	Los Angeles based architect and course tutor for three AAVS Haiti workshops from the first in 2014 through to 2016.
Elrica Metayer	Architect and educator in Haiti who worked closely with the AAVS Haiti 2017 workshop.

The author of this research moderated the sessions by asking pre-determined questions along with Elrica Metayer who moderated audience questions. Audience questions and answers are not recorded in this research as consent was sought only from formal participants in the symposium (Table 2). Questions were written prior to the event and shared with the participants one week prior to the session so that preparations could be made by participants to formulate responses. However, in each of the hour-long sessions only some questions were asked and follow up questions from participants were permitted if relevant to the theme. Pre-determined questions, and questions which followed up on discussions are listed in Table 3. The wording of some questions was influenced by preceding answers. A summary of the results are spread over three sections (Sections 1.7.4 - 1.7.6). The term *architect* is also used throughout the symposium results (Sections 1.7.4 - 1.7.6) rather than *design professional* since in the context of a discussion about Haitian construction, these terms are understood by the participants with the term defined in Haiti (CNBH, 2012). These results provide the basis to evaluate the applicability of a design approach developed in this research.

Table 3: Questions asked at the *Bamboo in Haitian Construction Symposium 2022*.

Chapter Section	**Theme**	**Question**
1.7.4	The role of a design professional and the context of Haitian construction	What proportion of building projects in Haiti have the involvement of an architect or seek regulatory approval?
		How do you think your [an architects'] designs can impact the informal construction sector, and can impact the buildings

		which do not have the involvement of an architect, engineer, or any regulatory authority?
		What forums exist in Haiti for architects and engineers to share good practice and collaborate?
1.7.5	Design processes, tools, and software use in the Haitian construction sector	What is the design process of a project in Haiti and what role does software play, if any, within that design process?
		Do you find that BIM is the standard across all offices or, is there a barrier to access because those platforms tend to be expensive to operate, and are there open-source platforms that create a little more access for people and allow more people to be involved in design and architecture?
1.7.6	Material culture and cost in Haitian construction	As we see materials such as sand for concrete becoming scarce and their costs are increasing, are you seeing this trend and a reduction in the quality of construction materials in Haiti?
		What are the challenges when suggesting a material other than concrete or steel to a client on a project?
		Would clients and end users be more comfortable with hybrid systems, where bamboo is used for certain elements of construction?
		How can the best practice and exemplar projects with bamboo actually proliferate into the informal [self-build] sector?

1.7.4 Symposium: Results - The role of a design professional and the context of Haitian construction

It is hard to put an exact percentage on the number of buildings in Haiti that have the involvement of an architect or seek regulatory approval, but it is common knowledge that the vast majority of construction in Haiti does not seek approval from a regulatory body. A significant proportion of construction in Haiti is self-built. An indication of this is the ratio of architects per capita, which is shown as one per 40,000. Few people come and seek an approval or have the means. The approvals process in Haiti was noted to be geared towards establishing taxable assets, without adequate capacity to enforce code compliance or structural verification. Impacting the public discourse on architecture and design can impact the informal construction sector in Haiti. In Haiti the architect is often referred to as an engineer, *in many cases the word architect does not appear in conversation*. However, when these situations occur, it is an opportunity to educate and draw attention to the role of an architect to foster a conversation. An example of this is Aetypik, an online platform created in 2015 to showcase Haitian creativity and a virtual library of projects that are being made in Haiti, to make the architecture and urban design scene more accessible, and visible. The *CNIAH* which is the *Collège National des Ingénieurs et Architectes Haïtiens*, the Haitian licencing body for architects and engineers, is making a great deal of effort to be more present in the public realm and share training for AEC professionals. The internet has been an important tool for this as now one can use the website to see who is a registered architect or engineer. There is also *Kout Kreyon,* which is an initiative to connect and network young architecture, engineering and construction (AEC) professionals in Haiti.

1.7.5 Symposium: Results – Design processes, tools, and software use in the Haitian construction sector

In Haiti it is more of an effort to accompany the client throughout all the steps, reinforce principles, and maintain the needs of the end user, if they are not the same as the client. The role of the architect in Haiti is dependent on good communication (also discussed as important to impact the informal construction sector and client attitudes, as stated in 1.7.4), and the software facilitates this with clients to convey design intent and reassure the client of the progress. The design process followed by practicing architects in Haiti varies. However heavy use of *Autodesk AutoCAD* (Autodesk, 2022a) takes place and now in architecture practice building information modelling (BIM) software (platforms such as *Autodesk Revit,* Autodesk, 2022b) are important to work in 2D and 3D, and gather data. This allows the office to be more time efficient, more productive, and it assists in the management of multiple projects at once. The 3D aspect of the software is an important communication tool. The expense is an issue, but the purchase of licences is an investment when setting up a practice as there is an immediate and clear positive impact on projects and time efficiencies. Not every practice in Haiti follows such an arrangement, but it is clear that software use is much more mainstream than it has been. Architecture practices and consultants in Haiti use different softwares so there is an issue of compatibility. One reason for this is that AEC professionals often study in the Dominican Republic or the United States, each teaching a different palette of software. This is a challenge for both practice and education in Haiti as it is difficult to train for the “correct” software used in the profession and this range is more expensive to purchase. More difficult is that often, Haiti does not appear on the list of countries that receive software support, and even credit cards from Haiti are often not accepted. So, there are obstacles in the way of mainstreaming softwares in the AEC profession in Haiti. Since software is becoming more and more necessary in Haitian practice, the cost of licences is a big issue for the future capacity of design professionals in Haiti. In addition to this are the basic infrastructural challenges that confront software use such as inconsistent electricity provision or internet access.

1.7.6 Symposium: Results – Material culture and cost in Haitian construction

There is often little to no consideration of the theme of sustainability from clients on projects. Living in Haiti is described as “urgency living”, a constant need to address urgent problems making it difficult to think years into the future. However, in the construction world in Haiti, the two things clients ask are for fast and cheap, let alone environmental requests. In the construction sector in Haiti cost-cutting is observed to impact quality. An example of a common occurrence if not checked by professionals onsite is steel rebar quality. This then reduces the performance of a reinforced concrete column. Future increases in construction material costs will of course reduce quality. Importation of materials is a major issue due to inflation and currency fluctuations. These impact material quality. This is a serious issue in Haiti since so much of Haiti’s building materials are imported. Finding opportunities to use more locally sourced materials can alleviate this. Additionally, consumer protection is almost non-existent given the distance from producer and user with imported materials. An example of this is in the imported steel, for which the dimensions of the steel rebar are either wrongly advertised, or a lack of education in required specifications for use, results in the cheapest being ordered. Even those who do have the means to order the correct specification will sometimes find the wrong steel is provided or is of inadequate quality. This is an increasing trend, so locally sourced bamboo becomes an opportunity to both decouple material costs from currency fluctuations and the opportunity to inspect the material before purchase and delivery to site. In Haiti these purchasing roles are described as “blurred” and informal. In many cases whoever the builder is—or in the case of self-build projects, the end user—may be purchasing the materials without any construction or material knowledge. In some cases, the client may have already purchased materials at the outset of the project. There is suspicion of the contractor or architect purchasing materials, with concern the contractor will inflate prices to take a cut. When the client buys their own construction materials, they do not know the necessary specification or quality. In the case of concrete masonry unit (CMU) blocks, sometimes these blocks just deteriorate at the point of sale. This highlights the limited role of the architect or engineer to ensure material quality since ultimately the purchasing is going to be done by someone else. Good design translating to a good quality building requires a good quality of material to be used. The case for hiring an architect (design professional) or even an engineer is not often clear for a client what the cost is for. The builder or *boss*[4] may be at the site all day, but the engineer will just come by once or twice a week. Physical absence of the architect or engineer creates a mistrust of professionals which architects, or construction industry professionals in Haiti have to deal with. Therefore, before the project even kicks off, the architect has to justify and communicate their role.

The main challenge to bamboo or timber as an alternative to steel and concrete materials is the security concern with timber or bamboo and designs have changed because insurance companies will not insure. Currently a prevalent issue is that Haiti (but more precisely Port-au-Prince) is experiencing extensive social and economic instability. So, a client may say, "Ok, this is nice you've offered something different [bamboo], but all in all, if someone fires a bullet at my house, am I going to die?"

Concrete is now prevalent in the consciousness of Haitian society as a modern, highly efficient and fast material to build with. People like concrete and it is perceived as easy to work with. This abundance of professionals willing to work with concrete mixed with a lack of alternatives makes masonry construction the relatively low-cost go-to construction method. There is the relationship to social status and a link to the use of natural materials to poverty. A way to change this would be if bamboo was to be used in major buildings where the bamboo can demonstrate structural adequacy, not only aesthetics. Maintenance and additional costs will be a consideration with timber and bamboo, as would material availability which could delay projects and make a project programme more vulnerable to security issues, as well as a lack of knowledge in the construction sector. When aware of the seismic risk, roughly 80% of 30 families who one of the symposium participants worked with, responded that they preferred bamboo as a material but commented that they did not have the skills to build with bamboo and could not conceive a design of a building with bamboo that they would want to

[4] The term *boss* refers to a senior builder or site supervisor in Haitian construction.

live in. Therefore, in the end the preference was concrete. So, this lack of expertise and the psychological challenge to envisage a liveable, beautiful space with bamboo presents a challenge. Establishing the correct design and construction capacity for bamboo and presenting these designs to the public is critical for bamboo to be accepted by clients and end users alike. There would be no push back from clients if bamboo were to be suggested for elements like doors and windows, or shades, but for more structural elements, clients are more afraid of it. A market for bamboo can incentivise those with rural land to make money from planting bamboo. Since many of those who have migrated to the city from rural areas still own land in rural areas, this is an opportunity potentially available to even some of the poorest citizens in urban Haiti. As bamboo is introduced slowly into the public eye through projects, people will be interested in the economic opportunity that creates. Cost is a major consideration, but it is more true to use the term *value*. Clients in Haiti would invest in what is right but if a client does not understand the bamboo, or does not believe in it, a lower cost would not matter, and therefore the bamboo would not be used. What is clear though, is that the first disaster with a bamboo structure, will crush the whole endeavour instantly. Those who design and build with bamboo need to ensure these buildings are durable and exemplarily constructed, the moment people see bamboo is a material which is accepted, it is easier for it to be copied.

1.8 Concluding comments

This chapter states that increasing the use of non-standardised bio-based materials in construction, and reducing the proportion of manufactured materials is crucial. This research will focus on the minimally processed form of bamboo—full-culm bamboo—which due to its favourable speed of growth, proximity to construction needs, harvesting patterns, and mechanical properties, can supplement other construction materials to reduce GHG emissions and restore ecologies. The growing regions of tropical woody bamboos are in areas that need adequate buildings. They are the most vulnerable to the effects of natural disasters, deforestation, and climate change, and are experiencing population increase.

Design professionals possess the ability to reshape material preferences in construction by envisioning and advocating for locally sourced non-standardised materials and producing exemplar projects, which have potential to influence the informal sector. There is a need, however, to overcome negative societal perceptions of bamboo which acts as a barrier to use and innovation (explored in Chapter 2). The incorporation of bamboo into contemporary design practices requires insight into design professionals' tools and methods (explored in Chapter 4), whilst recognising the context of tropical low- and middle-income countries (LMICs) where bamboo grows. Focusing on one- and two-storey buildings would provide wide applicability and aligns with the scope of ISO 22156 (2021). The symposium outlined evaluation criteria for this research to ensure that developing a design approach to promote full-culm bamboo durability, is applicable in a LMIC context (in the case of this research, Haiti). The key themes emerging from the symposium in Section 1.7 will be used as evaluation criteria for the design approach to discuss the outcome of this research and suggested future research in the conclusion (Chapter 6). These key themes are:

- Ubiquitous informal construction sector and even projects which seek regulatory authority will not be subject to code compliance or structural verification. Supporting public discourse on architecture and design can impact the informal construction sector in Haiti.

- Communication is crucially important for the design professional with clients, end users, and other AEC professionals and organisations.

- There is a lack of expertise in the construction sector and a challenge for clients and/or end users to envisage a liveable and desirable space with bamboo.

- Predominant use of 2D drawing and BIM software but there are challenges for compatibility between other professionals and disciplines, and infrastructural challenges to software use which includes cost, inconsistent electricity provision, or internet access.

- Lack of control for the design professional over material quality for both cementitious materials (such as CMU blocks) and steel rebar due to no consumer protections for imported materials. Material quality is susceptible to price volatility and blurred material purchasing roles by clients themselves.

- Locally sourced bamboo becomes an opportunity to decouple material costs from currency fluctuations and the opportunity to inspect the material before purchase.

- Bamboo structures would need to demonstrate security for occupants and structural adequacy, not only aesthetics. If the structure fails, this will immediately revert attitudes.

- Maintenance and associated costs will need to be communicated to clients which may negatively impact attitudes to bamboo.

In discussing the challenges of bamboo in construction and investigating the societal attitudes to bamboo, this research can at times present a negative aura. This is not the intention. Bamboo is a remarkable material and though there are many challenges to develop bamboo use in construction and awareness in design professionals, these challenges are minor compared to the contemporary global challenges of climate change and reducing material quality in tropical LMICs.

2 Chapter 2. Decoding attitudes to bamboo in design and construction

Globally, the palette of construction materials requires diversification (UNEP, 2019). Bamboo is a strong, renewable material resource that can be viable in tropical LMIC construction. However, this transition must understand intangible societal attitudes to the use of bamboo in construction. The engineering profession has made great leaps forward to provide the required information and guidance to design practically with bamboo (Harries, Trujillo, et al., 2022; ISO 19624, 2018; ISO 22156, 2021; ISO 22157, 2019). Yet, as seen later in this chapter, it is the role of the design professional, to understand negative perceptions and synthesise client need with bamboo technical knowledge into designs a client will desire. As noted in INBAR (2003):

> [Bamboo] is widely perceived as a temporary, poor man's material. However, with careful specification and design, safe, secure and durable bamboo shelter is achievable at a price that is within reach of even the poorest communities in developing countries. (p. 2)

Liu et al. (2021) states that, "Changing the image of bamboo as a 'poor man's timber' would go a long way to making this grass plant the tradition of the future" (p. 2). It is in this endeavour that this chapter is conceived. This chapter looks to decode attitudes to bamboo in society and in the architecture and engineering professions to discover the most challenging of the sociological barriers to wider bamboo use, but one which design professionals can be at the forefront of augmenting. Schumann et al. (2019) put forward a categorisation of the attempts made by design professionals and engineers to alter the negative perception of bamboo. These are listed in Table 4 with some additional commentary.

Table 4: Proposed means of addressing societal attitudes to bamboo (Schumann et al. (2019), with an example project suggested.

Category	Description	Example project or reference
Macro scale assemblies	Aggregating full-culm bamboo poles into large unique forms.	ZCB Pavilion in Hong Kong (Crolla, 2017).

Unique composite joinery	Systems, which use unique and modern methods of construction for joinery to create connection nodes between bamboo poles	German Chinese Pavilion in Shanghai in 2010 (DETAIL, 2010).
Elevation of material	Using traditional joinery techniques, but the design of the building and function challenge the preconceived notions of bamboo as an inferior material.	Green School, Bali (ArchDaily, 2010).
Concealment of material	Projects in which the bamboo is concealed behind another material to create the image of a non-bamboo structure.	Base Bahay housing in the Philippines by Base Builds and the Hilti Foundation (Base Builds, 2023).
Material transformation	The full-culm bamboo material is processed into a manufactured form where it is used in a standardised manner, such as Engineered Bamboo Products (EBPs).	Bamboo solar carport by BMW and Moso Bamboo (Souza, 2021).

From Table 4, “Elevation of material”, “Concealment of material”, and to a lesser extent “Macro scale assemblies” are applications of full-culm bamboo and relevant in this research. Manufactured bamboo building elements, or EBPs, are discussed as future research (Section 6.2.5), and bespoke composite specialised joinery will incur a cost barrier for many opportunities to use bamboo in tropical LMICs, particularly on the typology of one- and two-storey residential units. It should also be noted that concealing the bamboo has many benefits to protect the bamboo from environmental factors. But, if this is a design decision only to address negative perceptions of the material, then this is not a widely applicable strategy to develop wider full-culm bamboo use and acceptance. Often clients may wish to expose the bamboo externally or internally. Furthermore inspection, ventilation and ability to maintain the bamboo—all objectives of ISO 22156 (2021)—are improved through having the bamboo visible.

2.1 Methodologies

Methodologies are described in detail in each section of this chapter. This chapter is a methodological journey from literature review, through quantitative surveys to qualitative interviews to understand how design professionals can elevate the material of bamboo in a manner which can help a client to confidently use bamboo in a project. This chapter attempts to document and categorise societal and professional perceptions of bamboo and proposes means of addressing these in construction to move bamboo towards becoming a mainstream construction material. This is achieved through the following methods:

- To situate the current place of bamboo in global architectural discourse, taking a historical perspective to understand how attitudes to bamboo have manifested.
- To produce both qualitative and quantitative data to explore attitudes to bamboo and identify a major challenge that design professionals can focus on as the basis of a design approach.

2.2 Literature Review

2.2.1 Use of the term "poor man's timber"

Instances of bamboo being referred to as "a poor man's material" occur throughout tropical low- and middle-income countries (LMICs) from Africa (Akoto et al., 2016, p. 89), the Americas (Gutiérrez, 2000, p. 10), and Asia (Khan, 1994, p. 1). Maurina and Prastyatama (2017) observe that bamboo is, "considered as low-class material, even called as 'the poor man timber' by many modern builders" (p. 850). Lobovikov et al. (2011) reports, "the international climate change and bamboo communities have been disparate until very recently, and that bamboos have traditionally been somewhat marginalized as the 'poor man's timber'" (p. 272). Auman et al. (2018) mention "bamboo is still perceived as a 'poor man's timber' by many people" (p. 5). Koenigsberger (1971) observes, "Developing countries are likely to be slow in adopting any method that makes timber visible from the outside until they have overcome their prejudice against timber as a poor man's material" (Methods of using timber in housing section, para. 3). He continues, "Unable to afford the expensive manufactured materials, which are often imported, the newcomers employed their rural skills and used whatever materials came to hand" (Social factors section, para. 10). Koenigsberger (1971) refers to timber, and also makes it clear that this attitude applies to other bio-based materials such as bamboo. It seems the use of steel or concrete creates a perception of permanence more important in that it establishes a permanent dwelling and a higher relative position in urban society.

The perception of poverty and bamboo is also observed in Vélez et al. (2000), "Social climbers from the lower rungs of society…still want nothing to do with bamboo. In their eyes it represents the poverty from which they have fled" (p. 58). In a 2019 interview in Pier (2017), Simon Velez was asked whether there is a political element to working with bamboo. In response, Velez agreed, stating:

> I don't understand why, but there is. Because the academic world here [Central and South America and the interviewee is based in Colombia] hates bamboo; It's the poor people's wood. They really hate that kind of alternative material. There is a big prejudice against those natural materials, because they have the meaning of poverty. Since we are a poor country, they decided we have to show the world that we are a civilized country, and that we use concrete; we use brick; we have steel; and we have glass. I'm not an enemy of those materials, but there are many other materials. (para. 15)

Also in a Latin American context, Gutiérrez (2000) observes, in reference to traditional bamboo housing, that, "bamboo is customarily regarded as 'poor man's timber'" (p. 10). Historically as Trujillo (2021) observes, bamboo was used as a timber replacement in the seismic system "estilo temblorero [tremor-proof style]" (p. 9). This was an early engineered *bahareque*—a type of construction using bamboo frames and interwoven bamboo with clay or mortar to create walls—but, "in general, the wealthier the owner, the less bamboo would be used" (p. 10). This sentiment is mirrored in India. Rao et al. (2009) remark that, "by the very act of working with bamboo, their [community members'] children would be identified by the society as belonging to a lower caste" (p. 20). In Ghana, Akoto et al. (2016) reference a similar experience in which they document that community members were of the view that people living within bamboo houses are poor and living in a bamboo house is seen by community members as a shame on the family. Taking a global perspective, Janssen (2000) writes, "Bamboo is still considered as the poor man's timber in most parts of the world, and living in a bamboo house can be a stigma on the family" (p. 142).

Janssen (2000) observes that there are instances where homeowners of bamboo houses cover the bamboo in alternate building materials which are potentially structurally compromising to avoid social stigma. Similarly, Akoto et al. (2016) documents that people tend to plaster their houses to make them look like concrete houses if they are constructed with bamboo. This could be both for technical reasons to protect the bamboo externally, or to mitigate the societal prejudice. Where bamboo is available and could perform as a resilient material, Bakker (2020) highlights cases of societal preferences for unsafe applications of alternate materials to bamboo. Origins of this attitude may emerge from the performance of the material and relative lack of natural durability (Arup & Shelter/NFI Sector, 2018), or the fact that bamboo has historically been overlooked due to the fact that bamboo is different anatomically than a tree (Lobovikov et al., 2011).

In the Ghanaian construction industry, Opoku et al. (2016) conducted a survey of building contractors to gauge their perceptions of the factors that inhibit bamboo use. This survey concluded that the problem of social acceptability was a key factor inhibiting wider construction industry use. Other factors were the non-specification of bamboo for building projects by architects, a lack of adequate bamboo processing companies in Ghana, and insufficient cooperation from government (Opoku et al., 2016). Staying in Ghana, Akoto et al. (2016) carried out surveys with community members in three Ghanaian towns across the country to reveal urban stakeholder perspectives on bamboo in housing. Their surveys found that the perception of bamboo as a housing material for the poor was cited in just under half of all responses (Akoto et al., 2016). In addition, other perceptions of the material included the perception that bamboo is not durable with nearly a third of responses, a lack of appropriate technology (which is interpreted here to mean a lack of knowledge and expertise in the construction sector), and unsuitable bamboo species for construction (which is interpreted here to mean that there is both a limited diversity of species and those that are available are relatively less suited to construction). The conclusion of the study suggested that it is important to raise awareness of bamboo through education to ensure good design, construction expertise and also develop a bamboo construction infrastructure locally in order to provide treated bamboo to the community (Akoto et al., 2016). People involved in developing bamboo housing were also asked the major barriers they found in their work. One third of respondents also thought that a lack of technical knowledge and community misconceptions about bamboo housing were major barriers (Akoto et al., 2016).

From this initial review of literature, the following sub-headings have been developed as initial categorisations to continue the literature review to understand more information behind why bamboo is perceived as a poor man’s timber. Therefore, the following subheading follow these initial categorisations:

1. Material performance, quality, and durability (Section 2.2.2)

2. Lack of knowledge, construction industry awareness, or formalised supply-chains (Section 2.2.3)

3. Species availability and use of “wrong [*sic*]” species (Section 2.2.4)

4. Ease of construction and ease of access to the raw material (Section 2.2.5)

5. Cultural associations and westernised attitudes (Section 2.2.6) – Reviewing this area presented some fundamental considerations which underscore many other issues, therefore this section is larger.

2.2.2 Material performance, quality, and durability

All building materials are subjected to physical, chemical and biological degradation (Addleson & Rice, 1991). However, like most lignocellulosic materials, bamboo has poor natural resistance to biological degrading agents (Kumar et al., 1994). Durability is defined in ISO 22156 (2021) as the ability of bamboo to, “resist degradation of geometric, physical or mechanical properties when subject to an intended service environment for an intended service life” (Clause 5.7). Bamboo which is not treated with preservatives and subject to unprotected exterior exposure or in contact with the ground has an average life of less than one year (Liese & Tang, 2015a). Degradation from exposure to sunlight and rain (excess moisture) can be seen in Figure 21.

The anisotropic behaviour and characteristic strengths of bamboo makes it comparable to hardwood (Archila et al., 2018), however, bamboo does not store as many toxins that assist in imparting natural durability as do most wood species (Janssen, 2000; Kumar et al., 1994). This is exacerbated by the fact bamboo culms are hollow, having no protected core and the potential to degrade from both the outside and inside of the culm. Additionally, the anatomical structure of the bamboo culm makes drying more difficult than for wood (Kumar et al., 1994).

Figure 21: Two bamboo poles of the same species (*Guadua angustifolia*) from the same region. The left pole is used as a frame which has become grey, coarse and split because it has been exposed to the sun and the rain over a period of time and is used to support newly treated and drying bamboo poles (right). Photo by author, Ecobamboo bamboo treatment facility, outside Candelaria, Valle del Cauca, Colombia, 2022.

A major problem is that fungus is able to grow when moisture content exceeds 20%, potentially further degrading the material (Liese & Tang, 2015a), such as a common white-rot fungus (*Schizophyllum commune*) (Ashaari & Mamat, 2000). This is a challenge to durability considering bamboo should be used in the countries where it is grown which are often in humid tropical locations. Durability and material degradation is an important recurring factor when considering why society perceives bamboo is a *poor man's construction* material. Kaminski (2013) states, "durability has demoted its [bamboo's] modern position to a poor man's building material" (p. 14). In terms of durability, it is a fact that bamboo has lower natural durability compared to comparable materials such as most timber species (Janssen, 2000). Arup and Shelter/NFI Sector (2018) cite Kaminski (2013) and record the stigma of bamboo as the "poor man's material" in reference to the use of bamboo in refugee camps in Bangladesh. Here, bamboo is used in most structures in the camps due to wide availability, despite being more vulnerable to insect attack and rot than timber. They cite durability as a major contributing factor to negative associations of the material, "Durability is the main reason why bamboo is considered a 'poor man's construction material', and why so many bamboo structures do not last" (p. 9).

The lack of design input into these low cost bamboo houses means that often the bamboo structure suffers from poor finishing (Appiah-Kubi et al., 2014). The bamboo used is not treated to enhance durability or is incorrectly treated for its intended use. A lack of design input and the use of untreated bamboo will exacerbate aesthetic and durability issues. Given the locations these statements are referring to, durability can have a proportionally much larger impact in these contexts, as Ngab (2001) reports, "durability is an important design consideration in developing countries in particular. These countries cannot afford to build in the first place. The cost of repair of deteriorated structures take up a significant portion of expenditure" (p. 1343). Koenigsberger (1971) notes the issue of durability creates a notion that manufactured materials are worth investing in over organic materials:

> In the absence of statistical evidence on the durability of houses in tropical cities, bankers and their surveyors and valuers will take a lot of convincing before they abandon the notion that inorganic materials are better and more worthy of financial support than timber and other organic materials. (Economic factors section, para. 19)

2.2.3 Lack of knowledge, construction industry awareness, or formalised supply-chains

Tekpetey (2011) remarks that there are poor processing facilities in Ghanaian construction for bamboo. A lack of infrastructure is also documented in Akoto et al. (2016) and Opoku et al. (2016). A lack of processing infrastructure reduces the ability to standardise the material and ensure a consistent quality product. A lack of development of bamboo in construction means that today, arguably, bamboo must find a place in a construction industry dominated by manufactured materials. As described by Buckingham et al. (2014) since bamboo can be a substitute for timber, historically this substitutability has hindered bamboo developing its status and place in its own right (Buckingham et al., 2014). Many successful examples of bamboo structures today, demonstrate straight poles and timber technologies adapted for bamboo. Lack of knowledge and awareness is reflected in, and ultimately compounded by the lack of exposure to bamboo during architecture and engineering education. Full-culm bamboo has often been likened to other straight building elements such as timber or steel (Fairs, 2015; Newsweek, 2010; Walker, 2014).

The availability of mainstream materials such as concrete and steel is a hinderance to the use of bamboo as a building material. In Indian construction, Chaurasia et al. (2019) note that due to urbanisation and the development of infrastructures producing other industrial materials, the use of bamboo has been restricted to few rural areas. As a result of the affordability and availability of other materials, Chaurasia et al. (2019) state that bamboo is considered as "inferior", or "temporary" (p. 1), being considered as a low class material. The same is noted in Ecuador and Colombia. Parsons (1991) observes that the native bamboo is the material of choice for the *barrios populares*, the informal settlements peripheral to urban centres. The distinctive exposed bamboo poles have given an image to these neighbourhoods emanating the temporality of housing designed to only last until other materials, such as brick or cement blocks, are acquired. As modern tastes, technologies, and industrial materials have gained ascendancy, Parsons (1991) has noted that bamboo has been seen more and more as the "poor man's lumber" (p. 133), the commonplace building material that *campesinos* (a native of a Latin American rural area) live with throughout their lifetimes.

2.2.4 Species availability and use

Akoto et al. (2016) found that the availability of adequate species of bamboo was a barrier to wider use of bamboo in housing. This is also addressed by Appiah-Kubi et al. (2014) as they note that the predominant species in the regions of Ghana where their study was based was

Bambusa vulgaris (Appiah-Kubi et al., 2014). Though there may be variations, experiences in Haiti as part of this research show that *B. vulgaris* is more crooked and more prone to insect attack than other species such as *G. angustifolia*. As a result, the aesthetic and durability issues of certain species, as compared to others, can make it more challenging for more 'suitable' species to engender themselves positively. For example, the experience of *G. angustifolia* in Colombia would be more positive than the experience of *B. vulgaris* in Haiti. This is analogous to extrapolating the performance of one timber species from another. As Liese and Tang (2015a) remark, since species vary in their properties, their suitability for different products also varies. It is a recurring issue with attitudes to bamboo that bamboo is a diverse range of over 1600 species yet is conflated to reflect the local experience of local species.

2.2.5 Ease of construction and access to the raw material

Cost is a reason for negative perception argued by Trujillo and López (2016) citing the inexpensive nature of full-culm bamboo when purchased locally. Appiah-Kubi et al. (2014) note bamboo is seen as an inferior stopgap building material. Both Manandhar et al. (2019) and Puri et al. (2015) report reasons for the notion of bamboo as a poor man's timber as being due to its being the choice of material for most low-cost housing given the abundance of material found in certain areas. In rural areas bamboo has been an essential material for construction of temporary housing (Khan, 1994). This is due in large part to the reduced cost and therefore value placed on the material; since bamboo is less expensive than construction materials like steel, cement and even wood, it is perceived as a material of the poor (Kumar et al., 1994). The ease of availability, mixed with the knowledge of rural populations to work with bamboo, makes it the optimal material for those who have emigrated to the cities and need to construct their shelter themselves. In reference to Latin America, Gutiérrez (2000) suggests that bamboo is customarily regarded as "poor man's timber" because it is used as a temporary solution, and therefore becomes the image of low cost, temporary housing of the poor, a material which is to be substituted as soon as improved economic conditions allow (pp. 10, 54). In Nigeria, Borisade et al. (2020) remark that bamboo is often referred to as "green gold" which introduces itself as a, "cheap and plentiful resource" (p. 11). The "plentiful" nature of bamboo is related to the fast growth cycle of bamboo. However, a second reason relates to how governments perceive the value of bamboo and the ability to access bamboo compared to hardwoods. Hardwood forests are often on government land (FAO, 2006). However, almost two thirds of bamboo stand on land which is accessible to communities or the public, reinforcing a notion that this is a material available to the poor (Lobovikov et al., 2011). The abundance of bamboo on publicly accessible lands also creates difficulties for the state to generate revenues from taxation which is possible with materials that need to pass customs checks and require a large processing infrastructure. A lack of tax revenue from raw products could manifest as a lack of interest in promoting bamboo as a mainstream construction material. Although bamboo may often be "cheap and plentiful" (Mera & Xu, 2014, p. 2), in many communities, it has greater value in forms other than a construction material. This can be as bamboo flooring, charcoal, or furniture. The construction sector will compete against often more lucrative value-added products for domestic markets or export (Kafle et al., 2023; Liang et al., 2023).

2.2.6 Cultural associations and westernised attitudes

Mukhopadhyay (2008) states that in regions where bamboo is used in many ways within the local culture, often the material will be incorporated into the architecture as well. "The use of bamboo so far has been more traditional than technical, and it has the image of being the building material of the poorer class" (p. 102). Historically, living in a bamboo house suggests the occupant would have bamboo utensils and furniture, which is not the case in a concrete, masonry, earth-based material, or steel structure (although more likely for timber). Concrete, for example, is clearly a building material unaffected by other first-hand experiences at smaller scales. A means of addressing this is for bamboo to appear clearly as a structural material, different from that used for non-building elements. This is supported in Belcher (1995b), which observes that in Asia, bamboo has the notoriety of the "poor man's timber" because for many people, bamboo is a critical part of a rural livelihood and culture (p. 1). This would include a clear distinction between commonly used species for construction (the information in ISO 22156 (2021) is based on the data from 15 species) and species for other uses. Belcher (1995b) provides a list of objects for which bamboo is considered the material of choice which includes household utensils, farm tools, fish pens and water pipes and Buckingham et al. (2014) explains bamboo is used for products such as paper.

Finally, it is important that in many of these cases, there is a notion that living in a bamboo house represents a lack of social advancement. It is the opposite of modernity, it is from a bygone time, a rural time, a time when humans were forest dwellers, not city dwellers. This notion of bamboo as an inferior material has its roots in colonialism. As Turnbull (2016) states:

> Not only has its [bamboo's] key role in the development of science and technology been largely overlooked by Western historians of science, but its contemporary uses tend to be contemptuously undervalued as simple and traditional. It was dismissed as 'poor man's timber'. (p. 812)

Attached to this, is the idea that bamboo is invasive and a weed, and therefore it is not a "productive" material or crop unlike timber, which was well regarded as a construction material. Schumann et al. (2019) looked at the perceptions of bamboo and the barriers to bamboo in construction; colonialism plays a central theme in their study:

> Known colloquially as 'poor man's timber', bamboo carries a longstanding cultural aesthetic stigma, particularly within a western context. The perception of bamboo as an informal or unrefined material results from a combination of racism, classism, imperialism, and a lack of investment in the development of its material possibilities. (p. 308)

This negative societal attitude has much to do with how progress has been considered and non-Western or non-European history and technology has been viewed (van Leerdam, 1995). Eurocentrism has been defined as, "an attitude, conceptual apparatus, or set of empirical beliefs" which cast Europe as the "primary engine and architect of world history" and the "model of progress and development" (Sundberg, 2009, p. 638). Europe is the only continent, other than Antarctica, which has no indigenous bamboo (Clark et al., 2015; Lobovikov et al., 2007) and an absence of using bamboo in construction. The *tropics*—where bamboo had been used for millennia as a construction material—were mostly annexed by the only inhabited continent with no awareness of bamboo as a construction material. During the age of European imperialism, technologies, materials, and designs were imported from Europe to their colonies (Wibowo et al., 2018).

European architects and theorists believed that the variety of architectural forms, and the peoples that produced them, could be hierarchically arrayed along a timeline from primitive to modern (Cheng, 2020). An example of this is in Viollet-le-Duc (1876) as an early account of bamboo structures in a formative architectural text of the time. The bamboo structure is composed of, "Great roofs, made of thick bamboos, bent and covered with reeds very ingeniously disposed, sheltered the interior from rain and heat" (p. 31). A principle of protection by design (presented in Janssen (2000), and discussed in Chapter 3) is also referenced as "The building rested on a base consisting of large stones" (p. 31). In Fergusson

(1855), Asian architecture is separated outside the chronology of architectural development stating, “The simple fact is, that China possesses scarcely anything worthy of the name of architecture” (p. 133). Fergusson (1855) describes the “peculiarity” of the architecture is due to the peculiarity of the material of bamboo:

> This [local characteristic architecture] arises from the timber they possess most easily available for such a purpose being a small pine, found everywhere, in the south at least, which has the peculiarity of being soft and spongy in the inside; but the outer rims of wood, just under the bark, retain their hardness and strength; so that practically it is a hollow wooden cylinder; and if the carpenter were to attempt to square it, so as to form a framing as we [Europeans] do, it would fall to pieces; but merely cleaned and used whole, it is a very strong and durable building material, though one which requires all a Chinaman’s [sic] ingenuity and neatness to frame together with sufficient rigidity for the purposes of a roof. (p. 141)

Racialised views notwithstanding, the description in Fergusson (1855) is interesting as it shows a favourable opinion of the material as durable and strong when it is used correctly. The description also highlights the peculiar nature of bamboo to a European audience requiring the comparison to timber and the delineation between the “us” and “our” material culture, and “them” and “theirs”. Fletcher (1931) conceived the *Tree of Architecture* diagram (Figure 22) in which non-European styles, as discussed by Baydar and Nalbantoḡlu (1998), are shown terminating without further development. China and Japan are on the bottom row on the far right.

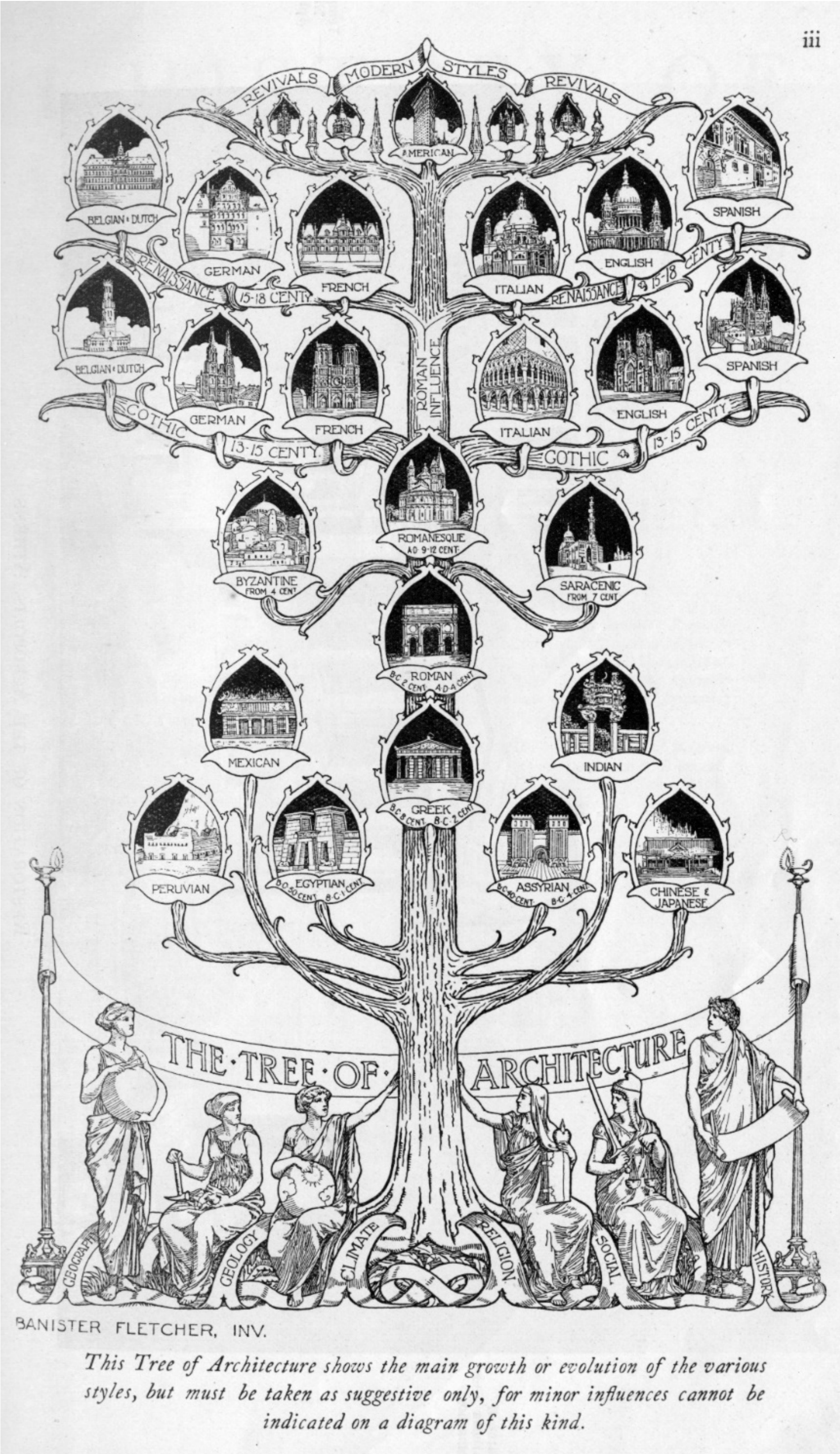


Figure 22: Sir Banister Fletcher. *A history of architecture on the comparative method for students, craftsmen and amateurs*, 9th ed. (London, Batsford, 1931), p. III. This design first appeared in 1921 in the sixth edition of the history of architecture. Image and description from RIBApix. RIBA Ref No: RIBA111570.

A catalyst to engendering views of bamboo in the European psyche was facilitated through colonial exhibitions which took place in European countries in the later nineteenth and twentieth centuries. An example of this is at the Paris Exposition of 1889 where an exhibition was created of *Human Habitation* (Hales, 2017). The Colonial exhibitions which were held by European powers were stark evidence of the beliefs and intentions of the colonial powers regarding how they saw themselves and the "backwardness" of their colonies (Morton, 2000, p. 119). Morton (2000) contends that one of the purposes of these exhibitions was to conjure and present a "degeneracy or ignorance relative to" European culture at the time, translating from Zahar (1931), noting "the quality of materials used" were a means to show the strengths or naivetes of a race (p. 318). Charles Garnier and August Ammann created an exhibition of *Human Habitation* which was an important part of the 1889 Exposition. In the book which accompanied this exhibition, *L'Habitation Humaine* (1892), Garnier and Ammann, in a similar vein as Fletcher's 1896 *Tree of Architecture*, lined up Chinese, Japanese, Eskimo, Aztec, Incan, African, and Australian dwellings into a section called "Peoples isolated from the General Movement of Humanity" (Cheng, 2020, p. 148). It was in this zone, cordoned off from the "General Movement of Humanity" in which bamboo was used to execute domestic dwellings for the Javanese Village (Figure 23).

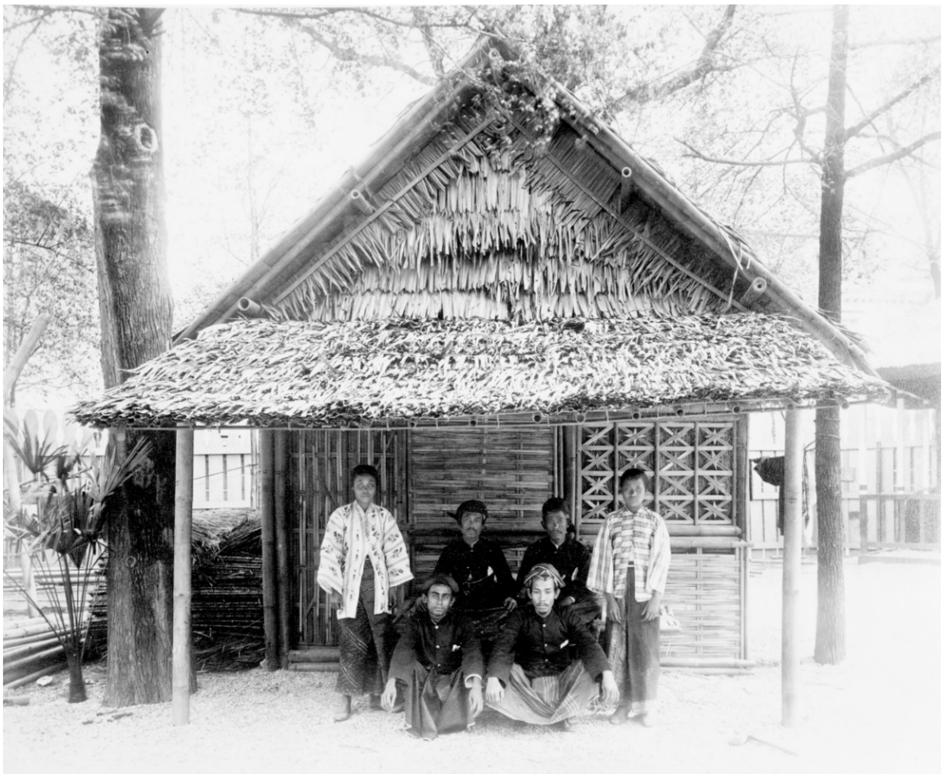


Figure 23: Six people posed before the *Javanese house* at the Javanese Village, Paris Exposition, 1889. *Exposition Universelle de 1889*, Paris, France. Photograph retrieved from the Library of Congress, https://www.loc.gov/item/94500849/

Morton (2000) illustrates that architecture was employed to show inherent differences between Europe and its colonies. In this atmosphere, any use of bamboo by European architects would run the risk of creating a "undesirable hybridity" (p. 213). Unlike a steel or a sawn timber beam, the natural variability and the protruding nodes of bamboo can appear asymmetrical, superfluous, irregular, or ornamental. In Loos' seminal work *Ornament and Crime*, published in 1913, a text which still influences architectural education today, Loos equated future progress to the extension of a racial genus. Loos speculates that a lack of ornament indicates cultural development (Cheng, 2020). One of the most prominent architects of the twentieth century, Le Corbusier, references Loos in his own statement when in, *L'art Décoratif D'aujourd'hui [The Decorative Art of Today]* he, "affirms" that "the more cultivated a people becomes, the more decoration disappears" (Le Corbusier, 1925/1987, p. 85). After likening decoration as the work of the "savage", Le Corbusier goes on to say that "No practical or elevated argument excuses or explains iconolatry. Since iconolatry thrives and spreads as virulently as a cancer" (pp. 12, 85). Cheng (2008) identifies that for Loos and Le Corbusier, the ideal of architectural purity is linked to culture and civilization. These same voices emerge in Chapter 4 of this thesis, when discussing methods of design, pure geometry, abstraction of architectural form, and where they urge the replacement of "natural materials by artificial ones" to avoid the "lurking…treacherous knot of old world timber" (p. 214).

Bamboo is influential in Chinese architecture, as noted from Fergusson (1855) to Vélez et al. (2000). As Vélez et al. (2000) records, it is possible that bamboo preceded clay tiles as a roofing material, and the theory goes that clay roof tiles are based on bamboo canes. The curvature of the Chinese pagoda roof can also be traced back to when a bamboo roof structure would bend under the weight of the roof covering and create the concave roof form recognisable as distinctly East Asian today. Bamboo featuring as it did in Fergusson (1855) and Viollet-le-Duc (1876) on the Chinese House, is of no surprise since Asia is home to the greatest number and variety of bamboo species; for example, 626 species are native to China whereas only 56 are native to Colombia (Akinlabi et al., 2017). In fact, the origin of the word bamboo comes from Malay "mambu" (Harper, 2023), with the word introduced to Europe probably by the Dutch in the 16th Century as, "A thicke reede, as big as a man's legge, which is called Bambus[5]" (OED, 2023a). This use of *bamboo* as a word introduced from Asia has also been grounded in the architecture seen as traditionally Chinese or Japanese. The term bamboo is also tantamount with Asia or Asian. Hyun (2005) coined the term "Bamboo Ceiling" to describe barriers faced by many Asian Americans in the professional arena. The term "Bamboo Curtain" was used to refer to the Cold War political demarcation between Communist states in East Asia, particularly the People's Republic of China, and capitalist and non-Communist states (Kaplan, 2008).

In Indonesia, prominent Dutch architects of the time of colonial rule, and those in positions to shape architectural education in the colony, referred to local building traditions as the "poor hut of a forest dweller composed of rough wood and tree bark" and the "primitive kampong house built of wood or bamboo and bilik" (van Leerdam, 1995, p. 36)[6]. Arguably these attitudes fostered a negative attitude to bamboo and this attitude pervaded into education. Dutch Colonial laws banned bamboo as a building material in urban areas in Indonesia which restricted the use of a low-cost material that also had low associated labour costs (Jessup, 1985). The hollow form of bamboo was thought to provide refuge and breeding spaces for disease-carrying pests. Though there were many local designers still working with bamboo, European architects, Henri Maclaine Pont, and Thomas Karsten, argued against the blanket ban of bamboo. Their position as members of the European ruling elite, who arguably shared the racialised view of colonial societies (Bliek, 2023), made their advocacy for bamboo for purely practical reasons worth investigating. In a 1922 conference paper addressing public housing in Indonesia, Maclaine Pont (1922) noted that the banning of bamboo as a construction material was impractical and looked at bamboo housing to identify construction practices that avoided open bamboo culms with joinery which prevented gaps between poles (van Leerdam, 1995). The design guidance also suggested a gap between the bamboo frame and the surfaces of the roof and walls so inspection and cleaning would be easy to perform (Vries & Segaar-Höweler, 2009). Learning from Javanese culture, Maclaine Pont presented this local material resource in a way which demonstrated new methods to eliminate the

[5] Quote cited from Oxford English Dictionary (2023) referring to W. Phillip, translation of J. H. van Linschoten, Discours of Voyages East & West Indies i. xxx. 56/1

[6] All quotes from van Leerdam (1995) are translated into English from the original Dutch using an online translation tool, therefore the exact translation may be different to that stated.

hollow breeding spaces offered by bamboo and demonstrated enhancements to resist insect infestation (Figure 24) (Jessup, 1985).

Figure 24: Model for a Javanese house executed with application of the *purely wilah* system for both the substructure and the roof grating. Caption and photo reproduced from Maclaine Pont (1922). https://colonialarchitecture.eu/ [Caption translated by author, using online translation software, 2023]

Bamboo growing regions which were former colonies or de-facto colonies of the Global North did not have a mainstream knowledge for local materials such as bamboo and in many cases architectural design was influenced by those educated in Europe. In a bid to break with the old world, it is also apparent *Modernism* became a style representing progress for the newly independent nations whether this be in Asia, Africa or the Americas (Jessup, 1985; Manful et al., 2022; Muthmainnah & Kurniawan, 2018; Restrepo Ochoa, 2022; Uduku, 2006). On independence many tropical countries had a workforce of design professionals trained in "the West" for materials other than bamboo. Modernity would continue to reign in the work of practicing designers in former colonies and this was another form of lasting colonisation. Therefore, far from decolonisation as a chance to break the bonds of European influence, the construction industries, material infrastructure and design education remained aligned to the West (Han & Kurniawan, 2018; Mignolo, 2012). These are seen in the form of legacy building codes which prescribe European technologies rather than being performance based, colonial laws which banned bamboo due to its hollow form (Jessup, 1985), and the dominating role European languages still play in academia and scientific advancement (Chakrabarty, 2000; Mignolo, 2012) (this is discussed as future research in Section 6.2.6). It is recognised that this has become manifest in how architecture has been theorised, practiced, and taught the world over (Chiganze et al., 2021; Loo, 2017; Yashaswi, 2019). The influence on contemporary architectural design practice is profound of this legacy. With this historical perspective, it can tell a lot about the character of today's contemporary attitudes and knowledge gaps towards bamboo in architectural design.

2.3 Professional attitudes: Quantitative surveys

To understand how contemporary design professionals and students perceive bamboo, and to understand how they can begin to engender bamboo into their work, it is important to understand the attitudes of architectural design professionals, engineers and students of architecture and engineering toward the material. Surveys have been used to gauge the attitudes of design professionals by Bing and Yi (2015) to understand Chinese architects' attitudes to low-carbon architectural design; to determine knowledge gaps and research needs in the field of bamboo construction, Opoku et al. (2016) to gauge perceptions of building contractors of barriers to bamboo use, and Kitek Kuzman et al. (2018) to understand architects' attitudes to engineered timber in Central and Southeast Europe. The latter is a good precedent for a study of attitudes to bamboo, as it was designed to identify knowledge gaps and the willingness to use engineered timber. Societal attitudes have been studied by Gold and Rubik (2009) to understand the perception of timber as a construction material in Germany, and Akoto et al. (2016) carried out surveys to determine what benefits stakeholders perceived from using bamboo in construction in Ghana. This is a good reference to understand perceptions and embedding these principles in the design of bamboo structures.

2.3.1 Survey methodology

A self-administered online survey was carried out which contained a series of questions intended to gauge the attitudes of built environment professionals and students to bamboo. This was designed in a similar vein as Kitek Kuzman et al. (2018) to identify knowledge gaps, perceived challenges, but also pinpoint the opportunities for bamboo to develop. The survey was split into two sections. Firstly, to gain insight to respondents' attitudes to bamboo, and secondly to understand the design methods and the tools used in design. The results of this second section are presented and discussed in Chapter 4, as this pertains to the design methods and tools discussed in that chapter. This survey was conducted online and the request was sent to design and engineering professionals and students within the author's own network in the UK, Colombia, Singapore, and Haiti, and an invitation to participate was sent by email to the architecture and/or engineering departments of: Isthmus University in Panama, Universidad del Los Andes and La Universidad Nacional de Colombia, in Bogota, Colombia; Newcastle University in the UK; Nanyang Polytechnic University in Singapore; the Institut Teknologi Bandung, in Bandung, Indonesia, and the Architectural Association in London, including students who participated on the *AA Visiting School BambooLab*[7] workshops prior to enrolment. Surveys were administered in each case through a gatekeeper who would be a member of staff of the academic institution, or a person within an architecture practice. They would share a website link to the survey, therefore anonymity would still be ensured and with little to no perceived influence of the gatekeeper on responses. This survey ran for 30 months. After one year, the online survey was adapted to be bi-lingual and translated into Spanish alongside the English. This was checked with Spanish speaking colleagues within this field of research (who collaborated in Section 4.5.3 of this research), to ensure accuracy of meaning.

Surveys such as this one are advantageous in their transparency in which the methods, procedures and implementation can be assessed by others (Hakim, 2000). There are internal and external validity problems with surveys, internal being the questions themselves are incomprehensible or ambiguous resulting in a problem of obtaining the right information, and external being problems with the sampling and securing the involvement of respondents (Robson, 2002). This is particularly true with self-administered surveys which typically have a low response rate and given the anonymity, it is difficult to know how representative the responses are (Robson, 2002). Similar surveys have been used within the construction industry. In a survey of architects' awareness of sustainability, China, Bing and Yi (2015) recognise the non-response bias which could affect the results, in that those who have little interest in this issue may not reply. The way to reduce this (though not eliminate non-response bias) is to keep the survey as short as possible and be clear and transparent about the survey length by including a progress bar at the top of the survey.

[7] The AAVS Haiti workshops continued as annual bamboo focussed workshops with the Architectural Association School of Architecture beyond 2017 moving from Haiti to Myanmar in 2017, Indonesia in 2018, and online in 2020 and 2021 at which the author co-directs with Dr.-Ing. Andry Widyowijatnoko.

2.3.2 Respondent demographics

The survey started with a series of multiple-choice questions to understand the demography of survey respondents which can be later used to filter results. However no information was asked which could be used to identify the participants as this information is not required and anonymity can encourage frankness and honesty (Robson, 2002). Questions included age (Figure 25), and profession (Figure 26).

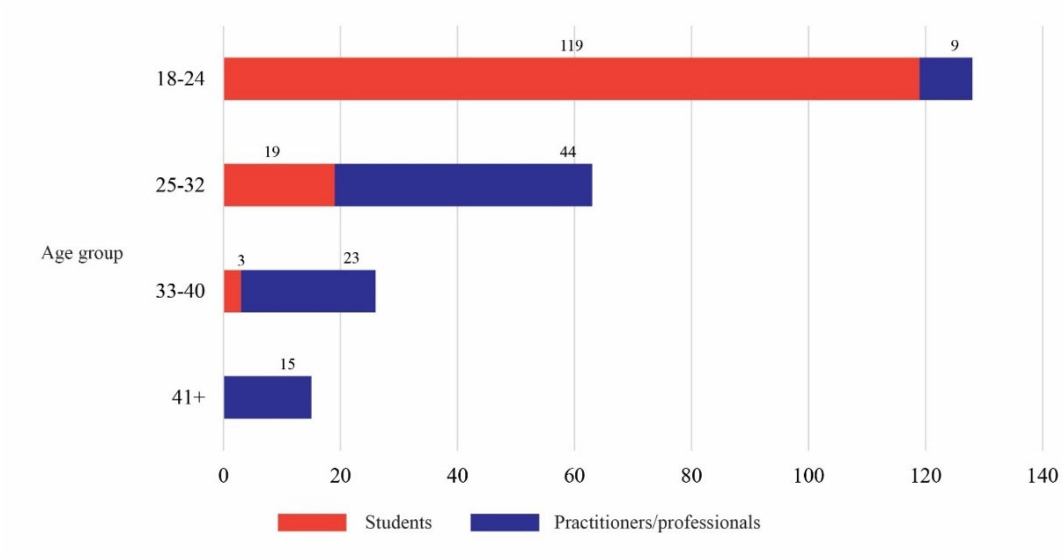


Figure 25: Age groups of survey respondents broken down by students and practitioners/professionals.

In total there were 235 responses to the survey. Three respondents recorded their professions as “Other” (Figure 26). These responses have been omitted from the survey results, therefore 232 responses are used.

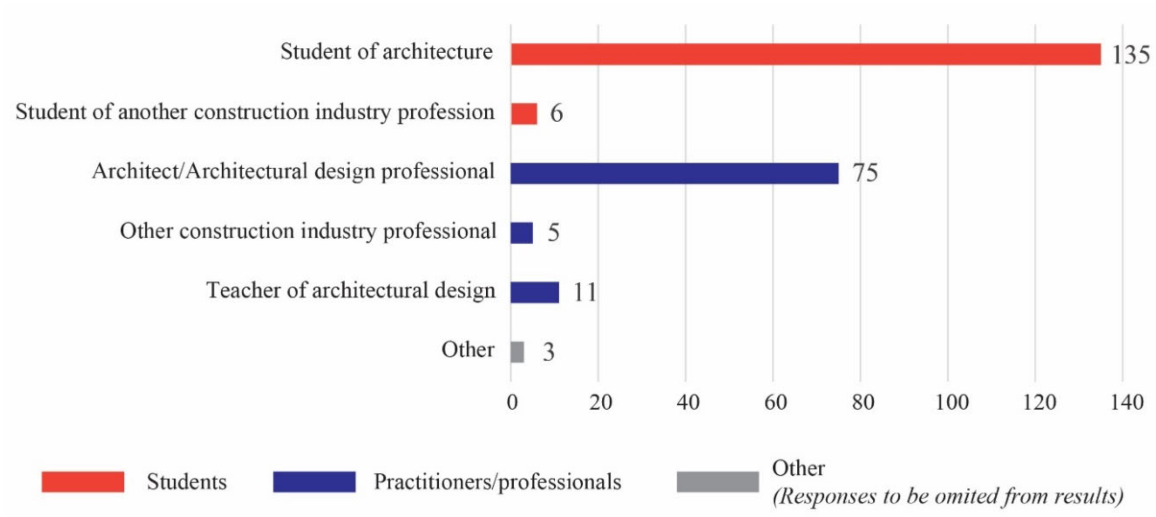


Figure 26: Profession of survey respondents.

In order to establish the relevance of these responses to those studying or practicing in bamboo growing regions, additional questions included, “Which location did/do you conduct most of your studies?” and “Which location do you work or practice?” (Which only professionals were encouraged to respond to). Even though there is the possibility that those who select “Australasia”, and “Other non-tropical and temperate context” may in fact be living alongside indigenous bamboo resources, the population centres of Australasia and the fact this survey was not circulated to universities in this region suggests this will not impact results. Given this survey is anonymous and the anonymity can encourage frankness, the use of geographic regions rather than countries were used (Figure 27).

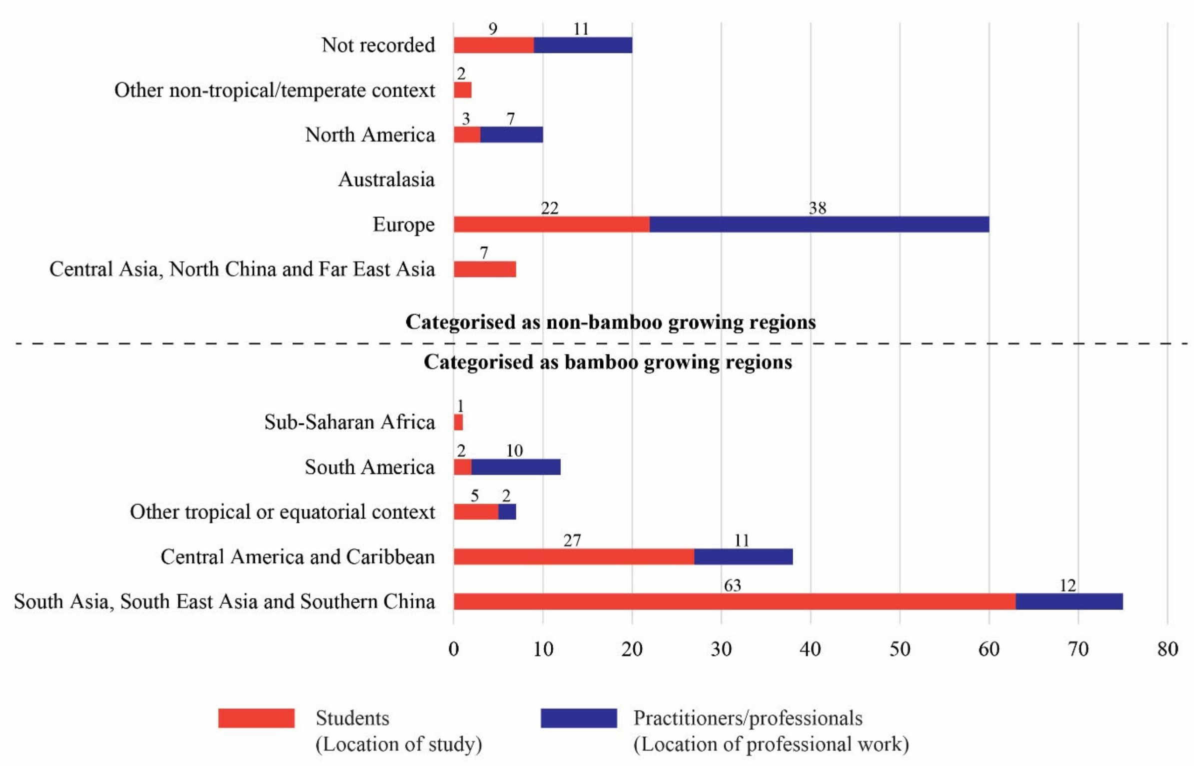


Figure 27: Geographic location of respondents: Location of studies (students), or location where professional work is carried out (practitioners/professionals).

2.3.3 Questions: Attitudes and perceived challenges of bamboo in architecture

Only two questions from the survey are included in this chapter (Table 5). Additional questions pertaining to design methods and software are discussed in Chapter 4.

Table 5: Q1 and Q2 in the survey to determine attitudes to bamboo in construction.

Number	**Question**	**Response format**
Q1	In ONE or TWO words, describe your first impression of the term “bamboo architecture”.	Text box – Open ended response
Q2	Which do you personally think is the biggest challenge when designing for bamboo?	Text box – Open ended response

2.3.4 Results: Q1 - Impressions of “bamboo architecture”

Reviewing all 232 responses, groupings were made. The results of these groupings are shown in Figure 28. Singular comments (only one response recorded), have been removed for clarity. Therefore, the only comments shown in Figure 28 are those with two or greater mentions. A full list of original responses along with their thematic categorisation is shown in Appendix G.

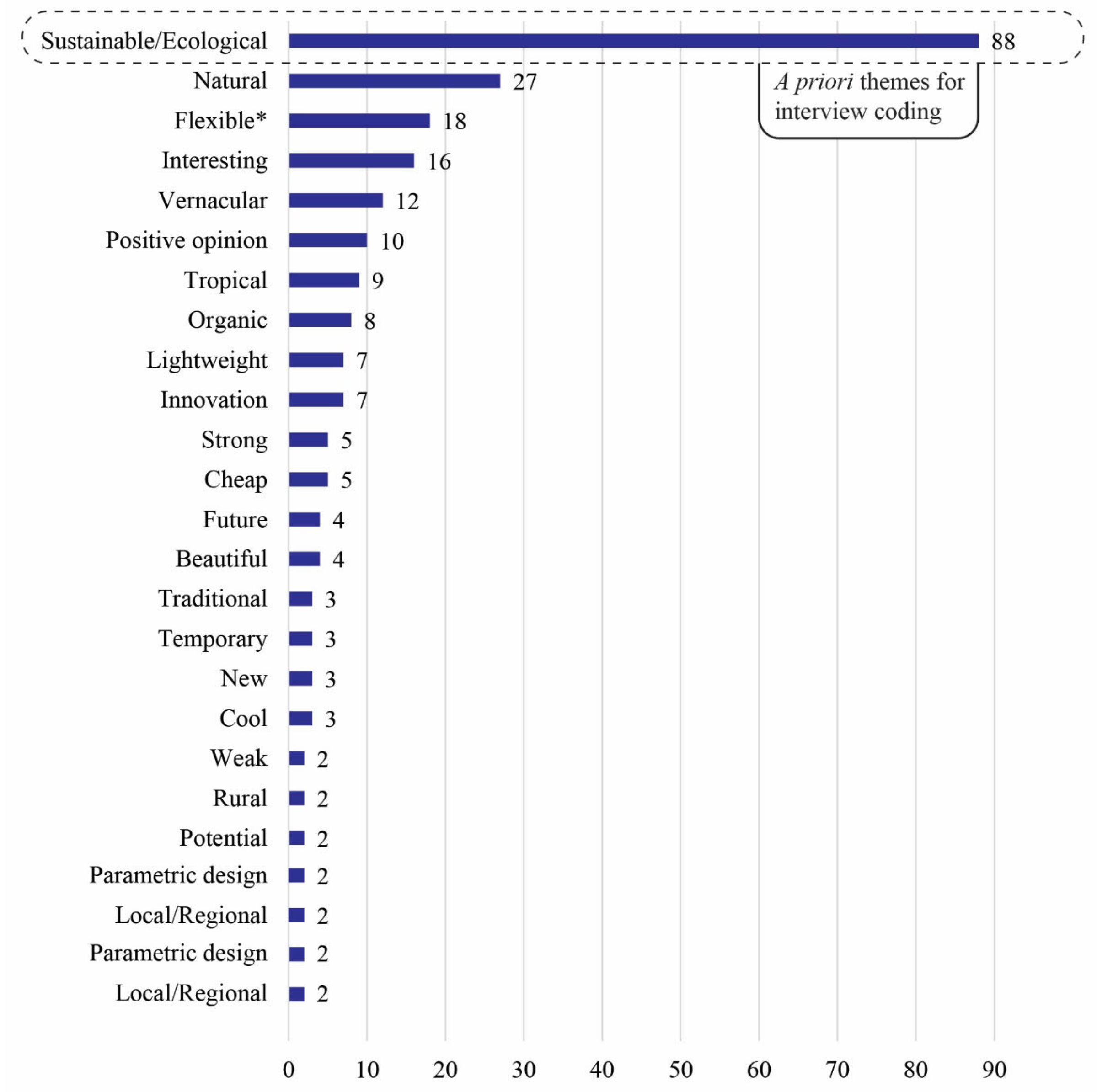


Figure 28: Categories of first impressions of the term "bamboo architecture" showing number of respondents. (*flexible could refer to both flexibility of use or the flexibility of the material property).

There is a bias toward positive responses resulting from the fact that respondents had already shown an interest in learning more about bamboo. Nonetheless, the overwhelming impression of bamboo architecture is positive and that of "sustainability" (88 responses). This was three to four times greater than the second response which was the notion of bamboo as a "natural material" (27), "flexibility" (18), "interesting" (16), and a series of positive opinions (9). "Vernacular" (12) and "tropical" (9) were also within the top results in the list. Responses below this reflect less than 10% of the highest value. "Flexibility", with 18 responses is ambiguous in meaning. It could refer to both flexibility of use or the flexibility of the material characteristic. "Tropical" was only noted by professionals/practitioners. This could also be due to more respondents who are European based design professionals in practice (as shown in Figure 29). Given the overwhelming positive impression of bamboo as sustainable, it is important that these attitudes are taken account of by design professionals and data is provided that can confirm the sustainable credentials of bamboo. This is also the highest ranked for both professionals/practitioners and students (Figure 29). As discussed in Section 1.5.3, there is an evident knowledge gap in the sustainability credentials of bamboo with ever increasing work to fill this gap (e.g., Göswein et al., 2022; Lou et al., 2010; Lugt and Vogtlander, 2015; Peng et al., 2023; Pomponi et al., 2020; Xu et al., 2022; Zachariah et al., 2016; Zea Escamilla, 2015). Ensuring good information on the sustainability credentials of bamboo in construction is therefore important. This positive opinion needs to be leveraged to engage more clients who may want to use bamboo, and a situation must be avoided where misrepresentations or myths of bamboo's sustainability credentials adversely impact this positive attitude. This will be discussed at the end of this thesis as a future research field (Section 6.2.2).

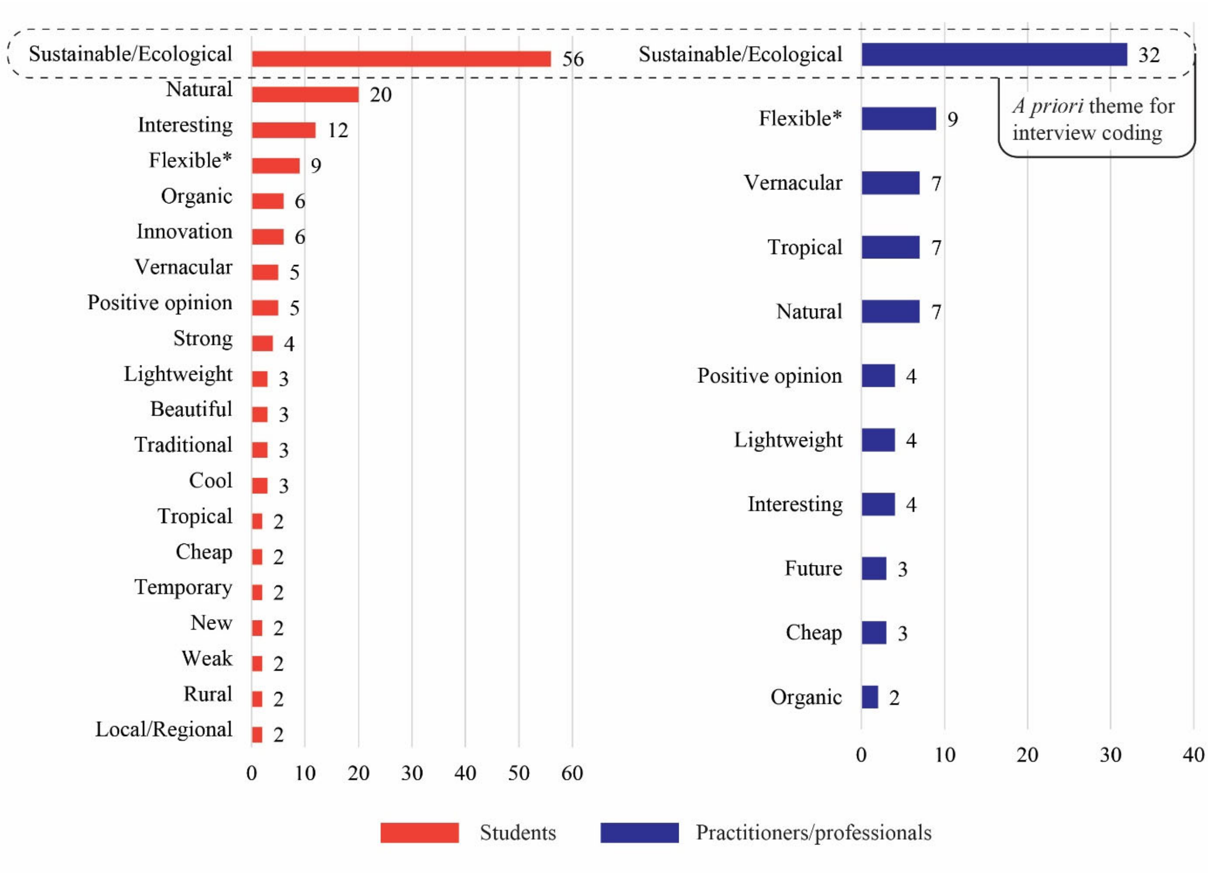


Figure 29: Categories of first impressions of the term "bamboo architecture" showing number of respondents, broken down by students and practitioners/professionals. (*flexible could refer to both flexibility of use or the flexibility of the material property).

2.3.5 Results: Q2 - Which do you personally think is the biggest challenge when designing for bamboo?

A second question which required a text response was, “Which do you personally think is the biggest challenge, when designing for bamboo?” This allowed for multiple words, or a statement to be added. In coding these responses, if more than one challenge was recorded these have been included in the results. Therefore, there are a total of 269 challenges recorded from 232 responses. The statements were grouped in themes which are listed in Figure 30 along with the proportion of responses containing each theme, broken down by whether the respondent was a professional, or student of architecture or another construction industry discipline.

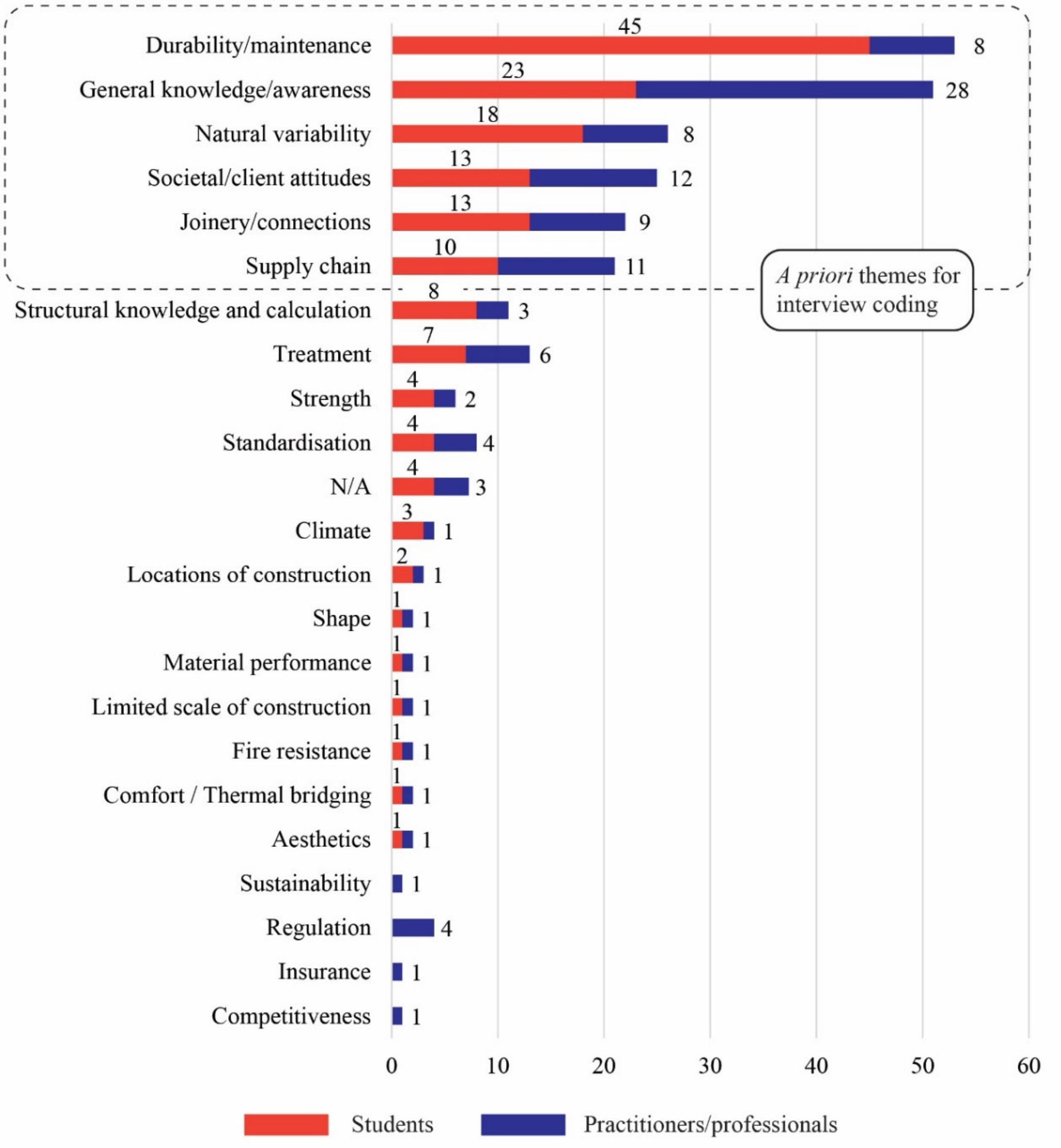


Figure 30: Consolidated themes with the number of responses broken down by students and practitioners/professionals.

The findings from Q2 (Figure 30) highlight a division between students and professionals/practitioners concerning their perceived primary challenges to design for bamboo. Professionals/practitioners primarily identified a lack of industry knowledge as the major challenge, possibly due to their higher exposure to the realities of the construction field. The hypothesis gains support from the sole professional identification of regulation issues. This stands in contrast to students who emphasised durability and maintenance challenges. This could be that many student respondents were attendees to workshops which discussed bamboo. Even though it was ensured surveys were completed prior to any workshop commencing (and information on bamboo being presented), their attendance alone indicates positive response bias which may include some knowledge of bamboo. However, with practitioners/professionals a positive response bias cannot be ruled out. Notably, more European-based professionals might explain their lower concern for durability due to less familiarity with the environmental realities of bamboo growing regions. However, confirming this is difficult as the demographic data collected cannot confirm the geographic background of respondents, only where they currently work or study. Even with just eight design professional responses, durability remains within one of the top challenges identified by practitioners/professionals. While surveys effectively spot trends, they lack the ability to explain. To delve deeper, engaging bamboo-experienced professionals through qualitative interviews seems promising to understand the "Why?" behind these attitudes, including the positive response from Q1. The analysis of survey outcomes reveals distinct thematic patterns, serving as a priori themes for qualitative interview coding. A full list of original responses to Q2 along with their thematic categorisation is shown in Appendix H.

2.4 Professional and societal attitudes: Qualitative interviews

The results from Q1 and Q2 in the survey show that there are some clear trends and have identified strong attitudes. However, these surveys prove limited to investigate the reasons behind these attitudes. Qualitative interviews can take this further and examine individual experience in depth (King et al., 2019). Additionally, by understanding the reasons behind these attitudes, through another methodology such as interviews, it could also be possible to gain insight into how such attitudes have been addressed for projects involving bamboo. Therefore, qualitative interviews were selected to be used with those working in the field of bamboo design, construction and architectural education. The choice of this method was also influenced by the experiences of the author prior to this research where conversations with those working in bamboo construction and the construction sectors of LMICs have provided personal accounts and much insight into this field of study. These interviews are from the point of view of those who work with bamboo, as opposed to end users or society in general. However, through documenting their encounters of working with students, clients, and end users, it is possible to learn from their observations, experiences, and how they have actively sought to engage with and understand societal attitudes through their work. Design professionals in this field can identify areas in which attitudes to bamboo can be engaged and perhaps leveraged.

The personal accounts from professionals in the field are profound to the base knowledge of the author prior to starting this research, additionally, the teaching experience of the author on the *AAVS Haiti* and associated community engagement group interviews. These implemented architectural models as visual aids to understand the attitudes of local residents toward bamboo housing. Such aids in architectural research interviews can be a primary mode of engagement (Lucas, 2016), as seen in the work of Lynch (1960) in *The Image of the City*, where city residents were asked to create maps of the cities in which they lived. These experiences highlight the importance and advantage of qualitative interviews over surveys to investigate underlying motives in a way that self-administered questionnaires cannot and allow for examination and theorisation of contextual effects (Robson, 2002; Yardley, 2017). This process of qualitative interviews to understand from design professionals a detailed examination of a personal lived experience, the meaning of that experience, and how participants make sense of that experience, can be defined as Interpretive Phenomenological Analysis (IPA) (Smith, 2011). IPA is generally idiographic, describing aspects of the social world by offering a detailed account of specific settings, processes or relationships (King et al., 2019). This study takes an idiographic approach in reporting the individual accounts of the interviewees to build a picture of attitudes to bamboo in construction.

2.4.1 Selection of interviewees

One challenge of qualitative interviews is a lack of standardisation which raises concerns of reliability and bias (Robson, 2002). As Trost (1986) explains, usually in quantitative studies a statistically representative sample of participants would be sought. However, the same is often not the case with qualitative studies. In qualitative interviews a sample with, “variations along the independent variables” is required (Trost, 1986, p. 55). This approach focuses on individual experiences, rather than seeking generalisable aspects across many cases (King et al., 2019). IPA challenges the traditional linear relationship between number of participants and value of research. Smith (2004) has argued the advantages of smaller samples and presents important guidance on how to conduct an IPA. Collins and Nicolson (2002) propose small sample sizes are the norm in IPA as the analysis of large data sets may result in the loss of "potentially subtle inflections of meaning" (p. 626). Reid et al. (2005) finds the mean number of participants involved in IPA research is 15. Smith et al. (1999) notes ten participants at the higher end of most recommendations for sample sizes with Turner et al. (2002) finding 12 participants created a data saturation point where no new themes emerged. In this research 14 participants took part in the present study into the lived experiences of engaging with societal attitudes to bamboo in design and construction.

When using qualitative interviews in architectural research, Lucas (2016) mentions two considerations. Firstly, architects may tend to present their work in as positive a light as possible, and second, there are aspects of a project that the design professional cannot answer; those which only long-term users can reveal. This is why it is good to have the end users' opinion of the buildings which they inhabit. However, this research focuses on the process of engagement and getting a project designed and constructed. In the case of end users, many may not in fact be the client or the body that invested in the project. This engagement with clients, suppliers, builders, regulatory bodies and end users is important. An understanding of the barriers faced at all aspects of a project from conception and funding through to construction and feedback from use is more likely able to be summarised by the design professional. The reported interviews are used together to define the challenges design professionals face when trying to design or build with bamboo.

In the selection of interviewees, persons within the author's own network of contacts to identify an initial list of approximately 20 interviewees that would represent the three disciplines within the fields of bamboo design and construction being investigated: engineering, architecture, and education, with approximately a third who would have experience of the Haiti context. Geographic diversity was considered, with a desire to provide voices of experience from the three continental regions where bamboo grows (Africa, Asia and the Americas) with a fourth being the specific locality of Haiti. Where gaps were identified, authors of research papers which showed the author had a perspective on the issue were contacted. In this selection of interviewees, it was apparent that the bamboo construction sector in Africa was conspicuously absent. As highlighted in Bystriakova et al. (2004), there is a lack of bamboo species diversity in Africa with only five naturally occurring species recorded on the continent, compared to 626 in China alone (Bystriakova et al., 2003). This could lead to fewer opportunities for design professionals to use bamboo in Africa compared to the Americas or Asia. Nonetheless, the role of bamboo as a locally available construction material does provide an opportunity in Africa for sustainable urbanisation (Bahru & Ding, 2021; Dalbiso & Nuramo, 2019; Tekpetey et al., 2020). As UNEP (2022) notes, the current lack of adequate housing across the continent, mixed with population increase will create a demand for new construction which has an opportunity to have a low carbon footprint and be adaptable to climate change. Table 6 summarises the professions, geographic location, and basic experience of each interviewee. To maintain confidentiality and maintain conciseness, each is identified hereafter by a letter. Two of the interviewees were also panel members of the Symposium discussed in Section 1.7.3. However, the only relationship of note prior to this study is Interviewee N, a co-supervisor of this research. Lastly, an attempt was made to select a group of interviewees that was approximately equally divided by gender, though gender has not been presented in Table 6.

Table 6: Interviewee profiles.

ID	Profession	Location	Experience
A	Architect and educator	Malaysia	Malaysian architect and educator who taught undergraduate architecture modules which required students to work with and learn about bamboo at a Malaysian university.
B	Architect and contractor	Malaysia	Malaysian architect and contractor who works with bamboo on projects in Malaysia.
C	Structural engineer	UK	UK based structural engineer with experience working with bamboo in El Salvador, Colombia, Ecuador, India and Bangladesh. Co-author of ISO 22156:2021.
D	Architect	Malaysia	Malaysian architect who has worked on projects which use bamboo in Malaysia and the Philippines.
E	Structural engineer	Costa Rica	Costa Rican structural engineer who works with projects utilising bamboo in Costa Rica.
F	Structural engineer	Ethiopia	Ethiopian engineer and educator who has worked on numerous construction projects using bamboo in Ethiopia.
G	Architect	Haiti	Haitian architect working in practice in Port au Prince, Haiti.
H	Urban designer and architect	Haiti	Haitian architect and urban designer, based in Haiti who has worked for Haitian government agencies.
J	Agronomist	Benin	Beninese agronomist and forestry scientist based in Belgium, with experience of the bamboo sector in Benin.
K	Architect	Colombia/Italy /China	Colombian/Italian architect who specialises in bamboo construction practicing in Italy since 2004 with numerous projects involving bamboo in Italy and China.

L	Structural engineer	Colombia/UK	Colombian structural engineer and educator who has worked in practice in Colombia and the UK. Co-author of ISO 22156:2021.
M	Structural engineer	Haiti	Recently graduated structural engineer, head of a bamboo construction advocacy and reforestation NGO, based in Haiti and former student of the AA Haiti Visiting School.
N[8]	Structural engineer	USA	Structural engineer and educator based in the USA with extensive publications and research with bamboo in construction; lead author of ISO 22156:2021.
P	Architect	Haiti	Haitian architect working for Haitian architecture practices and overseas NGOs on projects in Haiti, currently based in Canada. Tutored alongside the author on numerous AA Haiti Visiting School workshops from 2016 to 2017.

2.4.2 Interview methodology

Qualitative interviews can be categorised by the degree of structure in the interview which can range from fully structured with predetermined questions, semi-structured where the question order can be modified mid-interview, and unstructured interviews where the interviewer guides a general interest, but lets the conversation develop (Robson, 2002). Lucas (2016) suggests in an unstructured interview that the interviewer must be well informed about the topic to be able to respond and react to the interviewee.

The interview requires adequate time and there needs to be a clear procedure established to ensure that the interviewer can gather information. Although it is the responsibility of the interviewer to manage the interview duration and ensure it does not overrun (Robson, 2002), they must also get the interviewees to talk freely and openly. To facilitate this, Robson (2002) suggests that the interviewer should listen more than speaking, put questions in a straightforward and non-threatening way, eliminate cues which lead interviewees to respond in a particular way, and the interviewer should enjoy it.

Hoinville and Jowell (1978) list types of questions and actions which should be avoided in research which are either difficult to ask, difficult to answer or which invite distortion. These

[8] In the interest of full disclosure, interviewee N is a co-supervisor of this research.

include catch-all questions, long questions and tongue-twisters, unfamiliar words or phrases, generalisations or abstractions, negatives, hypothetical questions, leading questions, and secondary questions. Hoinville and Jowell (1978) also stress the interviewer is a point of contact between the researcher (or research) and the public, which requires accuracy in the recording of answers.

The objective in this study is to record and analyse those informal conversations which have been so crucial in the author's personal experience to understand the use of bamboo in construction. Such conversations were of course unstructured, but the goal in this research is to use an interview style which provides a greater level of structure that can be used to encode the transcripts whilst maintaining informality and flexibility. Therefore, in this study, the interviews are a series of questions on the themes which emerged from the literature review and previously reported survey. These have been developed into semi structured interviews which in some cases ask probing questions and ask the interviewee to think out loud. Table 7 shows there are approximately twenty questions which provide a structure, yet the order or exact wording of each of the questions was altered depending on the prior responses of the interviewees. Just under half the questions are tailored for the interviewee (shown as italicised in Table 7) and probe the specific context and profession of the interviewee, with each interview lasting roughly one hour. The first ten questions were considered key questions; if the interview looked like it would overrun an hour, these were asked first.

Table 7: Examples of questions given to Interviewee A and B.

No.	Questions for Interviewee A	Questions for Interviewee B
1	I take it you are aware of the phrase, bamboo is the "poor man's timber", have you had first-hand experience of a similar attitude?	I take it you are aware of the phrase, bamboo is the "poor man's timber", have you had first-hand experience of a similar attitude?
2	What do you think is the perception in the profession and society in Malaysia?	What do you think is the perception in the profession and society in Malaysia?
3	How would you best address that [this perception] for housing?	How would you best address that [this perception] for housing?
4	How would you define the role of the architect in Malaysia?	How would you define the role of the architect in Malaysia?
5	*How effective is architectural education in shaping the architecture profession in Malaysia?*	How would you define the role of the architect in achieving the UN SGD 11 [Make cities and human settlements inclusive, safe, resilient and sustainable]?
6	*To what extent are architects able to affect the choice of materials in Malaysian construction?*	Can you see a lack of bamboo [used for construction] being a remnant of the colonial legacy?

7	*What was the biggest positive you experienced with the students when working with bamboo?*	Can you see bamboo playing a strong role in Malaysian urban mass housing?
8	What was the biggest negative?	How were the details [of bamboo construction forms] communicated? What dialogue was had with the contractors to design the joints?
9	How would you define the role of the architect in achieving the UN SGD 11 [Make cities and human settlements inclusive, safe, resilient and sustainable]?	What species have you used in your works and does this affect your design work?
10	Can you see a lack of bamboo [used for construction] being a remnant of the colonial legacy?	How do you approach the question of natural variability of bamboo in design and construction?
11	Can you see bamboo playing a strong role in Malaysian urban mass housing?	*Tanggam [traditional jointing technique used to put together the traditional Malaysian timber structures], does this term apply to bamboo too?*
12	How were the details [of bamboo construction forms] communicated? What dialogue was had with the contractors to design the joints?	*Does the availability of material affect your designs?*
13	What species have you used in your works and does this affect your design work?	*Who designs the details [of bamboo construction]? Are they drawn or deferred to the contractors?*
14	How do you approach the question of natural variability of bamboo in design and construction?	Where do you get your bamboo from? Do you work with the farmers?
15	*How has your own impression of bamboo changed over the two years you have been teaching?*	*How do you conduct engineering tests on bamboo?*
16	*What are the students' perceptions of bamboo when they start the course and how do these change over the course?*	*Do you consider yourself a bamboo architect? Do you think that name even exists?*
17	*Do you think there are opportunities for the students to use bamboo in their professional work?*	*Has any of your portfolio wanted to use bamboo but, in the end, you lost the argument to the contractor or client?*
18	*Have you seen bamboo used more in construction in recent years?*	*How do clients respond when you want to use bamboo?*
19	Where do you get your bamboo from? Do you work with the farmers?	*Have you overdesigned a bamboo building to compensate and ensure robustness given a lack of construction expertise?*
20	What are the challenges for the next generation of architects in Malaysia?	What are the challenges for the next generation of architects in Malaysia?

21	What would be the best next step in raising the profile of bamboo?	What would be the best next step in raising the profile of bamboo?
Italicised questions tailored to the specific interviewee.		

2.4.3 Methodology: Recording

The interviews began in January 2020 with face-to-face interviews during fieldwork in Malaysia. However not long after these first interviews the world was gripped by the effects of a global pandemic, COVID-19. As such, interviews were shifted to be conducted in a remote format, similar to that of Seitz (2016). In this study, to maintain privacy and to ensure intimate familiarity with the data, transcription of the audio component of the interviews was completed manually by the author. Finally, it is also the responsibility of the interviewer to obtain informed consent, and this was obtained. In quantitative research as Ramos (1989) explains, "data are for the most part numerically expressed and manipulated, whereas data in qualitative research are tapped for meaning in the verbal realm" (p. 60). It was therefore important to apply the principle of process consent interpreted from Ramos (1989) to better ensure interpretation and synthesis of the author, to correctly understand the meaning behind what had been said by the interviewee. Therefore, all interviewees were informed that they may correct the record and that they will have the opportunity to review and correct or redact interview transcripts prior to them being included in this PhD research and published material. However, this was rarely the case and where this took place it was to rephase a statement, but not alter the meaning.

2.4.4 Methodology: Coding and template analysis

To code the data from interviews a template style of analysis described in Crabtree and Miller (1992) was used. This is a form of generic thematic analysis which involves developing a coding template and refining it through close engagement with the data (King et al., 2019). This type of analysis and coding template allows the researcher to define some a priori themes before the transcripts are coded. This is presented in a coding template. It is applied but can record other themes through the review of the interview data. A priori themes are quite easy to determine for a small group of interviewees who all are from a similar background or profession such as in this study. A priori themes may relate to important theoretical concepts or perspectives that have informed the design and aims of the study, or to practical concerns such as evaluation criteria that the researcher is to address (King et al., 2019). In this study, the a priori themes are those described previously as having emerged from the survey results in Sections 2.3.4 and 2.3.5. Societal attitudes was identified (Figure 30), however, this has been removed as an a priori theme since societal attitudes to bamboo has already been established as this basis of this research and the use of interviews is to investigate these challenges and source of these attitudes in more detail. The a priori themes are listed below. The first theme is to record the positive impression of the use of bamboo in construction identified in Figure 28:

1. Sustainability: Leveraging sustainability and environmental impact credentials of bamboo as an opportunity to encourage greater use.

Secondly, five dominant knowledge gaps identified in Figure 30, and therefore perceived challenges:

2. Lack of material knowledge
3. Durability
4. Natural variability
5. Joinery and connections
6. Supply chain

Finally, for understanding of the LMIC context where a design approach should be applicable a seventh theme was added:

7. Haiti specific comments which relate to material culture in the construction sector.

In addition to these a priori themes, other themes may emerge throughout the coding of the interview data, these are discussed in Section 2.4.12.

2.4.5 Results: Sustainability

One of the main drivers for bamboo being considered on any project is the environmental benefits of using bamboo. This is highlighted in Figure 28. When speaking to Interviewee B, it was clear that bamboo was considered on a project they were involved with due to the perceived environmental credentials of the material:

> Finding sustainable materials to work with, sustainable methodologies were always up there in the priority. So bamboo, when I found out more about bamboo and how it's actually contributing to sustainability and mitigation of climate change then it sparked an interest. [B]

Interviewee N who researches bamboo, recognises this perception of the environmental potential of bamboo:

> I always joke that if we could get Brad Pitt to build a bamboo home we would be set. It's about status. So concrete is more expensive and masonry is more expensive and therefore it represents the status…Sustainability has a certain cache…you may have a bamboo flooring because it is perceived as being green. Whether it is or not is another story. So I think the impression, the cache, we are slowly moving away from is putting up something which shows 'I am wealthy', to something which shows 'I am green'. [N]

The phrase, "Whether it is or not is another story" is important, implying the application of the term greenwashing. This term is defined as "falsely representing a person, company, product, etc., as being environmentally responsible; to misrepresent (a company, its operations, etc.) as environmentally responsible" (OED, 2023b). When the appropriate information is sought, full-culm bamboo, particularly when used locally, can have significant environmental benefits over manufactured materials. However, it is not appropriate to make blanket claims for the sustainability credentials of bamboo (this is discussed in Section 6.2.1 as a future research need). CO_2 absorption by a bamboo plant is affected by many factors, and the transportation of bamboo to a site will add GHG emissions to the embodied carbon of a construction project using bamboo (Liese, 2009; Lou et al., 2010; Yuen et al., 2017; Zea Escamilla & Habert, 2014; Zea Escamilla et al., 2018). As noted by Interviewee C, augmenting a construction industry where widespread knowledge of building with concrete and steel would need to be changed is a challenge in its own right. Although bamboo and timber could serve as carbon sinks (Churkina et al., 2020), both Pomponi et al. (2020) and Interviewee C emphasise that various factors need to be considered:

> There are still emissions with timber and we still haven't worked out how we can recycle timber at the end. It's the same with bamboo, I don't think it is a simple fix to the solution. Each material has its own problems and timber and bamboo aren't the perfect solution either…what are the whole life cycles of both, and what are the easy wins one can do? We'll probably find timber still wins, but timber definitely isn't as perfect as some people make out; and the same with bamboo. There are still questions about the connections, you will use steel, and you will still use concrete for the foundations. Maybe it is a lot better I don't know but I would want to see the big picture first…there are a lot of exaggerations and a lot of fake news in there. In the

next few years this will unravel and it will be clearer. My gut feeling is timber and bamboo will be a lot better but what I would like to see is that picture. [C]

Students and educators in architecture in bamboo growing regions are also pushing an agenda of sustainability in which bamboo features, as Interviewee A outlines when describing why bamboo was chosen for an undergraduate university module:

> Well, on a personal level it was because I feel that we need to somehow whatever is within our authority and power, we have to, you know, push to make education or introduce sustainability in education as much as we can…there is only so much sand, cement, concrete, glass and steel you can use before it becomes hazardous to the environment. So what is the alternative for a person who lives in a tropical country, bamboo obviously. [A]

This sentiment was also felt by the students that Interviewee A taught, and are noted with local architecture and engineering students in Panama, Indonesia, Myanmar and Haiti from the author's experience. Bamboo potentially represents a local alternative to imported materials which are susceptible to external currency fluctuations and damaging to the environment. One such student was M who went on to start up an NGO in Haiti to advocate for reforestation and construction with local Haitian bamboo. They explained that for many in Haiti there was a direct link between using bamboo and environmental regeneration, and linking the two can garner support for planting the material:

> We can use the bamboo to address landslides[9] in Haiti. As you know Haiti is a mountainous country, and we have a serious landslide problem. So they [local communities] invite me to connect bamboo as a solution to different problems in the community. When I go, I first present the bamboo, and go specific to the problem of the community and see how bamboo can be a solution for them. [M]

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[9] The author cautions that the use of bamboo plantation as a means of mitigating landslides is by no means universal. While the rhizome structure of some species may be appropriate to the purpose, other species may exacerbate the potential for landslides by creating a 'weak slip plane' just below the soil surface. Planting alongside deep rooted plants such as vetiver grass, can be good practice.

There may be a direct link to some between planting bamboo and ecological regeneration. However, when it comes to clients, it is not surprising that in Haiti (as discussed in Section 1.7.6) the notion of sustainability would not be as high on the agenda as other items, predominantly cost or value. This mirrors the same relegation of sustainability seen in the Global North. Without the enforcement of environmental standards, or policies (e.g., YM, 2023) it is doubtful the environmental benefits of bamboo will ever be the primary driver for choosing bamboo on a construction project. As H explains:

> If your client already has this sensibility [sustainability] the client will ask that their project includes this sensibility. If your client does not have this sensibility, there's education that you have to do and gear your client towards some choices and not others. Because here [Haiti] we are living in a country of scarcity, it's probably going to be your only client for the year, and professionals are trying to avoid those conversations that make you lose a project. [H]

H however suggests a means by which this sensibility can be imparted:

> There are things that we don't do enough. I try to find resources so we do it more, so it becomes a public conversation. The idea of having awards for a project. I think at least every two years we need to have awards for a best project in architecture, and best project in engineering, best sustainable construction project. Somehow to put it on the table like it is a conversation, so it is celebrated, the person who did it is celebrated, and the person who paid for it is celebrated too. Otherwise the conversation will never happen…If we don't do that, we can't move the debate in one direction or another and you need to find ways to move the debate. Right now it is blocked somehow because the decisions we make are so intimate. [H]

It seems sustainability is a key opportunity to develop bamboo use. Bamboo is only sustainable if the bamboo has a long service life, and in the author's experience, 100 plus years old *bahareque* housing, has been observed. Ensuring sustainability requires the design professional to do local research, ask the correct questions of treatment, sourcing and transportation, and design in a way to ensure as long a service life as possible. In locations such as Haiti, however, it seems sustainability will not be the main driver to develop bamboo use. In such LMIC contexts cost and value will be the main consideration not sustainability. Therefore, more data is needed on bamboo for some contexts, but other challenges need to be overcome for sustainability. It seems without government mandates, the opportunities presented by bamboo to be sustainable, will not drive bamboo use unless the other challenges are overcome first. These are studied in the following sections.

2.4.6 Results: Lack of knowledge of bamboo

This drive to use a material with perceived environmental benefits is so powerful that it can drive design professionals forward without properly considering the challenges of the material. This can be both naïve enthusiasm, or in some cases can be termed *greenwashing* through the use of bamboo, as described by Interviewee B:

> Within the architecture profession I think most people like the idea of bamboo but they don't go much deeper than designing something with a bamboo texture. They don't realize the challenges, cost implications, maintenance, how to design for it…When we mention bamboo, people who know bamboo would say yeah it is very sustainable, localised, so all these are very romantic notions. No one really wants to spend the time to know the material and design with it. [B]

The lack of construction industry knowledge was highlighted by Interviewee F, who adjusts the design stages of a project in order to accommodate this knowledge gap:

> When it comes to detailed design you do the design halfway. You put some guidelines as to how to put up bamboo, how to connect it, what considerations to take into account when you do the actual construction. So you put the guidelines but the job will only be complete when you do the work. So even what type of connection to use…So all these details would be actually decided upon at the actual construction work. [F]

Interviewee B noted the lack of construction expertise and the need to bring in expertise from elsewhere and how this would change the original design:

> We hired a bunch of Bandung bamboo craftsmen and they came from a very rigid framework…we just told them, this is the rough shape; this is the rough design, is this possible? They would say, 'Oh this part no, this part no'…We fell into their mould of design. [B]

Therefore, the design was taken to a certain conceptual level by the design professional, but the detailed design of the connections was done by the craftsmen. This can be a risk to the project, but Interviewee B identified this dependency as a business risk as well. Interviewee K also noted the lack of construction industry knowledge during the construction process, but highlights the ability of a project to be used to change attitudes and develop knowledge in the construction industry:

> The engineer [and also constructor] said that my project was the last one built because he thought it was kind of different and was not very easy to build, he thought. Then after when he started building it…we met in his office and we did some brainstorming about some questions…he was very impressed of the way of using bamboo in a contemporary way. He said he had never thought that bamboo could be contemporary…it was really interesting because he said that he understood how bamboo behaves whilst building [the structure]. [K]

This shows a lack of knowledge prevents contractors from engaging with the material. Anything unknown presents a risk to programme and cost for widespread bamboo use. Interviewee E noted a lack of knowledge in the construction sector as the biggest challenge:

> The biggest challenge for me is the people who work with bamboo, the artisans and the workers. We don't have this culture of bamboo in the construction sector, so most builders know how to work with wood and concrete but don't know how to work with bamboo. So I think this is the biggest challenge: we don't have the right handcraft technique to do that, in terms of construction. It is important to mention that over the years, some people have been acquiring abilities. [E]

Interviewee L noted the specialised nature of the construction and the lack of widespread knowledge present, with specific experience of the Colombian context:

> Yes. You have specialised construction. Let's say in a concrete building you can hire the concrete to be mixed and delivered and you will have a team of people who are experts in casting the concrete and making a slab and all of that. In bamboo construction I guess, it is difficult to say, you end up doing a lot of the design and building. So yeh, you take on more roles than you would take in other parts of the world. You take on the design concept all the way to the construction and hand over of the entire house. That is the situation in many cases. [L]

This means that the additional work, if not paid, can be a barrier to design professionals pursuing bamboo. To fill this knowledge gap, the introduction of the design standard for full-culm bamboo is a major step forward to provide design information. Though, there is still a challenge faced by a lack of construction industry information. ISO 22156 (2021) is an engineering code aimed at structural engineers; there are perceived differences between how a design professional and structural engineer may use the code. Therefore as Interview N notes, this lack of knowledge has impacted the conservativeness of the code:

> We [the engineering community] are ‘belt and suspenders’ people, so we tend to err on the conservative side. We need to have the user [of the code document] to have a certain level of expertise in order to use it correctly, or we dumb it down so much that we cannot use it. Or it’s remarkably conservative so it’s not possible to use. [N]

The interviewees so far have mostly explained a lack of construction knowledge in contractors or builders. However, a lack of knowledge in design professional awareness is hard to gauge through interviews with those who already have some experience of working with bamboo. What is evident is that the interviewees note that to design for bamboo requires a different approach than standardised manufactured materials. The need for material knowledge when designing for bamboo is also important and it is apparent that a design process that incorporates materiality is important. Contrary to mainstream architectural design *form-making* and *massing studies* (which are investigated in Section 4.2), those who work with bamboo document the use of design tools which allow for interaction and understanding of the material. A greater emphasis on physical model making and when digital tools are used, they are used in conjunction with other design tools, such as Interviewee L who reveals:

> [We] designed using *Archicad* in 3D and showed and printed models and plans for my clients and team, but physical models were the preferred tool for builders to understand the whole ‘concept’. For details of connections, they would have looked at the printed copies. [L]

Only one of the interviewees noted that their design process remained the same when designing for bamboo compared to other materials. All other interviewees referred to a need to adapt and respond to the characteristics of the material whether that be the eccentricities of the material itself, or the challenges presented by durability, joinery and a lack of construction knowledge from construction professionals. Interviewee A noted that pole is unique, and that “material itself informs and contributes to the uniqueness of the design process.” Interview L recalled “it was common to have to modify the design during construction despite having a detailed structural design that met the standards.”

It seems like designing for bamboo requires a consideration of both form and material considerations, the ability to think about different scales, or aspects of the projects in parallel even when one may impact the other. When thinking spatially of a design there is the need to consider the material, more so than would be the case through design for manufactured materials. The challenge in this is also how and when these lines of thought merge into the one design concept. The need to adapt throughout the design process and even on the construction site is a key theme with bamboo and embracing adaptability.

All interviewees noted some experience that related to a lack of construction industry awareness of bamboo. The impact of the lack of knowledge can be the implementation of bad practices. A lack of design experience can impact durability and the ease of maintenance. A lack of construction expertise can affect the project programme and cost. A lack of knowledge is evident but covers such a big scope, it needs to be refined. In fact, this a priori theme has only posed a question. Within the scope of a design professional's services, what aspect of knowledge do design professionals need support with?

2.4.7 Results: Durability

When asked what is the most commented on negative aspect of building with bamboo in their experience, Interviewee L suggests:

> Well there are different barriers. Firstly, in the places where bamboo grows, it is considered a temporary option, or a transitional material, whilst people save the funds or money to build their concrete and brick house. [L]

Colombia, where L is commenting on their experience, is a location in which a bamboo design standard NSR-10 (2010) exists, and bamboo is more widely used in a codified manner, than in comparable bamboo growing regions. Even in Colombia, however, there are examples where bamboo is exposed to sunlight and driving rain in a structure which can affect durability and in effect make it temporary. L was asked why architects and engineers may be designing bamboo in this manner:

> Many times it is the request of the client. So here I am talking about middle class or high income clients, who wanted the material to be exposed and [to] be seen. So, on some occasions we had to leave the bamboo exposed and make sure that we had enough material internally to make sure we had no structural failures from the material we knew would deteriorate and was not a good practice to leave exposed…It is that contrasting position. High income clients want to see the material, but the lower income they cover the bamboo…[lower income clients] want buildings that look like

> urban buildings, modern buildings. Modern, is one of the words that was used. So, they saw that look of bamboo was more traditional and old. [L]

Interviewee B referred to the fact that bamboo had produced problems with clients in the past. After initially proceeding based on the positive aspects of sustainability and cost, "[the bamboo] just created more problems than it could solve" explaining that bamboo is not just perceived as "a poor man's timber", but that it is seen as "just problematic." In a follow up question, B was asked whether durability was the main reason why bamboo was seen as being problematic:

> How they seal the seams, the cracks…the dust from powderpost beetles and stuff creates a huge housekeeping nightmare. So generally, in that market [in Malaysia] I think the reputation of bamboo is not good. [B]

Interviewee B explained that this was due to the material quality. It was commented that the material was sourced from rural areas of Malaysia where local communities would treat the bamboo by, "chucking the bamboo in the river", noting:

> There could be a case where if you let it soak in the river for long enough and if you harvest it the right way it could still be a viable treatment. It's just that I don't think the whole lot of them would actually do it properly. [B]

This lack of effective treatment resulted in negative perceptions towards the bamboo material. In addition to suitable design and use, material quality is important, and it is evident design professionals need to be aware of where material is being supplied from:

> We don't have a mature bamboo construction industry in Malaysia…you had to source from people who were not exactly very professional in terms of selective harvesting, quality control…30%-40% of the bamboo we sourced had to be rejected. [B]

It is important that bamboo is correctly seasoned and treated before being used in a structure. The design professional needs to be educated in assessing material quality and understanding what is a quality of bamboo that can be used to articulate the design:

> Even treatment was a steep learning curve for us I remember. It was hearsay. People would say, "Oh you treat it in 4% solution [of boric acid and borax in water] and treat it for seven days and that should be fine". But the reality is different species, different dryness, different thickness, all require different lengths of time for it to be fully

treated. So I remember the first batch even after the treatment we had lot of problems…with the powderpost beetles and pest infestation and that kind of stuff happening. [B]

These experiences are similar to those reported by interviewee C, who in their published work has recognised the perception of bamboo as a poor man's timber. Elaborating on this statement, it seems the durability and temporality of the material is key:

> There is a general feeling that I have got from communities because they understand that the bamboo generally is more susceptible to rot and insect attack than especially hardwood timbers. They do consider bamboo a poor man's material. [C]

C goes on to recall the experience of those living alongside bamboo and a knowledge of the local bamboo species:

> I was really impressed with the community's knowledge on durability. I asked about durability of different bamboo. Specifically, how long would bamboo last in different conditions? The results were fascinating. The bamboo sellers and the bamboo treatment workers grossly overstated what they considered to be the durability of bamboo, especially after treatment. Whereas the community was spot on, the community knew exactly how long they would last. I was really impressed by that. And then you can ask most engineers or architects who work in bamboo and they would get that wrong unfortunately. [C]

Firstly this identifies a knowledge gap in durability in design professionals that can be addressed through sharing correct information. Secondly, this experience shows that even though the informality of the sourcing of bamboo can be an issue, local knowledge of species is important and the design professional should therefore engage with those who are growing, selling, and using full-culm bamboo locally, which may be different persons. It is not just an understanding of the species as documented in literature, but an understanding of bamboo species as experienced where the bamboo is grown and used. An example of this is the authors own experience of *Bambusa vulgaris*. In Haiti *B. vulgaris* is the most common species but has a bad reputation for crookedness and poor durability. In Myanmar, however, *B. vulgaris* were much straighter, with a larger diameter and were the go-to construction species in the region[10]. This means the role of the design professional when designing for bamboo must extend to the sourcing of material and seeking local knowledge:

> So, the community seems to really understand the limitations of materials. They have learnt this through hundreds of years of building houses themselves and seeing houses collapse, and they know. It is a modern problem, and we [persons from outside the community] are going in and we are actually forcing knowledge and designs which is incorrect on communities who already know, but of course they are going to listen to a foreigner coming in, because they tend to believe what foreigners say. [C]

This point was discussed previously as being emblematic of *Western centric* or *colonial* attitudes and therefore important to record. Interviewee C agrees that these experiences cause a negative perception in the long term:

> I saw this in Latin America. In Costa Rica, the houses that I saw from the National Bamboo project…about 10% had suffered severe termite attack and that was because the [bamboo] had been poorly graded and there had been flooding in that region…The houses that had [experienced termite attack] the people said, “I don’t like bamboo”. All the other houses, people said “I really like bamboo”. [C]

Given the durability issues with the bamboo, a follow-up question asked after the most common errors made by design professionals:

> The biggest issue probably is when a structure is fully exposed to driving rain and sun. The combination of those will deteriorate [bamboo] very quickly. The second issue I would say is the buildings have not been properly considered for wind or earthquake loads and lacking [adequate] bracing and walls…durability issues are the biggest one but the lack of good engineering input is definitely a problem unfortunately. [C]

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[10] It must be acknowledged that there remain many inconsistencies in bamboo taxonomy and the two types of *B. vulgaris*, referred to may be different cultivars or, indeed, different species or even genus altogether. see: https://www.cabidigitallibrary.org/doi/10.1079/cabicompendium.8398.

Interviewee C agrees that many design professionals are designing bamboo structures without considering the material and how to ensure the design protects the bamboo from the environment:

> The problem is that a lot of materials have big weaknesses and those weaknesses are not taught in general…Especially with new materials, there is a lot of over-promotion of the material which can be detrimental, particularly with bamboo. Saying amazing things about it which aren't true or exaggerating certain properties…I think durability is unfortunately quite a big one there. [C]

Asked if they think there is less scrutiny of bad designs with bamboo compared to concrete and steel, C thinks it is about the same. Durability is also a clear reason why C thinks bamboo will not be used in urban housing in tropical LMICs. Asked whether there are any myths about bamboo that make life difficult, Interviewee C points out the following, "Well 'bamboo is stronger than steel', 'bamboo can be used in reinforced concrete', 'bamboo can be used outside once treated'."

These issues are myths that must be dispelled. It is apparent that the principles of designing for durability: protecting bamboo members in a structure from the rain, sun and the ground, are principles design professionals should prioritise:

> It's quite black and white, bamboo can be used where bamboo can be used. So, carpenters and architects and others can interpret that. We have described when and where bamboo can be used [in ISO 22156 (2021)]. So, not in contact with the ground, but it can be used outside but protected from UV and driving rain. When it's external, above ground but not protected from weathering, we had a big discussion and ended up putting a clause in which says bamboo can be used here if there is a design life of less than 5 years. So basically, we are saying permanent structures have to be constructed in a way where the bamboo is fully protected from driving rain and UV. [C]

A lack of awareness and knowledge of bamboo construction in the construction industry and of the requirements of the material emerges in the practical experience in Costa Rica of Interviewee E. Interviewee E explains that this lack of knowledge manifests as bad quality material being used in construction, which impacts durability:

> We don't have the correct hand-craft technique to do that [to use in construction]…In

> terms of the structure and in terms of the material, for me the quality of the material is not always the best. Because we don't have the quality check list…if I don't do the inspection, then the builders don't know how to qualify the material, so it is like a learning process…I think the quality of the material and the capacity of the workers are the biggest challenges right now. [E]

These issues with the lack of quality control of the bamboo material cause problems on projects:

> I got to a project and I found one of the culms, has a lot of insects inside. And it had been there less than one year. That is frustrating because if you are trying to make the cultural change, not just the technical, and you go to a project and the client sees that kind of experience with bamboo, and the worker says, "No! Bamboo is only for temporary structures!" [E]

Working in this field in Costa Rica is an interesting context for those wishing to work with bamboo. Costa Rica established a promising project to drive bamboo cultivation and construction nationally (Gutiérrez et al., 1993; Gutiérrez, 2000). Commencing in 1987, *The National Bamboo Project of Costa Rica* was based around: construction (760 demonstration bamboo houses in 38 rural communities nation-wide), cultivation (700 ha of *G. angustifolia*), and education (over 1000 professionals, technicians and family elders in methods of cultivation, production and preservation of bamboo) (Gutiérrez et al., 1993; Janssen, 1995). Interviewee E was asked about their experiences of these projects and if people still lived in these houses today. Interviewee E explained that in some cases occupants, "pulled down these bahareque houses and built a new [concrete] pre-fab social house." The main reason for this was the rain in Costa Rica, paraphrasing a comment from residents, "Oh with the bamboo with the rain! The rain will come and it's better to build a new house, after we have problems with the bamboo and bahareque." It was apparent that the opinion was that these houses are more susceptible to degradation due to moisture from rain than a concrete house:

> The humidity and all these things and I think this is the biggest fear of the people who work with bamboo, it is the weather situation, and that is the reasons that we have started to use bamboo as a combined material with wood, with concrete. [E]

The similar experience of bamboo perceived as a temporary material was reported by J who recounted experiences of bamboo's perception in Benin:

> It is something which can be used for a short-term utility. If we have a short-term need, or temporary construction then we can use bamboo. But if we plan for long lasting construction, for instance, people really feel bamboo is not strong enough. Bamboo is not resistant enough. Compared to trees…So to sum up, for temporary constructions then bamboo can be used, but when they think for long lasting constructions, bamboo is no longer considered. [J]

Like many bamboo growing regions and tropical LMICs, deforestation is a major issue in Benin. This has resulted in a switch from species of timber that were once used in construction to inferior species. It is apparent however that this shortage of high-quality timber will not necessarily mean a switch to bamboo:

> They [the Beninese population who live in proximity to bamboo] just believe that the bamboo is not durable, is not strong enough and they cannot make furniture with it. So for long lasting construction, they do not really feel bamboo is interesting for them, compared to acacia [wood]. [J]

This attitude that bamboo will not last in a structure was also the main message in a conversation with Interviewee D who designs with bamboo. This conversation opened by asking why Malaysia does not have a greater history of using bamboo in construction; ironic given that the word *bamboo* is thought to come from the Malay language (Harper, 2023; OED, 2023a). Interviewee D indicates that there has been “fear” in clients of the durability of bamboo:

> The same fear they [clients] have with timber buildings. The first thing people think about with timber buildings are termites, It’s the problem of no treatment standards, and no proper regulation perhaps. With timber and bamboo if you treat it properly it should not be a problem at all. [D]

This again reinforces durability as a major issue for bamboo in construction:

> There is this fear that you are going to build something which is not going to last, if you build out of bamboo especially. Then there is this worry of a regression of lifestyle. We don’t want to go back to living in a bamboo hut, or a kampong [traditional Malay village] house…our first proposal [for a local community centre] was bamboo, even though the client did not ask for it, and they saw it and within a minute they stated they did not want bamboo for this project. They want something

> modern, sleek and in line with their ethos as property developers in Malaysia. I suppose it is seen as going back to the past, in using such material, which does not make much sense. [D]

Firstly, this touches on a feeling that bamboo is not *Modern* in Malaysia. Interviewee D also highlights that durability is the key concern for clients that D has worked with, "Oh yes, durability was the first thing, but I could sense it was not something they were willing to explore." Their experience of bamboo on a high-profile project in Kuala Lumpur showed the challenges for design professionals to ensure quality of the material, even if the design of the building protects the bamboo from the rain and the sun:

> They cut it [full-culm bamboo] and brought it back to the workshop and started cleaning it with sand and water. It was then treated by being immersed in a concrete tank using boron and boric acid, and since we could not be there every day to check they treated this for a week, dried and then sent to the site. I was already worried that the structure may not last for too long, as the client had requested a life of 10 years. So, I was worried about insect attacks, so I said to the contractor that we needed to have all the bamboo which was sent to the site tested…[they] found that…the treatment had not been done properly. So, I had to reject the whole lorry load of bamboo. So, we had to wait another five to six months. So, the project was meant to finish in three to four months and it took a year and a half. [D]

It is apparent that the design professional has a role to play in making sure the bamboo is protected from the rain and the sun, and not in contact with the ground. However, the quality of the material and the quality of construction are outside the usual scope of a design professional, but important considerations when it comes to structures with full-culm bamboo. As interviewee D continues:

> You need to protect the bamboo from the sun and the rain to make it last, and what we found was that the handrails which are smaller and they are now deteriorating quite badly. They have been changed already once over, and they are due for another change. These are the parts which are exposed, and they are small and younger in age. [D]

This protection from environmental factors is also important even when the poles are stored onsite:

> The second batch which was sent to site looks beautiful. It looks dry. Two weeks after, it is placed on site and we had not even fixed it and it started to crack. It was so worrying. The contractor on site said they could hear it popping. It just cracking under the sun. [D]

The experience of interviewee F is similar. They explain the reasons why bamboo has a negative stigma attached to it is again inappropriate locations that the bamboo is used where there is no protection from driving rain and sunlight:

> I think it is mainly because of the wrong uses of bamboo. So you can see that bamboo is exposed to moisture, and ultra violet rays. It would deteriorate [more] quickly than most others materials used for construction purposes. For example in Ethiopia we use eucalyptus, we extensively use eucalyptus. So without any further treatment, without any chemical treatment whatsoever you can use eucalyptus for 20 plus years, even more than this 30 to 40 years. So they compare bamboo to this material. If it is not protected then it would damage very quickly, so I think they have basis when they say it is poor man’s timber, because whatever you construct or build using bamboo, is only for a temporary purpose. Furniture for a few years, building for just a few years. So I think it is on this basis when they say it is the poor man’s timber. [F]

It is interesting that even compared to other minimally processed bio-based materials such as timber, bamboo has a negative relative perception. To change the perception as a poor man’s timber, Interviewee F highlights the subject of durability again as the key factor:

> To build buildings that are more durable than what has been practiced. So we can do that. If we have exemplary buildings and exemplary products then we can show the society. We can produce products, or we can construct buildings that are as durable as those products and buildings built and produced. So for example, you can produce products, and then you can give them for free. For some people in the community so that they can go there and see these products, for example, if it is furniture, how it's performing, or something like that. You can use that as a showcase so you can somehow gradually change the perceptions of the people. The same is true with buildings. You can build exemplary buildings in big cities. You can allow people to use them. If it's a residential building for free for a few years, something like that, so that you can show to others that you can produce durable buildings using bamboo. So you can do that. I think this should be, or probably could be, the best approach to

> change their own perceptions that people have on bamboo. [F]

In recent years, however, there have been significant pushes to provide information that can be used by construction industry professionals to ensure that the bamboo is correctly graded, to improve material quality, and to ensure a design is durable. These include the promulgation of ISO 19624:2018, ISO 22157:2019 and ISO 22156:2021. ISO 19624 provides means and methods for grading bamboo material; ISO 22157 specifies means of obtaining material and mechanical properties of bamboo (i.e., test methods) and ISO 22156 is a design standard for full-culm bamboo. This includes design requirements for addressing durability within its Clause 5 and further guidance in Annex B. As Interviewee N explains:

> [ISO 22156 (2021)] looks more like a design code than the 2004 version. We have had a problem with durability and since it is a code document we have had to use words like 'shall'. But we've found ways around that to get good guidance in there…Durability is a good example of non-mandatory information. For example for concrete we can [specify details ensuring durability]. We can specify covers or certain mix designs. [N]

Interviewee N noted a lack of data for bamboo is shown as a challenge for durability and providing clear guidance to design professionals, but noted the importance of considering the site of the bamboo structure and how this can impact durability:

> One of the problems of bamboo and durability is that we do not have a lot of data…It's only going to crack if the moisture content falls below the moisture content the bamboo was at while it was being cured…The good thing about bamboo is that it needs to be used locally. It is inefficient to move it significant distances. So generally a lot of the problems that I may see from drying issues are not going to be an issue when you are using the bamboo locally and was harvested locally and is used in local conditions. [N]

In many cases design professionals need to be involved in this harvesting or at least in the supply chain to ensure material quality. Interviewee K notes this as well as the fact design professionals for bamboo are often referred to as "bamboo architects", in contrast to how architects who use concrete and steel are often simply "architects":

> It means that you are different. That you are exotic. That actually you stand up from your computer and you go to a forest. Working with bamboo you have to meet the

> material. With other materials you just have to order a catalogue. So it is quite different. [K]

This indicates, as with previous interviewees, that design is only part of the challenge to ensure durability in a bamboo structure. The design professional needs a knowledge of the material and also to be involved somewhat in the sourcing of the material. However, in the design itself there are also factors to consider that design professionals without knowledge of bamboo may overlook. As well as protecting the bamboo from insects, driving rain or UV light, that the design needs to afford, the design should consider replacement of members. If the bamboo pole is damaged or degrades in a structure it can be easily replaced. This will ensure a longer service life of the building. This is a design paradigm reinforced within ISO 22156 (2021), which is *design for replacement*:

> It is like a car. I think it is more modern to have a house that you can take care of like a car. You can change the parts when you need to change them and take care of them. This house can last for a very long time if you take care of it, if you don't take care of it, it will last less. [K]

K is discussing design for replacement and adaptability, a way of designing which allows damaged elements to be replaced when required. This decouples the service life of the material and the individual building elements from the service life of the building.

Interviewee A only began working with bamboo when they established a module for undergraduate students, Interviewee A's perception of the material prior to embarking on this pedagogical journey was explored. It seems that their initial perception of bamboo as temporary aligned with the other perceptions of the material as a poor man's timber, due to durability, but highlights the need to consider maintenance to counter this:

> I think one of the myths, is that you can't build anything lasting with bamboo, but after going through a lot of literature and seeing a lot of buildings which had been built with bamboo, it was just a matter of the method of maintenance which is different to a building built with cement and concrete. [A]

The access to good quality material was the biggest negative from the experience, and again reinforces the need for the design professional to be aware of material quality and involved in sourcing:

> So, the bamboo came and it was not fully treated. It came in many sizes, so it was a bit

> hard to work with because we had already had models to work with. But when we received the bamboo to build the one-to-one scale structure, the model had to be modified to fit with whatever bamboo we got from whichever supplier we ordered from…there are not that many suppliers who can provide the quantity of bamboo we were ordering. So they were trying to meet the demands where we were ordering by tonnes. So they may have even been giving us some green bamboo that had not been fully cured. [A]

Most interviewees noted durability as the biggest challenge and reason why bamboo is perceived as a poor man's timber. Experiences of the interviewees show this is a major issue, but one in which the designer of the bamboo structure has a big role to play in, when this is achieved correctly bamboo can be used for permanent structures. At this stage in the interview coding, it is clear that there are two issues associated with durability: (1) the quality of the material and how the material may decay in a structure over time through exposure to environmental factors, and (2) the quality of the workmanship including available construction knowledge and awareness of joinery techniques.

2.4.8 Results: Natural variability

Interviewee L noted the experiences with natural variability in the design and construction of bamboo structures:

> You design to an average or characteristic value, but when you get the pieces of bamboo that are lower or higher strength, we realised that in many cases we needed to put more elements than we needed. One other thing we had to do a lot was to be more selective in the type of material that we were using in construction. So yeh, redundancy is one, and selection is another, but that is during the construction process. [L]

In response to a question of the variability of full-culm bamboo, Interviewee F responded:

> The main problem is that bamboo is not a factory product. I would say it is impossible to find a uniform product. So, even in a culm as you know as you go from the lower part of the culm to the upper part, the diameter changes. So when you make connections, it's very difficult, especially if we're going to use it, unless you split it and convert it to some other form. [F]

The issue of natural variability also has an impact on construction time and joinery, as noted by Interviewee L. "When I was building with bamboo, natural variability was a hinderance, because again, I have a specialised team of bamboo builders…The irregularity [means] labour intensive work is required."

In the interviews the issues of natural variability did not come up as much as other themes. In addition to Interviewee L, Interviewees C and D noted that the challenge of natural variability of bamboo meant additional testing needed to be conducted in many cases which can be expensive and cumbersome. The variability of material quality and stock came up as part of the supply chain theme. It seems, however, that the issue of natural variability as pertaining to the use of bamboo in a structure can be addressed through redundancy and overdesign. The variabilities in the physical characteristics of the bamboo, such as the ovality of the culm, can cause issues with joinery and construction. In addition to the physical differences between culms, this highlights another important consideration. Given the variability of bamboo, changing a supplier may also be changing the physical and mechanical properties of the material used for a project. This is where grading comes into the design process. Switching a supplier for concrete will also change the material quality. However, a specification set by the design professional or contractor can render these differences of little consequence to the project. Awareness in the design professional for the material to be used can be crucial here and design professionals should also design in a way that can adapt to this change and can design in a way which allows the material to influence the final design; embracing change while not compromising the principles of the architectural design or functionality.

2.4.9 Results: Joinery and connections

In coding the interviews it is apparent that the joinery and connections is a documented knowledge gap. Some of the following interviewees were involved with the writing of ISO 22156 (2021) which provides insight into the current state of the codified knowledge in this area. Starting with the information from Interviewee N, connections were identified as the "weak spot" in knowledge of bamboo in construction. It is not just the knowledge of design professionals that is lacking in joinery and connections, but the state-of-the-art knowledge of bamboo in construction also suffers from a lack of knowledge on connections with bamboo (Harries, Mofidi, et al., 2022). This is an important aspect of the design of any structure and is important for the aesthetic, structural integrity and quality of bamboo structures:

> There is just not enough information out there in order to codify connections.

> Although we have put numbers [into ISO 22156] we are comfortable with, very often we permit design by testing. This makes sense if you are building a thousand or two thousand multifamily dwellings, you can afford to spend time and money upfront to take a look at running tests on connections. [N]

ISO 22156 (2021) contains an appendix which documents a series of example connections categorised using an approach proposed by Widyowijatnoko (2012) and ultimately integrated into ISO 22156. Interviewee N continues, "Given the fact the first version [ISO 22156 (2004)] only said 'connections should not fail', in the new version [ISO 22156 (2021)] we are miles ahead."

In the interview with C it is apparent that the design of the connection details should be a collaborative process:

> We have always done the details, but we have always got input from a local carpenter or local builder to see how easy it is to build, but we have done the details…Bamboo connections are very hard to do and it is very intricate carpentry to do it properly. [C]

The connection details are critical to a successful bamboo structure since, as C explains, "It tends to be the joints that fail in nearly all cases."

It is a fair assumption that since it is possible to grade and visually inspect the bamboo, it can be assumed there is a certain performance in the bamboo poles, however in the connections there can be hidden weaknesses. As a result, there needs to be a way to compensate for this and this is done through "over design, and you ideally want QA [Quality Assurance] onsite. An independent engineer or architect reviewing onsite."

The requirement for external support from a professional is also identified by interviewee F:

> The architect would do the design, but the actual connections and details has to be done by someone who knows bamboo…the detailed design would need to be done by someone who knows the bamboo. [F]

This means that there can be additional expertise and costs on the project to deal with connections. This shows the complexity of connections as a skill set the design professional has limited control over. Those closer to the construction seem best placed to advise or design the connections. In interviewing L who works with bamboo, the need for specialist skills and the labour intensity of making bamboo connections was identified as a barrier to the development of bamboo use:

> The other barrier which won't be a surprise to you is the need for intense labour to build with bamboo properly. Because you need the special connections, you need good carpentry skills to be able to connect fish mouth connections, if you want to build straight frames you need to be very skilled. [L]

The natural variability in the physical properties of each bamboo pole is what makes this process so labour intensive:

> I saw my carpenters and builders were moving the bamboo three of four times from a second floor down to the ground floor. I said, 'What's going on? Why don't you fix it?' It was a beam of bamboo between two columns. And they said that they were working with Fishmouth connections, and they wanted the piece of bamboo to fit perfectly, so they had to get it down to the lathe to sand the Fishmouth to the perfect shape. The irregularity is that labour intensive work is required. [L]

Interviewee D noted the following which again, explains the limited role of the design professional over this aspect of the design:

> We detailed it [a project] to a certain point, but we knew the site was so close to us [geographically] we were able to sit down with the carpenters from Bandung and there was a compromise…Every joint had a sample, and we went to see…So with the [project described], the details that we did were not interpreted 100% with what was built. [D]

Maybe this is a necessary split in design responsibilities. A design professional takes the design to a certain point in the design process and detailing is done by other specialists. The design professional need know only general locations and types of connections, but need not detail them. The input of specialists seems to improve this aspect of practice. In the interview with Interviewee B, this theme continues. The design of connections in a bamboo structure needs the input of construction experts with bamboo (also identified in Section 2.4.6). However, Interviewee B identified this as a business risk, "We saw that we need to mitigate the dependency on specialised craftsmanship."

Their response has been to look for joinery techniques which can be easily communicated and replicated and to design joints which can be constructed without special craftsmen. It seems the guidance for design professionals is to overdesign the connections, repeat the design of connections as much as possible and following design guidance in ISO 22156 (2021). Joinery shows the importance of skilled construction professionals in the project. As exemplified from B and D, a lot of the design will be completed before the joinery has been designed. A design at this point should already be correct for larger more wholistic design considerations such as the design affording protection from environmental factors. Joinery and connections benefit from external specialist input later in the design stages.

2.4.10 Results: Supply chains

The size and volume of material needed (usually including an excess *spoil*) can put those receiving the bamboo—whether the client, contractor or design professional—in a difficult position. To adequately cut the bamboo to form joints, there may be a significant percentage of the material volume as offcuts. They can be used elsewhere but then storage can be an issue to ensure the material does not get damaged and succumb to environmental degradation or insect attack while stored onsite. D notes that supply chain and durability are issues:

> A bag of cement is quite easy to transport, compared to bamboo. So if you get material transported which is bad, or is still drying and is then too young, you'll probably just accept it. The supplier knows you cannot send it back and will know you will probably accept 0%-20% of just bad material. This would never happen with steel or concrete…This is what happened to us. [D]

The ease of access to material and supply chains were noted by B when talking about the reasons why bamboo was suggested as a construction material on a project. Interviewee B goes on to note the challenges with limited supply chains for full-culm bamboo:

> We don't have a mature bamboo construction industry in Malaysia. So everything had to be from scratch. Sourcing bamboo material itself, you had to source from people who were not exactly very professional in terms of selective harvesting, quality control. So we ended up having to source a lot of bamboo that we had to reject. 30%-40% of the bamboo we sourced had to be rejected. [B]

Interviewee L also commented on how in some locations it is used in construction due to abundant availability:

> I was riding along an avenue in Armenia in Colombia, and in the morning I saw that

> some people were getting bamboo off a truck, and I went there again in the afternoon and they were already putting up a structure very quickly. They did not really need any specialised tools, and they were doing this with just minimal tools…It [bamboo] is considered a cheap, readily available, easy to use material that is for temporary structures. [L]

This documented ease with which bamboo can be harvested and used (without treatment) creates a problem which will only be felt later when the bamboo begins to deteriorate in this structure. This is recorded in the a priori coding theme of durability (Section 2.4.7). This is a reason why bamboo is seen as a temporary material and Interviewee L sees this as a major barrier for bamboo in construction. Even in architectural education, using bamboo in the classroom is a challenging experience. Interviewee A recounts the positive and unique aspect of bamboo in that bamboo poles were a fundamental learning tool, which allowed students to experiment through models and one-to-one construction, a practice not replicated with steel and concrete:

> They [the students] become very experimental using what they see on *YouTube* for example, of smoking bamboo, and actually being able to bend the bamboo. Those are things they become excited to do. I think it just becomes fun for them at the end of the day…They are very excited when things become hands on, and instead of building a model, they can build something one-to-one scale. [A]

The accessibility of full-culm bamboo made it much easier to bring this material into the class, than if it had have been another form of bamboo such as Engineered Bamboo Products (EBPs):

> I think just the accessibility in comparison to other forms of bamboo which is not as readily available. As much as the raw full-culm bamboo is not available, these other forms of bamboo are more expensive. I think it just boiled down to logistics. [A]

Interviewee E commented on the impact of supply chains for material quality:

> If we would have a supplier that can ensure quality that would be good, we have some suppliers in the area but we don't know if they have the material well preserved for example. I think the quality of the material and the capacity of the workers are the biggest challenges right now. [E]

K comments that the ease of access to bamboo, can also have a negative impact on the creation of a bamboo supply chain and the reduced potential for investment:

> From the forest to the construction site, you don't need any industry to develop it. That's why they [industry] want to make bamboo laminated, it's the business. You buy each pole for $3 [USD] and you can sell each sqm [engineered]. I don't know…$80, or whatever. So it is a huge percentage increase of the cost. [K]

With ease of access, comes a reduction in standards. With more money to be made from alternate manufactured material supply chains, there just is not going to be the investment in a full-culm bamboo supply chain. Furthermore, such a supply chain can be easily undermined by those informally cutting a natural product which could grow abundantly. A less formal supply chain may allow inferior material to emerge. It is therefore the responsibility of the client or the design professional to make sure that the bamboo is of a good quality and be willing to pay a premium to ensure this. Challenging supply chains can manifest in bad material quality, a phenomenon observed in the coding theme of durability (Section 2.4.7).

2.4.11 Results: Haitian built environment context

From this point forward, the interviewees are based in, or have direct experience of working in the Haitian built environment. As introduced in Section 1.7, Haiti is the LMIC context in which a design approach should be applicable within. Interviewees were also selected from the Haitian built environment to share perceptions of bamboo within the context of Haiti. Therefore, to conclude the qualitative interview coding in this section, responses pertaining to the Haitian built environment context are presented here. Their responses provide insight into the challenges in the context of Haiti and the infrastructure for material resources there. The interview format provides an opportunity to strengthen the symposium results (in Section 1.7) by concentrating on the a priori coding themes. Interviewee P notes:

> In Haiti there was a time you would build with wood, but there was too many fires and people went with masonry. Even those who kept wood in their houses, after a while they had to replace and repair. So considering the cost they would rather do something in concrete as you do it once and you are done with it. [P]

It seems that in Haiti, durability would be a major barrier to overcome.

> If you take the old houses in Haiti with wood structures, those woods were quality.

> These were very solid. So you see that when they are attacked by insects it's only the outer layers. You clean that up and the core is just fine. It is very rare that you would have to fix everything…It has more to do with the way we build. You want an assurance that your house will last without maintenance for a lifetime or more. This has something to do with the culture of the country. [P]

The idea that a house can last without maintenance for such a long period is not a realistic ambition, whether concrete, timber, or bamboo. Designing the structure in a manner in which elements can be replaced will be more challenging when confronted with this attitude. The sentiment of clients in Haiti as observed by interviewee P shows the context of reduced capital that can be expended on maintenance. Interview G notes a similar experience in the desire for permanence:

> Most of our constructions are residential or commercial. There is little social housing. In 99.9% of cases, individuals tend to build their houses after having saved or borrowed the funds. People will build depending on their financial situation. Building one's own house is such an expense that they expect their construction to last for future generations. Concrete reigns supreme, particularly in the case of lower income housing. [G]

Interview P echoes this theme, "For many people it is a status symbol to have a concrete roof…as time has evolved it is all about what makes you look rich and what makes you look poor."

Interviewee M was also asked about their experience working in different communities in Haiti, about bamboo, and the communities' view of bamboo houses or concrete houses:

> I can answer to this two different ways. Because I actually got to several communities and asked this question and gained feedback from people about this. If you have a choice to have a concrete house or bamboo house, what would be your choice? Many say they love the bamboo because of the ventilation, because it is cheaper, there is a lot of flexibility and to be safer for a potential earthquake…[however] they think the bamboo is not safe enough to keep people out of their house…if there was no insecurity, they would totally choose the bamboo. [M]

The relative weakness of bamboo to stop a stray bullet or to be resistant to fire in a protest was also raised in a community consultation exercise conducted on the AAVS Haiti in 2016 and again is raised in the symposium in Section 1.7.6. The opportunities and challenges of suggesting materials such as timber and bamboo to a client for construction in Haiti is described by interviewee G, and comments on material quality and supply chains:

> Steel would be used for a specific size of construction or an industrial building. Concrete is usually for residential or commercial buildings. Timber is getting worse and worse. The quality of timber that we import is so poor that I wouldn't recommend anyone doing anything with the timber that we receive. Even the timber that is treated and is sold as high quality timber just doesn't last more than a year now. [G]

The cost and quantity of the materials are mentioned as the biggest challenge to introduce bamboo into a project. If it is difficult to get adequate timber, concrete or steel, it will be also difficult to ensure bamboo is of an adequate quality:

> There is bamboo, there is well treated bamboo, but there is also poorly treated bamboo which is being used all over the place and it doesn't even last a year. So I think it would be cost, and I think there would need to be a lot of trust in the material. Concrete is a material that people trust. Timber is a material that people trust because of its traditional uses, but I am not sure how people would trust a material they haven't used yet. [G]

Interviewee H further reports that the quality of the standardised manufactured materials in Haiti are also getting worse and worse; this may be exacerbated by the corruption reportedly accompanying the current political and economic situation in Haiti. It can be easier to identify inferior bamboo through visual inspection and local supply chains than it would be to identify inferior steel or cement coming from overseas. The relatively low natural durability of bamboo means that in such a context, educating design professionals on parameters of material quality can be a way to ensure that good quality bamboo is sourced and used. As Interviewee H notes, durability would be a concern:

> Well, remember that you are living in the tropics and we have termites. So many people say no to wood and bamboo because we don't know how to deal with the termites. So we think that if we build out of timber and bamboo it is just going to be a temporary structure. So I think the issue of termites is what is holding back the use of wood and bamboo. Wood is still expensive since we still have to import it, so I don't know. I think people are factoring the cost benefit, it makes more sense in the long run to deal with concrete than wood in Haiti and bamboo. The knowledge of bamboo as a structural material and relevant material for housing has not really reached the masses

> in Haiti. So it is still seen as something that is exotic in many ways. [H]

Interviewee G noted that design professionals in Haiti do realise the structural and design possibilities of bamboo and its adaptability to tropical weather, however local bamboo is farmed in small quantities, and poorly treated for a long service life. When asked to describe the biggest challenge to introduce a material like bamboo into a project that G would be involved with in the role as a design professional in Haiti, demonstrating bamboo as an affordable durable material is important:

> In my case it would probably be cost and quality of the material. If it is cost effective and it is durable, and it is going to last for the next 50 years, I think a client would accept it. [G]

Interviewee G however notes that over time bamboo use has been seen more in construction, though the durability of the bamboo is a significant issue:

> By 2021, bamboo became more prevalent. I have seen it [bamboo] used in luxury housing as a decorative element and I've also seen local bamboo used in the countryside as veranda roofs, verandah screens, roof structures or structural elements. The unfortunate thing is that these local bamboos seemed poorly prepared and treated for long term use, and looked worn out. [G]

2.4.12 Discussion

The theme of *Societal attitudes* as identified in the surveys (Section 2.3) were not chosen as an a priori theme since this has already been established as this basis of this research, in that there is a societal attitude to bamboo and this research is attempting to determine the underlying causes. It is worth noting that all interviewees who had worked with bamboo had an awareness from their experiences that bamboo is perceived negatively in the vast majority of society. This has impacts on the concealment of the material as a design choice as noted by Interviewee L, and a preference to use materials such as steel and concrete. However, the aesthetic of bamboo and the perceived sustainability of the material has driven some more affluent clients to pursue bamboo and in these cases bamboo is often preferred to be exposed and shown. From the coding a series of themes in addition to the a prior themes have emerged in the interviews. These are:

- **The need for redundancy:** This was discussed as part of the conversation on natural durability recorded with Interviewee L. Redundant members are a way of ensuring that the natural variability of bamboo is taken into account and also can facilitate replacement of bamboo in a structure if a structural member were to get damaged.

- **Aesthetics of bamboo:** Both Interviewees E and L mentioned that clients are drawn to bamboo for its aesthetics and often wish to display it externally.

- **Material costs:** This covered three aspects in that full-culm bamboo can be: low cost due to abundance, low material quality or local sourcing; high-cost due to scarcity, treatment and/or transportation; and a stable cost. As noted by interviewee M, using materials sourced within a country such as Haiti, where many materials are imported, can be a way of avoiding the issues which are faced with price fluctuations due to construction material importation.

- **Dialogue/feedback loop between material characteristics and design:** The need for the design professional to also be aware of how to build with bamboo and also how a design needs to cater for the material more so than standardised manufactured materials. The way a design should be informed by the material performance was referenced by Interview K. Interviewee D and H noted the need to be involved in the construction, as well as the design professional to oversee the project which takes much more time and resource than most other projects. Interviewee A noted that this was also the case in the design of the structures in an academic setting.

- **The application of codes:** Interviewee M noted the use of codes to design for manufactured materials of steel and concrete is lacking for bamboo. This dominated the material culture for structural engineering in Haiti. Codes for bamboo offer an opportunity to teach structural engineers about bamboo.

- **Variation in species:** Interviewee J noted a lack of species availability which can lead to challenges to design for bamboo in Benin. Interviewee F also noted that a limited selection of species has an impact on design of bamboo structures in different parts of the country in Ethiopia. Therefore local knowledge of the design professional is critical to ensure that the design takes into account local bamboo resources which will also relate to the local construction knowledge.

- **Hybrid construction:** This theme emerged throughout the interviews, such as that with Interviewees A, D, E, J and K in that it is more common to design structures in which bamboo is one of a number of materials, for example, bamboo used in roofing.

In the context of Haiti a diversification of construction materials was also discussed by Interviewee H.

- **Western centric design and material culture:** This item was picked up by Interviewees A, D and J who noted that design sensitivities have been influenced by westernisation rather than a direct legacy of colonisation. Interviewee B did pick up on the issue that building codes are prescriptive and were introduced by colonial authorities. This has left little room for full-culm bamboo innovation which would be the case in a performance based building code.

Within the a priori themes identified through the survey results in Section 2.3.5, only the natural variability of bamboo seemed less of a challenge for those interviewed to deal with. Interviewees C and D both noted the impact this had on time and expense due to testing, and L noted the need to overdesign for redundancy. The importance of local supply chains and construction knowledge is evident to avoid price fluctuations and ensure one can check the quality prior to delivery, which is difficult with imported materials. A lack of material knowledge and a lack of construction knowledge (including joinery techniques) is a challenge, however a major reason this is a challenge is that it can affect the quality of the building and the adequacy of a design concept for a bamboo structure. In both cases the lack of material knowledge to design and build for bamboo is evident when the structure succumbs to issues related to durability. It is apparent that durability is a wider topic that encompasses more than just the environmental durability but to ensure that a design is durable and long lasting, first the design needs to be relevant for the site and supply chain in the vicinity. The quality of the material is important, craftsmanship and construction knowledge are also important to ensure a long service life of the structure. The material is susceptible to environmental degradation both when stored onsite and in situ in a building, and the temporary perception of bamboo with client and end users has a lot to do with the experiences of bamboo degrading. This last issue can be solved through adequate storage of the bamboo onsite, but also that the design affords protection to the bamboo to ensure that it protects the bamboo from the factors which degrade bamboo in a structure. Additionally, the structure needs the ability to replace damaged elements and reduce the impact to the client or end users if a bamboo element is damaged. This last item was identified as a major challenge in the LMIC context of Haiti where "permanence" is sought. Durability is the key consideration the design professional has the ability to control through their design which can impact societal perceptions of the material.

2.5 Concluding comments and what a design professional should consider

Bamboo’s historical reputation as an “alternative” material is underpinned by several factors. These factors include material attributes such as performance, quality, and durability, coupled with challenges arising from limited knowledge, inadequate industry awareness, and a lack of structured supply chains within the construction sector. The utilisation of incorrect species, coupled with the convenience of construction and accessibility to raw bamboo material, has also contributed to its perceived poor man’s timber status. Additionally, cultural associations and westernised viewpoints have played a role in shaping how bamboo has been historically perceived in the context of other construction materials. Such attitudes have been fostered through prejudice, and not technical practicalities of bamboo as a building material. Professionals and students in architecture and engineering positively perceive bamboo as a sustainable material but consider a lack of industry knowledge on the material and durability as the two key challenges for design professionals to overcome. Switching from quantitative to qualitative methods, interviews with those who work with bamboo and those who work in Haitian construction consider durability of the bamboo in a structure and the effect bad material quality on durability, as the main challenges to overcome for a design professional and where support can be given. Durability is comprised of a range of factors recorded through the interviews. These are all a series of concepts that a design professional should engage with to address durability in the design of a bamboo structure. These are:

1. **Material knowledge:** An understanding of which species is going to be used and where is it being sourced from.

2. **Local knowledge:** An understanding of local attitudes to bamboo as a construction material, where is the site, what are the transportation constraints to site, and what are specific local climatic factors which may impact a bamboo structure, as well as other vernacular knowledge that should be considered by a design professional.

3. **Treatment and supply chain:** A knowledge of treatment processes and the ability to assess the material before it is sent to a site and to design in a way in which changes can be catered for (such as material dimensions) if new sources of material are required, in that a design professional is able to be adaptable and flexible in the design vision.

4. **Construction and local workmanship:** Considering construction techniques which influence the design, and design for replacement and maintenance: considering how it is assembled and can be disassembled.

5. **Environmental vulnerabilities:** Understanding that bamboo will absorb moisture and is susceptible to excess moisture and sunlight and therefore the design needs to afford protection to the bamboo members.

6. **Inspection, maintenance and replacement:** To mitigate the impact that a bamboo element is damaged, the design of the bamboo structure affords the ability to inspect and replace elements to maintain a long service life of the structure.

7. **Joinery and connection detailing:** An understanding of joinery which can influence design decisions and be a series of connections which are as standardised and repetitious as possible in the design.

Using the above seven factors as list of areas to investigate durability in full-culm bamboo structures, the next chapter investigates durability in more detail through fieldwork in Colombia and a literature review. It endeavours to uncover the primary factors that contribute to the durability of full-culm bamboo, study good practice examples, and understand the durability factors the design professional can be most involved in mitigating by design.

3 Chapter 3. Full-culm bamboo durability and design guidance

"Correct design of all building details is a must; no chemical treatment will be good enough to solve the problems caused by incorrect design."

Jules J.A. Janssen (2000, p. 55)

3.1 Chapter structure

When used correctly, bamboo offers an opportunity to use a local resource which is environmentally sustainable. There are many challenges for the design professional to the use full-culm bamboo in a practical way to ensure a long service life. This chapter focuses on the factors which affect the durability of full-culm bamboo. Though at times this chapter may portray a negative aura as the challenges of bamboo durability are discussed, it should be remembered that these challenges pale into insignificance compared to the wider global challenges identified in Chapter 1. In the previous chapter, surveys ranked durability as one of the major challenges to using bamboo in construction, and interviews highlighted the importance of durability to the use of bamboo in projects. Understanding what affects bamboo in a structure and how these can be addressed can be the basis of a design approach to support design professionals when designing full-culm bamboo structures. This chapter was developed through a literature review and fieldwork in Colombia, visiting a series of projects to see first-hand, the issue of durability in bamboo structures. Kaminski et al. (2022) provides a comprehensive overview of how durability can be addressed in bamboo structures and provides an overview of the design guidance in ISO 22156 (2021). Kaminski et al. (2022) lists three main observed reasons why bamboo succumbs to decay in a structure. These are:

- **Bamboos vulnerabilities:** Misconceptions of how bamboo is attacked, and how treatment can mitigate these.
- **Design decisions:** Externally exposed bamboo as an aesthetic design decision.
- **Design standards:** The lack of standards and guidance for designing durable bamboo buildings.

This chapter addresses each of these topics with a literature review and case study research. It does so by answering the following questions:

- **Bamboos vulnerabilities:** How is bamboo attacked by biological agents and how does treatment affect these?

- **Design decisions:** How can we ensure bamboo durability by design?

- **Design standards:** What do the recently published ISO 19624 (2018) and ISO 22156 (2021) state as design guidance?

This chapter answers these questions through the following identified factors that affect durability established in Section 2.5. Environmental vulnerabilities have been separated into two sections given the range of factors that are to be considered:

- **Durability - Abiotic factors and insect attack:** Understanding that bamboo will absorb moisture and is susceptible to fungal growth due to excess moisture, as well as damage from ultraviolet (UV) light and attack by insects. This means the design needs to afford protection to the bamboo members.

- **Durability - Elevated temperatures:** Understanding that bamboo will perform differently at elevated temperatures and how the design of the structure should mitigate temperature extremes.

- **Material and species availability:** A knowledge of which species is going to be used and where is it being sourced from.

- **Treatment methods and supply chain:** A knowledge of treatment processes and the ability to assess the material before it is used in a project.

- **Locality and context:** An understanding of the site location, cultural, and construction industry context, and transportation constraints.

- **Construction and workmanship:** A consideration of construction techniques which are available and influence the design.

- **Inspection, maintenance, and replacement:** To design in a way in which it can accommodate changes in material dimensions as a result of supply chain, to be adaptable and flexible in the design vision, and considering design for replacement and maintenance—how it is assembled and can be disassembled for replacement.

- **Joinery and connection detailing:** An understanding of joinery which can influence design decisions and be a series of connections which are as standardised and as repetitious as possible.

3.2 Durability in buildings and bamboo

All building materials are subjected to physical, chemical and biological degradation factors (Addleson & Rice, 1991). In LMICs, durability is often a greater concern, since the end user or client cannot often afford to expend great capital cost in the building, let alone afford the cost of continual repair of deteriorated structures over the life of the building (Ngab, 2001). A house is considered as durable if it is built on a non-hazardous location and has a structure permanent and adequate enough to protect its inhabitants from the extremes of climatic conditions such as rain, heat, cold, and humidity (UN-Habitat, 2003). Materials can impact a building occupants' emotional and cultural connection to a place and foster an impression of non-standardised bio-based materials as valuable, and durable, which UNEP (2022) describes as a critical aspect of sustainability that is typically underacknowledged. The *service life*[11] of bamboo structures is dependent on the rate of biological degradation affected by all those factors of rain, heat, cold, and humidity. In order for bamboo to be considered as a permanent building solution and a durable material, it is important to determine how the bamboo can be affected in a structure, and how design guidance has been established to ensure durability. For this chapter the term *durability* is defined as is stated in ISO 22156 (2021) which is the ability of bamboo to, "resist degradation of geometric, physical or mechanical properties when subject to an intended service environment for an intended service life" (Clause 5.7). Durability of building materials is subject to local conditions as well as to local construction and maintenance traditions and skills. This is evidenced in Section 2.4.6 in which the supply chain and knowledge of the local workmanship are crucially important considerations for achieving durable bamboo structures.

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[11] In this research the definition of *service life* (*working life* in European documents) is the period of time after installation during which a building or its parts meets or exceeds the performance requirements (WIS 4-28, 2019, p. 1).

The observed opportunity for bamboo in construction (i.e., why a client may invest in a bamboo structure over more accessible standardised materials), is the perceived sustainability benefits of using bamboo (Section 2.3.4). However, bamboo is only sustainable if it is used in a long-term application and stores the carbon for a long period of time. If the bamboo is only used for a temporary purpose and the bamboo is discarded it will rot and release greenhouse gases back into the atmosphere. Therefore, it is important to remember that the sustainability of bamboo is intrinsically linked to the durability of bamboo (Escamilla et al., 2014). The ability to replace bamboo elements should not be seen as a way of covering for bad design and it is important to consider durability and longevity (Naboni & Havinga, 2019). The expected service life of untreated bamboo is < 0.5 years when it is in contact with soil and 0.5–4 years for elements above ground but unprotected from exterior exposure (Kaminski, Lawrence, Trujillo, & King, 2016). Even though some species of bamboo show greater natural durability than others this is primarily against beetle attack (e.g., *G. angustifolia* as compared to *B. vulgaris*). All bamboo should be considered as having relatively poor natural durability and requires treatment and protection from moisture and sun (ISO 22156, 2021). The fact no bamboo species is known to have natural durability negates the use of an equivalent document to BS EN 350 (2016) – *Durability of wood and wood-based products. Testing and classification of the durability to biological agents of wood and wood-based materials.* Therefore bamboo is different to timber since each wood species has naturally occurring chemicals in the heartwood of the growing tree, also known as extractives. This makes durability species dependent (BRE, 1998; Koca, 2019).

3.2.1 Comparative durability of bamboo and timber

Both bamboo and timber are affected by abiotic factors and insect attack. Bamboo is generally more prone to decay than timber, owing to a shortage of certain chemicals that occur in most woods but are absent in bamboo (Janssen, 2000). Unlike timber, there are only minor amounts of resins, waxes and tannins and none of these have enough toxicity to provide any significant natural durability (Kumar et al., 1994). The hollow circular shape of bamboo is lightweight and highly structurally efficient. However, the poor natural durability is compounded by the fact that the bamboo culm being hollow has a high surface area to volume ratio, particularly when compared to timber. With typically thin walls, this means that compared to timber, for bamboo, a small amount of decay can have a significant effect (Janssen, 2000). In most tropical countries where tropical woody bamboos grow (Clark et al., 2015), the often high relative humidity adds to durability problems without adequate ventilation. A high moisture content (MC) in the bamboo provides an opportunity for fungal attack (Janssen, 2000). Moisture affects the bamboo material properties similar to the way moisture affects timber (Dunkelberg et al., 1985). Kumar et al. (1994) cites Sekhar and Rawat (1964) and Laxamana (1985) noting bamboo takes longer to dry than timber of the same density. In bamboo the radial passage of moisture is slower than in timber as no ray cells exist (Liese & Tang, 2015a). The thickness of the culm wall is an important factor controlling the rate. Liese and Tang (2015b) note that the structural composition of compact fibre bundles with thick walls (Figure 31b), hinders the loss of moisture during drying of culms. This also hinders the penetration of preservative liquid during treatment.

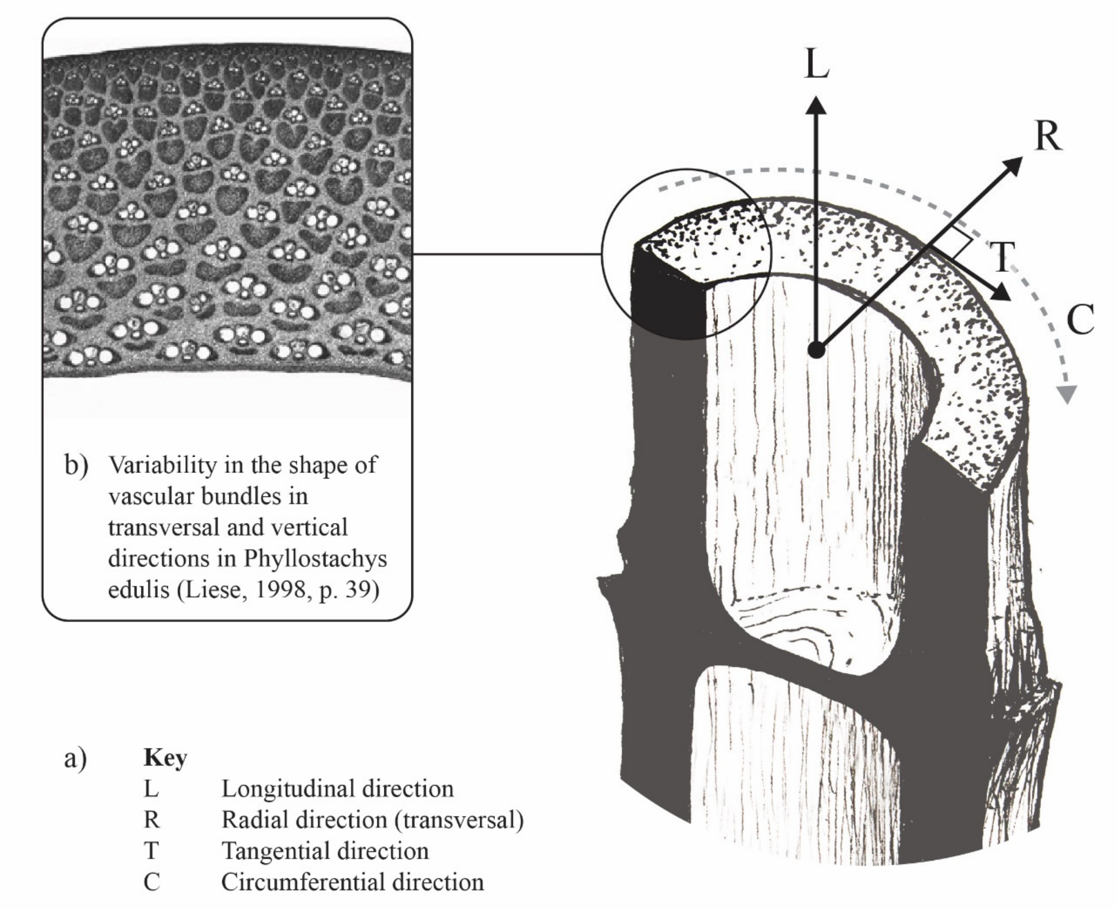

Figure 31: (a) Force directions in the bamboo (sketch by author), and (b) the corner of the bamboo culm highlighted to show the microstructure of the culm wall, with fibres more tightly packed towards the outer edge (image reproduced from Liese, 1998, p. 39).

3.2.2 The anatomy of the bamboo culm

Full-culm bamboo has a self-restraining cross-sectional form, coupled with large dimensional instability in the circumferential direction. As shown in Figure 31a, the direction perpendicular to the longitudinal (axis or axial) direction (L) of the bamboo pole is the radial direction (R). The circumference (C) is described by the tangential direction[12] (T) perpendicular to the radial direction.

The mass of the bamboo culm comprises about 50% parenchyma, 40% fibres and 10% vessels and sieve tubes (Liese, 1987). The cellulosic fibres are slender and present around the vascular bundles as sheaths and as isolated strands and account for about 60%-70% of the weight of the culm (Liese & Tang, 2015b). Bamboo is a fibrous material in which the fibres run in the longitudinal direction of the bamboo culm. As shown in Figure 31b, the density of fibres toward the outer wall of the bamboo culm is much denser with the percentage of fibres in the bamboo significantly greater in the outer third of the wall (Grosser & Liese, 1971; Liese, 1987). This means that the mechanical properties are different through the culm wall thickness. With more fibres, the tensile strength increases towards the outside of the bamboo culm wall, in the longitudinal direction of the bamboo culm. Given these differences across the wall of the bamboo culm, it should not be considered as uniform and therefore should be considered to have an outer layer, and an inner layer. The inner layer is characterised by higher amounts of lignin and the outer layer contains cellulose and pectin with an exterior waxy coating (Kumar et al., 1994). Silica particles also exist in the outer layer of the bamboo culm wall which provides some protection to the bamboo culm and makes the epidermal layer harder and more difficult to penetrate than the softer parenchyma interior. This leads to poor penetration of preservatives from the outside of the culm wall during treatment (Kumar et al., 1994), but can also blunt tools when working with bamboo more so than when using tools with timber. This also differs across species with *Bambusa oldhamii* purported to blunt tools more than other species. It is not just the relative impermeability of the bamboo skin that effects the ability of treatment solutions to flow into the bamboo perpendicular to the culm direction. Compared to wood, bamboo does not contain ray cells which restricts lateral flow of liquid preservation solutions (Kumar et al., 1994). However diffusion and flow of treatment solutions and moisture parallel to the direction of the bamboo culm is relatively easy with an increase in the proportion of parenchyma leading to proportionally larger water absorption capacities (Dunkelberg et al., 1985).

[12] The symbol T denotes tangential direction only in Figure 31a. Elsewhere in this PhD research T denotes temperature.

Bamboo shrinks when the MC reduces below the *fibre saturation point* (FSP), and the bamboo dries. The shrinkage in the bamboo when drying is appreciably greater than encountered in wood (Kumar et al., 1994). This is because the parenchyma tissue shrinkage is more pronounced in bamboo than in timber, while vascular fibres shrink as much as in timber of the same specific gravity (Liese & Tang, 2015b). There are major differences between shrinkage encountered perpendicular, and parallel to the direction of the bamboo pole (Yu et al., 2008). Two differences between the shrinkage of bamboo and timber is firstly that bamboo shrinks radially (Liese, 1987), and bamboo will shrink from the point MC is less than FSP. The pattern and effects of shrinkage on the bamboo is covered in greater detail in Section 3.4.2.

3.3 Relevant design guidance

3.3.1 ISO 22156:2021 and ISO 19624:2018

Recently, ISO Technical Committee 165 has published three international standards: ISO 22156 (2021), ISO 22157 (2019), and ISO 19624 (2018). These are model codes which are intended to be adopted (with or without an additional national Annex) by national building codes. ISO 22156 and 22157 are significant revisions of earlier "intent signifying" standards published in 2004 (Janssen, 2005). This chapter references the design guidance for full-culm bamboo promulgated by ISO 22156 (2021). Since knowledge of material quality was also identified as a key factor in the durability of bamboo structures, this chapter also references guidance for grading bamboo in ISO 19624 (2018). This document explains physical properties of bamboo poles, which if observed, would result in rejection for construction use. ISO 22157 is outside the remit of the design professional in this research and resides in the territory of the engineering professional. ISO 22156 and ISO 19624 provide guidance on design and material quality that can assist a design professional in the design of a bamboo structure and the specification and inspection of the bamboo to be used in that structure. Throughout this chapter quotes are taken from both documents where summarising or paraphrasing is inadequate. ISO 22156 (2021), Clause 5 - *Basic requirements of design*, is the guidance a design professional can follow as this design guidance includes the categorisations of Use class and Service class. For this reason, Clause 5 of ISO 22156 (2021) is the most heavily referred to clause in this chapter. Additionally, references are made to the non-mandatory guidance contained in ISO 22156 (2021) for information. These annexes are prefixed with letters *(A, B, C...)* and provide guidance to give additional information to achieve design and performance goals. In this chapter Colombian code document NSR-10 (2010) is also referenced to provide additional definitions to some key terms.

ISO 22156 (2021) is a model engineering structural design standard for construction with bamboo in its full-culm form. Originally published in 2004, this 2021 revision is the second such edition and replaces ISO 22156 (2004). This document addresses connection design, issues of durability and *light cement bamboo frame* (LCBF) shear panel design also known as *bahareque encementado* and *composite bamboo shear walls*, which is a new anglicised term for *modern cemented and engineered bahareque* (Kaminski, Lawrence, & Trujillo, 2016a) – which is discussed in Section 3.4.3. This document does not extend to cover thermal or sound insulation, fire protection (beyond highlighting the need), or other non-structural aspects of design. As such, bamboo structures may require consideration of additional requirements beyond the scope of ISO 22156 (2021). ISO 22156 does not apply to:

- **Structures made of engineered bamboo products (EBPs):** This includes engineered products such as glue-laminated bamboo, cross-laminated bamboo, oriented strand (or strand woven bamboo), or densified bamboo materials. Current information in this field is well documented (e.g., Gutierrez Gonzalez, 2020; Madden et al., 2018; Sharma et al., 2017; Sharma, Gatoo, et al., 2015; Sharma, Gatóo, Bock, et al., 2015), and new ISO standards are being developed such as ISO/CD 7567 (2023) and the recently published ISO 23478 (2022).

- **Bamboo-reinforced materials such as bamboo-reinforced concrete:** Bamboo-reinforced materials where bamboo is not the primary load-bearing constituent. This includes bamboo-reinforced concrete, masonry and soil and are ill-advised concepts (Archila et al., 2018; Harries, Rogers, & Silva, 2022).

- **Scaffold structures constructed with bamboo:** Guidance for bamboo scaffolding structural systems is documented in HKBD (2006), and described in Chung and Siu (2002); Chung and Yu (2002).

ISO 22156 (2021) is intended to be cited or adopted by a national building standard or an equivalent document. ISO 22156 (2021) permits an allowable load-bearing capacity design (ACD) and/or an allowable stress design (ASD) approach for the design of bamboo structures. ACD determines the maximum loads a structure can handle, considering strength and load factors. ASD focuses on stress levels within individual structural elements, calculating stresses induced by loads and comparing them to allowable limits based on material properties. Figure 32 shows a comparative diagram reproduced from Harries, Trujillo, et al. (2022). An advantage of using ACD over ASD is that the former is able to explicitly capture the anisotropic nature of bamboo (Harries, Trujillo, et al., 2022).

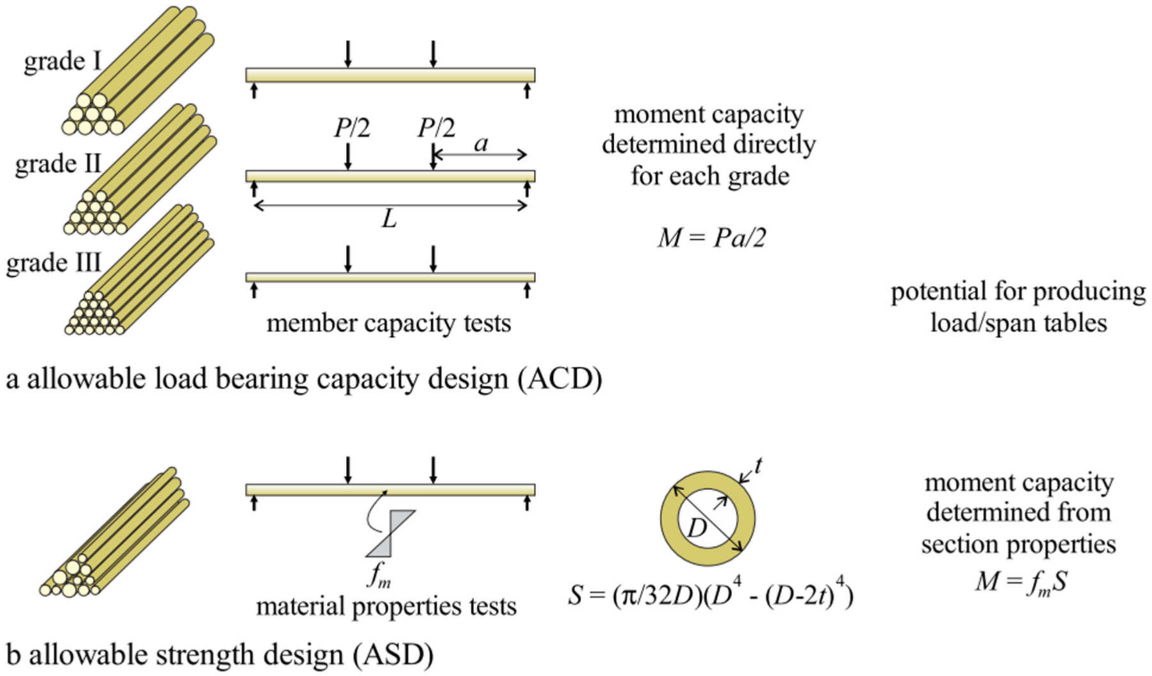

Figure 32: A comparative diagram of ACD and ASD. Image and captions reproduced from Harries, Trujillo, et al. (2022).

3.3.2 Maximum storeys and height limit in ISO 22156:2021

ISO 22156 (2021) only applies to one- and two-storey residential, small commercial or institutional, and light industrial buildings not exceeding 7 m in height. Considering safe fire egress for building users is a primary factor for limiting the scope of ISO 22156 (2021) to a two-storey and 7 m height. This also aligns with the guidance in Clause G.12.1.3 of the Colombian code NSR-10 (2010). Additionally, there is a lack of precedent data for bamboo structures over two stories which could be used to inform a code document. 7 m or two stories of height, are also similar to the available lengths of bamboo used in construction. Full-culm bamboo is more suited to balloon construction, rather than platform construction (Figure 33). Therefore, the available lengths of bamboo would facilitate balloon construction at two stories or 7 m. Over this height, platform construction may be required. There are benefits to platform construction such as the ease of construction and transportation with shorter lengths of material (Burchell, 1984, pp. 3-6). Anything larger than 5 m to 6 m in length would be more difficult to transport without articulated vehicles. The 7 m height is measured from the mean roof height, however each national code may interpret this differently. National codes may also be free to specify if the two stories of bamboo can be in addition to other floors of other materials. For example, multiple floors of an RC frame with two stories of full-culm bamboo on top.

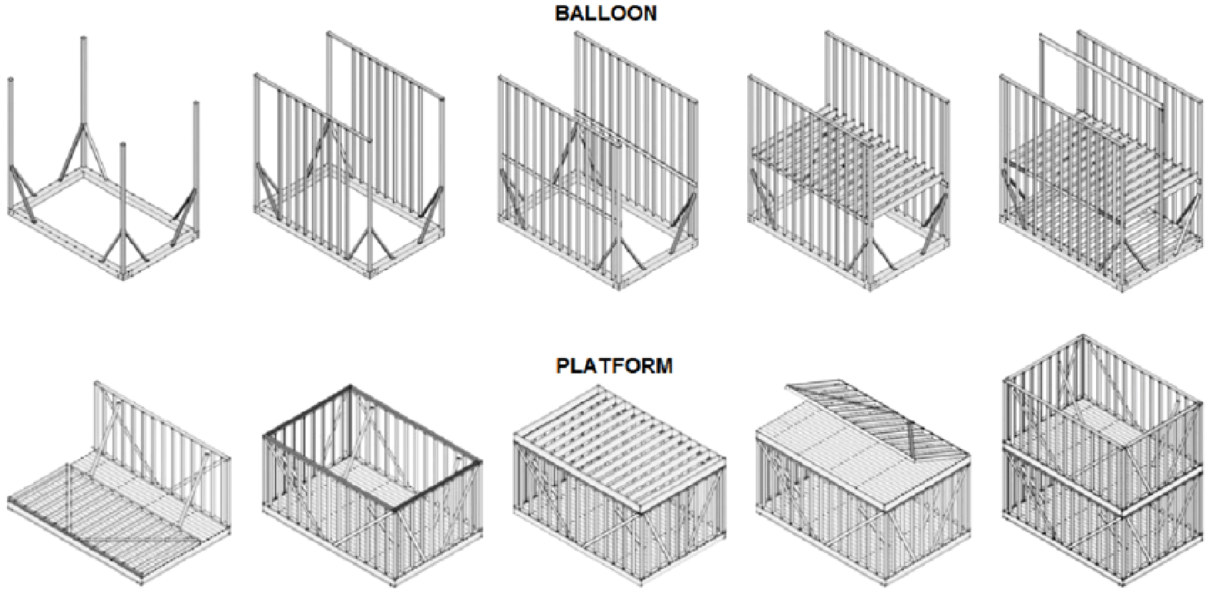

Figure 33: Example of the different assembly framing sequences of balloon and platform reproduced from Almeida De Araujo et al. (2016), originally sourced from O´Brien (2010).

3.3.3 The need to consider durability as outlined in ISO 22156:2021

ISO 22156 (2021) Clause 5.7: Bamboo shall be considered "non-durable", requiring preservation, in terms of its resistance to the following:

- fungal attack;
- attack by wood boring insects and termites and,
- marine borers for bamboo exposed to a marine environment.

Fungal attack is covered in Section 3.4.5 of this chapter, attack by wood boring insects and termites is covered in Section 3.4.7, and marine borers for bamboo exposed to a marine environment is not relevant for this research as this is applicable to a Use class in which bamboo should not be used and still conform with ISO 22156 (2021).

All bamboo is to be considered as non-durable (ISO 22156, 2021, Clause 5.7). No species of bamboo is known to have significant natural resistance to biological attack whether this is from abiotic factors or attack by insects. ISO 22156 (2021) outlines a series of general recommendations for designing durable bamboo structures.

> **ISO 22156 (2021) Clause B.2 (for information):** General recommendations for designing durable bamboo structures are as follows:
>
> - After harvesting, keep bamboo protected from rain and moisture; allow the bamboo to breathe (air flow around culms) in storage while it is still green.
> - Only dry bamboo should be used in construction.
> - Structural details (particularly connections) should be designed to ensure standing water is unlikely to accumulate or enter the inside of the culm.
> - Bamboo shall not be used in conditions in which it is in contact with standing water or soil.
> - In a structure, to the extent possible, bamboo should be protected from water and rain (i.e., "protection by design"):
>   - elevate bamboo above the ground level on a plinth or upstand, isolating the bamboo from the plinth or foundation with a damp-proof membrane.
>   - use water-proof roof coverings.
>   - use of long roof overhangs or verandas to protect bamboo members from driven rain
>   - use of durable and water-proof finishes
>   - expose bamboo to the extent possible in the interior of the structure to permit drying should it get wet.
> - Where there is a risk of subterranean insect attack (such as termites), bamboo should be elevated on a solid plinth or upstand, such that ground-based insects need to build visible shelter tubes to access the bamboo; these can be destroyed when they are found.

Sustainability is not covered in ISO 22156 (2021). However, a consideration of sustainability in the early design stage is critically important. There are documents which can provide guidance on what design professionals should consider when designing a bamboo structure (e.g., ISO 15804:2012+A1:2013, etc.). ISO 19624 (2018) is a standard for grading bamboo, much of which is beyond the remit of the design professional, however, ISO 19624 (2018), Clause 6 - *Visual grading,* provides informative guidance that a design professional can follow to check the condition of the bamboo, and the physical properties of the bamboo.

3.4 Durability: Abiotic factors and insect attack

Abiotic factors encompass non-living components like temperature, soil, water, and sunlight, all of which can impact the durability of full-culm bamboo. Bamboo has poor natural durability and as such it should be considered as non-durable (ISO 22156, 2021), and must be treated with preservatives to be used in a structure. Though treatment can reduce the risk of attack by insects (as discussed in Section 3.4.7), no treatment can protect the bamboo from all abiotic factors which can affect the bamboo in a structure. To paraphrase Janssen (2000), no treatment can protect the bamboo from bad design or inappropriate placement in a structure. ISO 22156 (2021) provides guidance on how design professionals can increase the durability of a bamboo structure. This section looks at which factors affect the durability of the bamboo and to what extent.

3.4.1 Effects of relative humidity on moisture content

The physical and mechanical properties of bamboo and the structural performance of bamboo are affected by the moisture content (Correal, 2016; Q. Xu et al., 2014). The moisture content can impact the dimensional stability, bending strength, creep performance, toughness, density, and durability of bamboo (Correal, 2016; Liese & Tang, 2015b). The moisture content of bamboo is influenced by the environment in which it is located (Gonzalez et al., 2012). The Colombian code document NSR-10 (2010) describes this condition:

> [Bamboo is] a hygroscopic and porous material that absorbs water present in the environment in the form of vapor or liquid. If the humidity [EMC] of the Guadua [bamboo - as this code specifically refers to only *G. angustifolia*] increases, its mechanical properties will decrease, it will begin to swell, it will transmit heat and electricity more easily and it will become more vulnerable to biological attack… (Clause G.12.12.4.4) [Translated from Spanish to English using online translation software]

The moisture content (MC[13]) is not necessarily uniform throughout the bamboo culm. During growth, the internodes of a bamboo culm can contain up to a quarter more moisture than the nodes (Dunkelberg et al., 1985). MC also varies in the components of the culm wall—the vessels, fibres and ground tissue. Reported MC is therefore intended to be an average across the culm. MC is determined as the difference between the weight of the in situ bamboo and its

[13] MC is the terminology used in this PhD research, whereas *W*MC is the abbreviation used in ISO 22156 (2021).

weight following oven drying (ISO 22157, 2019). Conventionally, this is given as a percentage of the dry weight as follows:

Equation 1: Equation to determine MC (%).

$$\text{MC (\%)} = \frac{\text{wet weight} - \text{dry weight}}{\text{dry weight}} \times 100$$

Freshly harvested bamboo may possess MC of up to 70% (Minke, 2012) or higher, impacting its mechanical properties. The fibre saturation point (FSP) is the moisture content in the bamboo at which the free water in the cell cavities has been driven off (ISO 22156, 2021). For most bamboo, FSP is in the vicinity of 30% (Correal, 2016). To mitigate fungal attack, maintaining the moisture content (MC) of bamboo within structures below 20% is crucial (ISO 22156, 2021; NSR-10, 2010). For most air-conditioned structures, *equilibrium moisture content* (EMC[14]) is assumed to be 12% on many sites. However, as discussed in Section 1.2.6, experience in regions where bamboo grows, also referred to as vernacular knowledge, indicates this can often be in excess of 12%. Table 20—which is discussed in Chapter 5—is an example of these regional variances of expected EMC of the bamboo. Local knowledge is very important here (as discussed in Section 3.4.4 and 3.8.1). Wang et al. (2022) notes that with the exception of tensile strength, mechanical properties increase as the MC falls below FSP.

Humidity denotes the volume of water vapor in the air (Curry, 2015). Liquid water transforms into water vapor in warmer air due to increased thermal energy, allowing warmer air to hold more water vapor compared to cooler air. Relative humidity (RH) gauges the proportion of water vapor present relative to the saturation capacity of air at a specific temperature. The EMC of bamboo is influenced by environmental factors, including temperature (T) and relative humidity (RH) (Gonzalez et al., 2012). Effective ventilation eliminates stagnant moist air and dissipates moisture-bearing (and often warmer) air traversing bamboo surfaces (Simpson, 1997). Hence, ensuring bamboo in a structure maintains its intended (i.e., designed-for) EMC is imperative. As already described, EMC must also be kept below 20% to mitigate fungal growth. Furthermore, designing well-ventilated environments for bamboo

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[14] EMC is the terminology used in this PhD research, whereas *W*EMC is the abbreviation used in ISO 22156 (2021).

structures is paramount, as environmental factors, particularly within the RH range, can impact MC. Awareness of unique site factors (e.g., proximity to water bodies, coastal locations, etc.) is important as there are contexts which can increase moisture in the air and ventilation can bring moisture into a space. This is discussed in further detail in Section 3.4.4.

Moisture content (MC) refers to the current water quantity within bamboo (Equation 1), while equilibrium moisture content (EMC) is the point at which the MC is in equilibrium with the environment it is situated within and is estimated by Equation 2. The EMC is where the bamboo is neither gaining moisture from—nor losing moisture to—the environment (ISO 22156, 2021, Clause 3.5). EMC is a function of the hygrothermal environment; that is, the synergistic effects of T and RH. There are no known studies establishing validated T-RH-EMC relationships specifically for bamboo. Bamboo chemistry and morphology however, is similar to softwood timber and the *Hailwood-Horrobin* (H-H) sorption model (Hailwood & Horrobin, 1946)—calibrated for wood (i.e., in Papadopoulos & Hill, 2003)—equating ambient T and RH to EMC has been shown to model bamboo sorption relatively well.

Equation 2: Hailwood-Horrobin (H-H) sorption model to determine EMC (%).

$$\text{EMC (\%)} = M_h + M_s = \frac{1800}{W} \times \frac{K_1 \times K_2 \times \text{RH}}{100 + K_1 \times K_2 \times \text{RH}} + \frac{1800}{W} \times \frac{K_2 \times \text{RH}}{100 - K_2 \times \text{RH}}$$

Zhang et al. (2018) considered 14 species (from five genera) of bamboo and determined that the sorption isotherm at 25 ºC was lower than that typically adopted for softwood timber. Other studies report similar findings for *Phyllostachys edulis* bamboo (Chen et al., 2021; Mania et al., 2019). No known study has determined isotherms for bamboo over a range of temperatures; additionally, as shown by Zhang et al. (2018), sorption behaviour of bamboo is species dependent. Thus, it is proposed that adopting the H-H model for softwood timber is appropriate for bamboo and yields marginally conservative (i.e., high) estimates of EMC for bamboo. Figure 34 highlights the relationship between moisture content of the bamboo, temperature (T) and relative humidity (RH) following the H-H relationship.

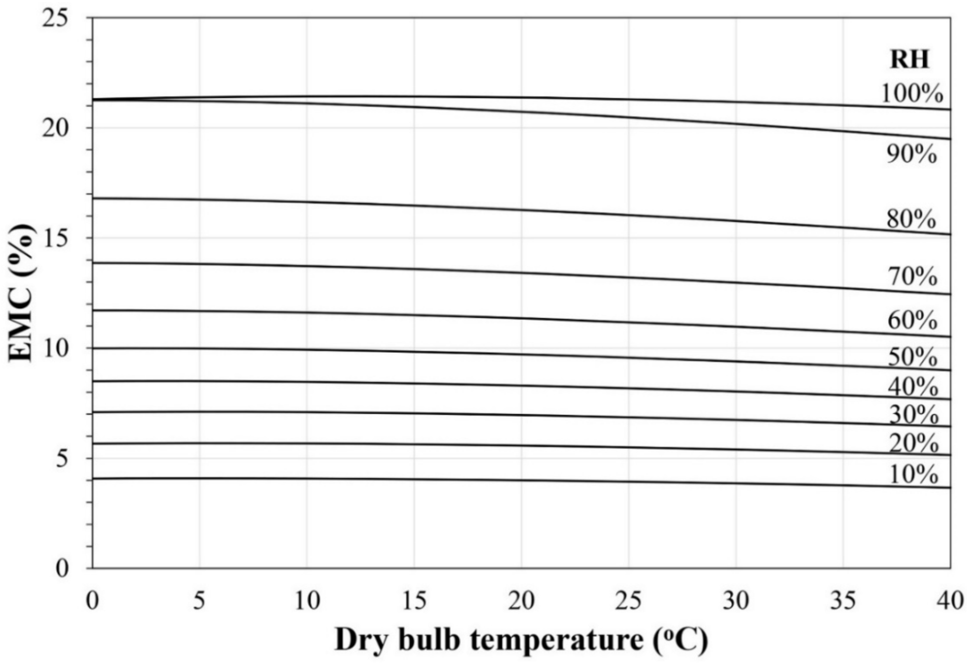

Figure 34: Hailwood-Horrobin (H-H) model showing the synergistic effects of relative humidity (RH) and ambient temperature on the expected equilibrium moisture content of bamboo (EMC).

Figure 34 shows that RH has more of an effect on the EMC of bamboo than temperature. Ensuring adequate ventilation and avoiding excess moisture is important to ensure an adequate EMC in the bamboo. As Janssen (2000) describes this:

> The bamboo used in a building might get wet. To address such a possibility, the design of the building should be one that allows unrestricted airflow to facilitate quick drying. This might be a burden on the creativity of the designer, but the effort would pay on the long term. (p. 56)

The required information to inform a design professional of T, RH, and EMC of the bamboo is included in NSR-10 (2010), Table G-D-1. EMC of bamboo has been studied by Hamdan et al. (2007) and Gutiérrez González and Briceño Roncancio (2015) who note that at 40 ºC *G. angustifolia* showed an EMC of 22.95% at 90% RH and 17.4% at 80% RH and that the bamboo specimens took roughly two weeks to achieve their EMC. This suggests bamboo should arrive onsite 2-3 weeks before construction due to this acclimatisation (Gutiérrez González & Briceño Roncancio, 2015).

This consideration for bamboo is analogous to and aligns with considerations for human comfort. In general, a healthy environment for bamboo and timber is also a healthy environment for occupants (WHO, 2009). Allen et al. (2017) lists the, *9 Foundations of a*

Healthy Building, with moisture and ventilation two of these. Hygroscopic cultivated bio-based materials such as bamboo align much closer to the environmental needs of a building occupant than steel or concrete. In effect, if there is excess moisture and mould on internal bamboo members, it is equally a sign that the building is inadequate for the occupants, not just the bamboo. In the case of ventilation for example, bad air quality has a detrimental impact on cognitive functions (Shaughnessy et al., 2006; Wargocki & Wyon, 2007). Building regulations try to overcome this by stipulating minimum air changes in a room (e.g., Approved Document F, 2021, Clause 1.27 [England and Wales]), listing objectives of a design (e.g., Haitian CNBH 2012, Clause OH1), or insisting on the avoidance of poorly ventilated spaces (e.g., Colombian NSR-10, 2010, Clause G.12.12.4.4). There is clear evidence that excess moisture causes damage to the building fabric, the growth of mould, and the release of chemicals which may be within the materials of the building fabric (NIOSH, 2022). These then become the causes of a wide range of respiratory or allergic health effects (Mendell et al., 2011). Buildings need good ventilation. However in areas in which there are security fears (such as those described in Section 1.7.6), or in locations of significant urban density, it is not possible to have large, exposed sides of the building which will allow through ventilation. It is for the design professional to be aware of this need and design accordingly. Though materials such as bamboo are susceptible to excess moisture and sunlight to a greater degree than concrete and steel, it is important to highlight again the design decisions that ensure a healthy environment for bamboo, can also ensure a healthy environment for humans.

3.4.2 Hygrothermal effects, shrinkage, and fissures

Q. Xu et al. (2014) records that when immersed in water, bamboo absorbs most moisture through the inner culm wall, or the cut ends, due to the less permeable silica-rich outer skin of the bamboo exhibiting reducing water penetration. Moisture causes dimensional changes to the bamboo (Correal, 2016), and this change of the physical dimensions will be uneven (Yu et al., 2008). Expansion and shrinkage with MC variation can damage the bamboo over time. If this dimensional change occurs when the bamboo has already been drilled to place bolts, the shrinkage and swelling can lead to splitting from the holes. Shrinkage can also crack the bamboo. This is more likely if the drying is uneven for example one side of the bamboo with a high moisture content is exposed directly to heat from sunlight (Liese & Tang, 2015a). Changes in temperature and humidity may produce steep moisture gradients between surface and inner layers. The cracking which is caused through the uneven drying will often form *fissures* on what Liese and Tang (2015a) term the *weather side*. This differential in drying results in differential shrinkage which can ultimately lead to cracking and splitting which will damage the bamboo structurally (Figure 35). Bamboo is more likely to split in the longitudinal direction as shown in Figure 35 - Figure 37. This is referred to as longitudinal splitting, or a fissure. ISO 19624 (2018) describes the fissure as, "Longitudinally oriented separation or split of the bamboo wall running parallel to the fibres at the end of a culm or at any internode of the piece that may or may not penetrate through the entire wall thickness" (Clause 3.4).

Figure 35: Bamboo poles exposed to UV light and rain, showing longitudinal splitting, or fissures. Photo by author, 2020.

Hone et al. (2020) notes that the bamboo species *Phyllostachys edulis* (commonly referred to as *Moso*) splits within one week at room temperature if the RH falls to 35% or less. ISO 19624 (2018) prohibits the use of bamboo poles with signs of splitting where the split—also termed as a fissure—are greater than 1 mm in width over 20% of the length of the piece of bamboo. If the split extends through three or more nodes, then that pole is not to be used, regardless of the width (ISO 19624, 2018).

In addition to affecting the culm load bearing capacity, splitting allows moisture and pest ingress beyond the silica rich epidermis further affecting durability. When fissures appear that go through to the cavity of the bamboo (Figure 36), water collects inside which can lead to subsequent deterioration by fungi and insects (Liese & Tang, 2015a). Chemical treatment cannot prevent this condition as this is a consequence of the physical characteristics of the bamboo, and shrinkage induced stress (Liese & Tang, 2015a). Preventing extreme heat and moisture is the only way to avoid this condition. Keeping the bamboo out of direct sunlight, away from the ground and shielded from the rain, is an approach known as protection by design. Even onsite during construction the effects of heat can dry the bamboo and make it difficult to work with. This is documented by Crolla (2017), during the construction process with full-culm bamboo in Hong Kong in 2015—a project discussed in more detail in Section 4.4—it is noted that an unusually hot summer had dried and stiffened the poles onsite meaning in some cases notches were cut into the bamboo to meet the required curvature.

Figure 36: A crack in a painted piece of bamboo in which insects have penetrated inside. Photo by author, 2022.

Figure 37: Painted bamboo used as an external signpost. Photo by author, 2022.

ISO 22156 (2021) Clause B.3 (for information): Paints and varnishes should not be considered to protect against water ingress or biological organisms although they may offer some protection against bleaching caused by UV radiation.

Applying external coverings to the bamboo such as paint will also not protect the bamboo from conditions causing fissures. Painting will not prevent the swelling and shrinkage of the bamboo due to the exposure to environmental factors. These cracks can be seen splitting the bamboo wall and with it the paint as evident in Figure 37. Moisture will now be able to penetrate into the cavity, resulting in degradation to the bamboo. Paint can also cause an impermeable layer on top of the bamboo pole, the result of which any moisture escaping from the bamboo will be trapped and pool on the surface. This vapour barrier will facilitate condensing of moisture below the finish, which can expand both the culm and the finish (Minke, 2012). It is then possible for this, like a blister, to break through the paint and make the paint flake away and also the bamboo to crack.

ISO 22156 (2021) Clause 10.7.1: Straps used to provide radial clamping force shall provide uniform bearing of the strap around the circumference of the culm and shall not result in damage to culm wall when tightened. All components of metallic clamping straps shall be appropriately protected from corrosion based on their environmental exposure.

A way to mitigate the impact of splitting can be through the addition of metal clamps or plastic zip-ties in the structure. The guidance of ISO 19624 (2018) should still be considered, and metal fasteners are not a solution to the requirement to not use split bamboo described in ISO 19624 (2018, Clause A.2.5.1). Also, metal straps may provide some structural support to resist the effects of splitting. However, the increased susceptibility through fissures of the bamboo to abiotic factors and insect attacks will still remain.

3.4.3 Driving rain, splash zones, and the need for raised foundations

Bamboo must not be in direct contact with the ground. Placing the bamboo into the ground will degrade the bamboo as moisture in the ground will be absorbed into the culm wall and insect attack will be more likely. *Graveyard tests,* in which short sections of bamboo or timber are part submerged into the ground (similar to the condition shown in Figure 38a), were shown in Kumar et al. (1994) that on some important Indian species, the average life of untreated bamboos is less than two years.

Figure 38: (a) Bamboo pole placed into the ground, and (b) the effect of rain splashing at the lower portion of a bamboo column even though it is raised above the ground. Photos by author, 2022.

An increase in the moisture content of bamboo can also happen through exposure to rain hitting the bamboo. In bamboo growing regions where tropical woody bamboos grow, it will most likely be the case that rain will be more regular, more intense, and approach more horizontally than rain in temperate regions. The increased force at which the rain hits the ground as well as the horizontality of the rain means that there are areas which may be susceptible to rain which at first glance—or if the design professional is not based locally—may not appear obvious. Dripping from roof eaves can degrade the bamboo if the edge is not properly covered as seen in Figure 39.

Figure 39: Bamboo purlins degraded at the edge of the roof eaves. Photo by author, 2022.

At the ground level the rain can splash upwards and hit the lower parts of a bamboo structure, even if raised from the ground. Therefore, it is important to raise the bamboo on a durable plinth to a height which can avoid flooding or splashing from rain. Even if the bamboo is raised from the ground, the splashing can still reach and degrade the lower part of the bamboo (Figure 38b). Therefore, the height above the ground should be considered by the design professional based on the local climate, flood risk, and risk of insect attack. Since the bamboo mostly absorbs moisture through the culm wall (Q. Xu et al., 2014), the cut bamboo is facing the ground and therefore placed in a vulnerable position.

The foundations are important and Gutiérrez (2000) notes they have two main functions. Firstly, they have to transmit the loads to the supporting soil, and second, raise the structure from the ground to prevent the deterioration of the organic material by fungal attack caused by moisture. If this is not done then the effects of this can be seen in Figure 40 where timber has been used to raise the bamboo but this is of an inadequate height and material to perform the second of these functions.

ISO 22156 (2021) Clause B.2 (for information): Where there is a risk of subterranean insect attack (such as termites), bamboo should be elevated on a solid plinth or upstand, such that ground-based insects need to build visible shelter tubes to access the bamboo; these can be destroyed when they are found.

Figure 40: Bamboo poles in contact with a timber upstand on insufficient height. Photo by author, 2022.

Figure 41 shows examples of bamboo foundations in which the bamboo is adequately raised from the ground. These show a range of different combinations from a raised concrete foundation (Figure 41a and Figure 41b) and using bamboo only for the second storey or roof structure (Figure 41c). Raised foundations will also mitigate the risk of attack by insects. Elevating the bamboo structural elements on concrete footings (elevated plinths) is also one of the protection by design principles, with the phrase often used to describe protection by design principles, "big boots and a big hat". This refers to a footing of 40-60 cm in height and the roof overhang to protect from driving rain (Stamm, 2022), and described in ISO 22156 (2021) as "long roof overhangs or verandas to protect bamboo members from driven rain"

(Clause B.2). In importance of the footings—big boots—is that direct rain has less salts and microbes than raindrops rebounding from the ground. As the splash from raindrops rarely rebound higher than 40 cm, this is considered a relatively safe plinth height, and the 40-60 cm plinth also evaporates the moisture generated by capillarity of stone/concrete in high groundwater levels (Stamm, 2022). Lower plinths may have constantly rising moisture that could wet the bamboo, so its recommended to paint the bottom of the pole or add a damp proof membrane (DPM) as a barrier (ISO 22156, 2021; Stamm, 2022). Such dimensions are not within the ISO standard though is an example of vernacular knowledge which can be used to inform the design professional and give input data to in ISO 22156 (2021) which states that "elevate bamboo above the ground level on a plinth or upstand, isolating the bamboo from the plinth or foundation with a damp-proof membrane" (Clause B.2). In all cases a pole of bamboo sitting horizontally on a plinth is to be avoided.

Figure 41: Good practice examples of raising the bamboo above the ground: (a) Concrete foundations at UTP, Pereira, Colombia, (b) *piaje* (tollgate) outside Manizales, Colombia, and (c) The University of Gran Colombia, Armenia, Colombia. Photos by author, 2022.

Embedding the bamboo in concrete is often seen in bamboo structures, but this is bad practice. The concrete will slightly contract as it cures whereas the bamboo will swell and shrink in reaction to the environment. This will allow gaps to form, and water to pool around the bamboo in the concrete. This water can increase the MC of the bamboo in the manner discussed previously. Minor cracks—produced by the shrinkage of concrete—moisture can also be infiltrated and affect the bamboo (Gutiérrez, 2000). Additionally concrete is a high alkaline environment which can break-down the cell structure of lignocellulosic materials such as bamboo (Pickering et al., 2016).

Another way to protect the bamboo from external environmental factors is to conceal the bamboo behind a rendered frame. However, ventilation and inspection of the bamboo structure would need to be considered. So, render may only be applied to one side, or a cavity in the wall to allow inspection may be required. A technology which is worth noting is bahareque (Figure 42) (Kaminski, Lawrence, & Trujillo, 2016a; Lopez et al., 2004; Trujillo, 2021), also known as *quincha* (van Drunen et al., 2016), or light cement bamboo frame (LCBF) construction (ISO 22156, 2021). When used in structural applications as shear wall panels, LCBF panels are required to have a height-to-length ratio no greater than 3 (ISO 22156, 2021). Braced LCBF systems shall not exceed three stories and 9 m in height. Unbraced LCBF systems shall not exceed two stories and 7 m in height (ISO 22156, 2021). A DPM (Figure 42, Item 4) should also be used to stop the bamboo elements absorbing moisture from adjacent hygroscopic bricks or concrete.

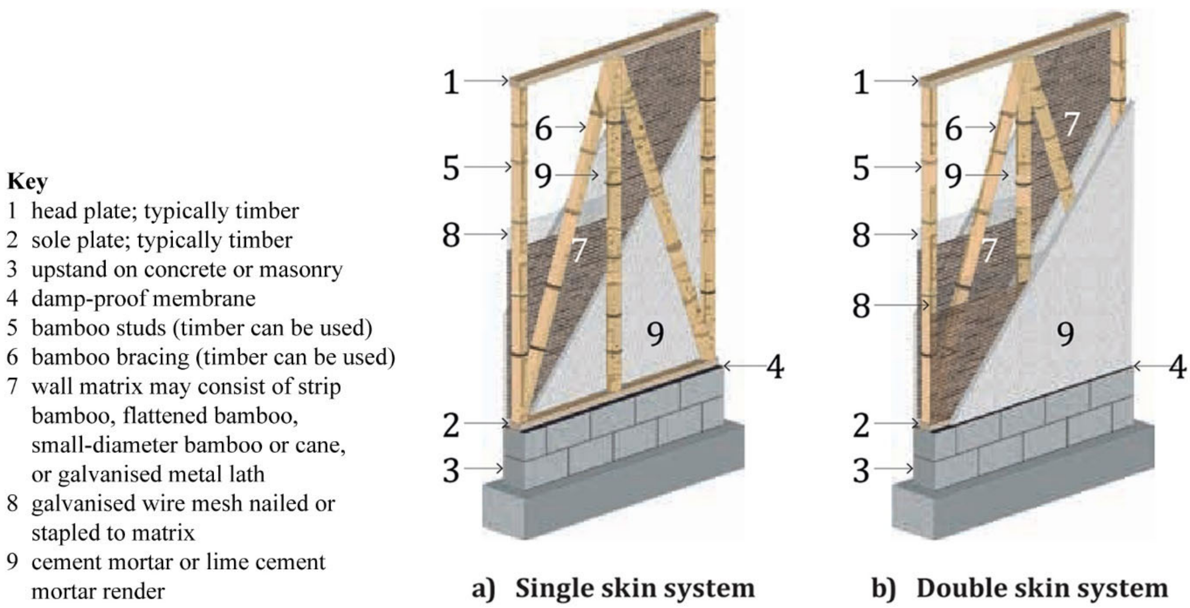

Figure 42: Examples of LCBF (engineered bahareque) construction, reproduced from ISO 22156 (2021). Originally sourced from Kaminski, Lawrence and Trujillo (2016a).

Similar to the durability requirements of timber, with bamboo, horizontal elements in façades are more vulnerable than vertical ones, as the rain runs off easier and no moisture beds develop between wall plaster and bamboo pole (Stamm, 2022). As seen in Figure 42, no horizonal bamboo poles are used which the hollow section could allow moisture to pool, but instead timber studs are used (ISO 22156, 2021; Kaminski, Lawrence, & Trujillo, 2016a).

3.4.4 Ambient moisture and mould

Mould can cause damage to the building fabric (NIOSH, 2022). Even in well-ventilated open sided structures which provide sufficient roof overhangs to protect against UV light and rain (such as the *ZERI Pavilion* in Manizales, Colombia in Figure 43), ambient moisture and mist adjacent to the building can raise the EMC of the bamboo to a level where mould growth occurs. As seen in Figure 44, the side of the building facing the forest contains a mould that is not apparent on the opposite side facing away from the forest. As can be seen in Figure 45, mist rises into the structure early in the morning, and creates an environment in which over time, the EMC of the adjacent bamboo increases.

Figure 43: *ZERI Pavilion* by Simón Velez, outside of Manizales, Colombia. Photo by author, 2022.

Figure 44: Comparison of two sections of the façade of the *ZERI Pavilion*: (a) showing a face of the façade facing the forest/vegetation, and (b) a face of the façade facing south, away from the forest. Photos by author, 2022.

Figure 45: Mist from forest in early morning rising adjacent to the structure. Photo by author, 2022.

Occasional rain and even frequent moist air does not affect round bamboo with its silica skin, as it evaporates quickly. However, over time lichens and even moss build up and create a green layer (Figure 44). Unchecked and uncleaned (i.e., annual washing away of the lichen is recommended by Stamm, 2022), this could increase to a point (over 18-20% EMC) where fungi can begin to grow.

Though ventilation is key to ensuring moisture which may build up within a structure has the ability to be drawn away, there are cases where the proximity of the structure to high levels of moisture may mean that facilitating ventilation is creating a means for moisture to enter the structure. This is important for the design professional to consider. ISO 22156 (2021) responds to this addition to the requirement that "building details shall be such that the bamboo shall remain air-dry by ventilation and ensure that if the bamboo does become temporarily wet, it will dry before material deterioration can occur". The design should ensure that a condition "likely to draw water or moisture into the bamboo, is mitigated" (Clause 5.7). For example, if the bamboo structure is placed next to vegetation which will emit moisture (Figure 45), or the site is located next to a water body, or in a coastal location. The later will also create conditions where the steel joinery in the bamboo structure will be more vulnerable to the saline moisture. One possible way of classifying these environments is in ISO 12944-2 (2017) - *Corrosion protection of steel structures by protective paint systems - Part 2: Classification of environments* in which environmental conditions and their corrosivity are categorised.

3.4.5 Fungal attack

Bamboo will be susceptible to fungal attack if the moisture content of the bamboo exceeds 20% for an extended period of time (ISO 22156, 2021; NSR-10, 2010). This is analogous to timber (e.g., code documents such as CNBH, 2012, Clause 1.6.3, recommend EMC ≤20% for timber used in construction). When bamboo is drying it is particularly important to check for external cracking. Moisture ingress in the bamboo cavity will allow the fungi to thrive and the bamboo to deteriorate (Liese & Tang, 2015a). Bamboo is susceptible to white-rot fungi. A common white-rot fungus is *Schizophyllum commune* (Figure 46) easily recognised by its white fruit body with a radial lamellate underside (Ashaari & Mamat, 2000). Fungi cause discolouration and decay of bamboo. There are many types that infest and attack bamboo under different environmental conditions (Liese & Tang, 2015a). All fungi use the chemical components of the culm cells, either from cell contents (bluestain fungi) or from the cell wall (rot fungi), as their energy source (Liese & Tang, 2015a). Although fungal spores are present everywhere, they require certain conditions for germination, further growth, and for the enzymatic degradation of the substrate (Liese & Tang, 2015a).

Figure 46: White-rot fungus, as a result of excess moisture. Photo by author, 2022.

Moulds grow on the bamboo surfaces Figure 44a, but bluestain and rot fungi (soft-rot, brown-rot, white-rot fungi) grow mostly inside the substrate, and some develop mycelium on its surface (Figure 46), especially under humid conditions (Liese & Tang, 2015a). Later, fruit bodies may be formed on the outside for the release of new spores (Liese & Tang, 2015a). With white-rot fungi the enzymatic degradation of bamboo leads to a loss of cell wall substance which results in a reduction of strength properties (Liese & Tang, 2015a). The relation between mass loss and strength reduction appears more severe in bamboo than in timber as the weight loss concerns mainly the strength-giving fibres (Liese & Tang, 2015a).

Areas with RH above 70%, a regular occurrence in the tropical contexts of tropical woody bamboos, can facilitate mould growth (Tang et al., 2012). Different mould species produce large quantities of spores, of which some species can cause skin irritations, respiration problems and allergic reactions for human beings, particularly in indoor environments (Liese & Tang, 2015a). The mycotoxins produced by some moulds can be highly toxic to humans and animals.

ISO 22156 (2021) Clause 5.7: The following general considerations for durable structures are required:

- construct only with bamboo that has achieved its equilibrium moisture content, w_{EMC}, for the location of the building. Moisture content, w, shall never exceed the fibre saturation point, w_{FSP}, which, if unknown may be assumed to be w_{FSP} = 30 %;
- building details shall be such that the bamboo shall remain air-dry by ventilation and ensure that if the bamboo does become temporarily wet, it will dry before material deterioration can occur; and,
- building envelope permeability shall be such that negative pressure resulting from heating, ventilation and/or air conditioning, likely to draw water or moisture into the bamboo, is mitigated.

This ventilation in bamboo structures is pertinent to the usual building typology of tropical regions where tropical woody bamboos are appropriate in construction. A dynamic space, as described by Restrepo Ochoa (2022). It opens the structure to natural ventilation to remove stagnant air and visual inspection. The rate of air flow, or air speed though a space, can be an indication that stagnant air would be removed.

3.4.6 Sunlight and UV light radiation

UV and visible light radiation causes photodegradation which can affect the surface colour of the bamboo (Yu et al., 2021). UV radiation breaks down bonds of the lignocellulosic polymer causing the bamboo surface to turn grey and coarse (Liese & Tang, 2015a).

Figure 47: Gradient of colour from yellow (shaded) to white (unshaded). Roof of the University of Gran Colombia, Armenia, Colombia. Photo by author, 2022.

Figure 48: Roof overhang and masonry lower story, of the University of Gran Colombia, Armenia, Colombia. Photo by author, 2022.

Figure 49: The effects of sunlight (with exposure to driving rain) on the outermost bamboo column. Photo by author, 2022.

The photo-discoloration of the bamboo when exposed to UV light (Figure 47 and Figure 49) is a process which involves complex physical and chemical reactions. There have been studies attempting to clarify the mechanism of wood weathering (e.g., Teacă et al., 2013; George et al., 2005). It has been shown that the degradation process is triggered by the formation of free radicals by UV irradiation (Wang & Ren, 2008). The wood constituent polymers show different capacity in absorbing UV light to form radicals. Lignin is extremely susceptible to UV irradiation, leading to formation of aromatic free radicals (Wang & Ren, 2008). These free radicals further react with oxygen to produce carbonyl and carboxyl groups, resulting in photo-degradation of the bamboo or wood surface. Due to UV degradation, a thin region of the outer surface degrades. In timber, this effect is minimised but with the thin-walled hollow bamboo, the effect can be more substantial and negatively affect moisture permeability. To protect the bamboo from UV light, roof overhangs are one way of achieving this as shown in Figure 48 and Figure 50.

Even after treatment of bamboo, when the bamboo is drying it should be protected against UV light and moisture (Janssen, 1979). Timber exposed to the weather loses colour and becomes grey (WIS 4-28, 2019). However, unlike timber, for bamboo there is no classification for discoloration. With timber, BS EN 13017-1 (2001) would place UV discoloured timber into *Appearance class B, C* or *S*. This helps the client understand the nature of the appearance of the timber and aids communication between design professional and client. A codified Appearance class does not yet exist for bamboo, therefore for clients and end users, discolouration is a surprise, or difficult to prepare for.

Figure 50: Roof overhang of a classroom building at the University of Gran Colombia, Armenia, Colombia. Photo by author, 2022.

Though not used structurally, an example of the impact of UV light can be seen in the *Parkhaus Zoo Leipzig* project by HPP Architekten and Krahnstöver & Wolf in Leipzig, Germany. Here untreated bamboo has been in-situ for 20 years. These poles are untreated, been well-ventilated and vertically installed with detailing which avoids contact with the ground (Figure 51a-c).

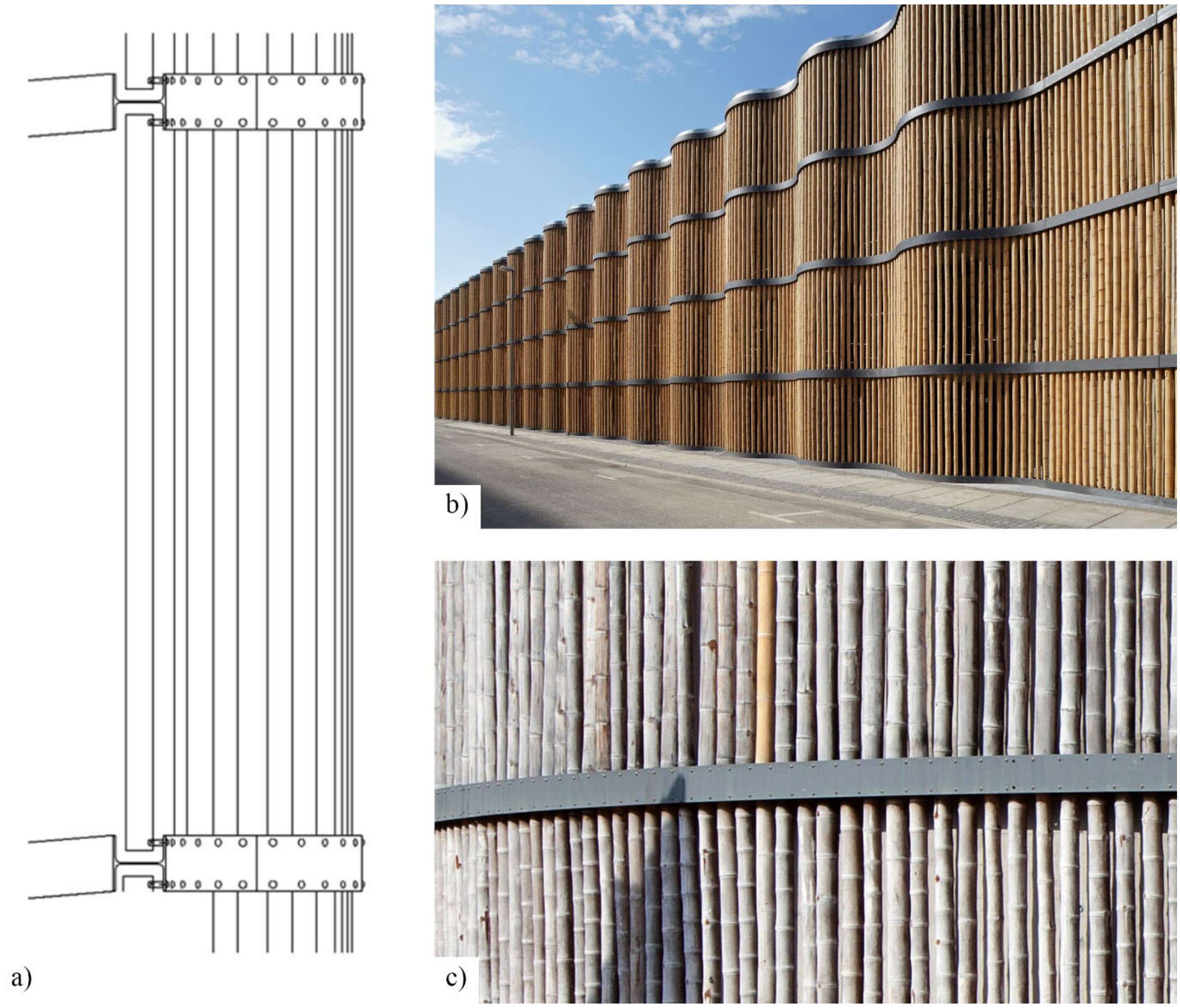

Figure 51: *Parkhaus Zoo Leipzig* project by HPP Architekten and Krahnstöver & Wolf GmbH in Leipzig: (a) Bamboo connection detail showing the bamboo avoiding contact with a location where water may pool and moisture could affect the bamboo. Image by HPP Architekten, reproduced from Archiweb (2016). (b) The façade with bamboo façade members when the project was relatively new. Image by HPP Architekten / Bertram Kober. (c) The façade showing a pole recently replaced, and other poles in situ for ≈8 years. Image taken 2011 by Thomas Robbin, from imageBROKER.com GmbH & Co. KG / Alamy Stock Photo.

Bamboo poles with a diameter of 8-12 cm in lengths of 2.6-4 m were installed in 2004 (Krahnstöver & Wolf GmbH, 2016), and the author understands that after 20 years are only now due for replacement. Even after 20 years in situ, bamboo has not degraded to the point where poles have detached and only in some cases where poles are in proximity to vegetation, has the bamboo shown signs of mould. As can be seen in Figure 51c, the effects of bleaching and ambient moisture on the bamboo poles can be seen over a period of ≈8 years (Figure 51c taken in 2011), when placed alongside newly replaced bamboo poles. As shown in Figure

51a, this is due to good detailing to avoid contact with the ground—attached with ≈5 cm above the beam—so the bamboo is not in contact with standing water. The non-structural use of the bamboo in this context has been successful and shows that there is an interesting architectural and mercurial quality to the facade as it is replaced over time and creates a texture of the bleached bamboo adjacent to the new bamboo poles (Figure 51c). This non-structural use of the bamboo here has also potentially offset the use of carbon intensive manufactured materials as a façade element.

These cases highlight that it is the synergistic effects of regular excess moisture and heat from sunlight which is the major concern rather than exposure to UV radiation in isolation when used as structural applications. Though a temperate environment, and non-structural, the *Parkhaus Zoo Leipzig* project would be a relevant case study as the basis of future research which could bring more knowledge of the UV effects on bamboo into code documents. More research is required to know the effects of UV light on bamboo (Rao et al., 2022; Yu et al., 2021), and through the limited research on this phenomenon for timber, the impact on bamboo could be informed by research in this field (e.g., Teacă et al., 2013; George et al., 2005).

3.4.7 Insect attack

Bamboo is prone to being attacked by similar insects to those which attack wood. However bamboo is more likely to bio-deteriorate due to its higher starch content (Liese & Tang, 2015a). A higher starch content makes bamboo more prone to insect attack from powder-post beetles (Plank & Hageman, 1951). There are two types of insect attack to be aware of: beetle attack (borers), and termite attack (Kaminski et al., 2022). Bamboo with starch is susceptible to beetle attack (Yudodibroto, 1985). Termites are also attracted to the starch in bamboo. However, termites (Figure 52) can depend on cellulose rather than starch for a source of food (Liese & Tang, 2015a; Sajap et al., 2000).

Figure 52: A bamboo column where the base has likely seen termite attack and the bamboo has been eaten way. Photo by author, 2022.

Warm and moist climatic conditions in tropical regions favour the development of insects (Liese & Tang, 2015a). Insects can cause damage to growing bamboo, felled bamboo culms and finished products. Over 50 insect species have been reported attacking bamboo growing in the Asian region, with the maximum damage caused by *Dinoderus minutus*, also known as *ghoon borers* or more commonly in English speaking world, *powder post beetles* (Liese & Tang, 2015a; Wang et al., 1998). Powder post beetles can start attacking felled bamboo within the first 24 hours and cause devastation in stored bamboo culms. The effects of the attack include reducing the tissue in the bamboo and turning the wall into a flour-like powder in which only a thin outer shell remains (Liese & Tang, 2015a). When the internal bamboo tissues have been eaten away, the remaining outer shell can make it difficult to notice the full extent of bamboo degradation, therefore it is important to inspect the bamboo closely for signs of small holes (as highlighted in Figure 53), or different sounds when knocking a machete or rigid implement against the bamboo outer wall. A knock will mean the bamboo is intact, whereas a thud or slight echo may be because there are cracks, fissures, and increased moisture in the bamboo. Any indentation to the bamboo, or the absorbing of the blow of the machete, will also indicate by feel if the bamboo tissue is compromised. The powderpost beetles once inside the bamboo can exist through many stages of their life and go through a complete metamorphosis, passing through four stages of development: egg, larvae, pupa and adult (Hidalgo-López, 2003; Liese & Tang, 2015a). Starch, soluble carbohydrates and protein are the essential food requirements for a borer attack. Therefore treating the bamboo in a way to reduce the starch is imperative to prevent beetle attack, and this treatment should be non-toxic (Hidalgo-López, 2003; Kaminski et al., 2022; Liese & Tang, 2015a).

Figure 53: A painted bamboo structural member with a small hole covered in cobwebs where insects have burrowed. Photo by author, 2022.

The prevalence of individual species varies according to country, climate, soil, temperature and altitude, among other factors. Unless it is categorically known that insects which attack bamboo do not live in a specific region because they cannot survive there, it should be assumed that all bamboo is at risk of insect attack (ISO 22156, 2021). If national standards do not specify the risks of insect attack, local or national experts should be consulted for advice on the risk of insect attack and appropriate measures of treatment or protection. The larval activity depends on the availability of starch. Younger culms with a higher moisture content are more easily attacked than older ones which contain less starch and moisture (Liese & Tang, 2015a). Flowering bamboo culms with their low moisture content contain a low starch content as starch has been used for seed production. This reduces the likelihood of attack. The incidence and severity of borer attacks depends also on the bamboo species (Liese & Tang, 2015a). Although no systematic record seems to exist, it is well documented that *B. vulgaris*, for instance, is relatively vulnerable (Liese & Tang, 2015a). ISO 22156 (2021) notes that where there is a risk of subterranean insect attack (such as termites), the bamboo structural elements should be elevated on a solid plinth or upstand (Figure 41). This is so that if insects were to build visible shelter tubes to access the bamboo, they could be easily identified and destroyed.

3.4.8 Use class and Service class

In ISO 22156 (2021) designations exist for the Use class and Service class of bamboo members in the structure. In wood construction Use class is a designation associated specifically with material durability. Table 8 shows the Use class designation used in ISO 22156 which is identical to that prescribed in ISO 21887 (2007) for timber. Kaminski et al. (2022) notes such classifications are an effective way of forcing good durability practice for the design professional. Based on Use class, preservation and protection against biological attack (fungal, insects and termites) is prescribed. Bamboo may not be used (and remain in conformance with ISO 22156) when designated Use class 4 or 5. Bamboo used in a Use class 5 scenario, would be susceptible to attack by marine borers within a short time. As Liese and Tang (2015a) notes, no protection of bamboo marine structures appears possible by technical means and chemical treatment risks negative environmental impact through the leaching of preservatives. Bamboo designated Use class 3.2 will have limited service life of 0.5-4 years (Kaminski, Lawrence, Trujillo, & King, 2016). Use class, while clearly related to Service class is qualitative and does not specifically consider expected EMC and does not affect the strength or stiffness values of bamboo used in structural design. Typically, Service class 1 is expected to correlate to Use class 1 whereas Service class 2 may be Use class 2 or 3. ISO 22156 (2021) Annex B provides additional informative guidance on the means of ensuring durability, and methods of preservation of bamboo.

Table 8: Use class designation reproduced from ISO 22156 (2021).

Use class	service conditions	typical uses	Protection against biological agents		
			fungal	insects	termites
1	interior, dry	framing, pitched roof members	-	yes	yes
2	interior, occasional damp (possibility of condensation)	framing, roof members, ground floor joists, framing built into exterior walls	yes	yes	yes
3.1	exterior, above ground protected from driving rain and UV radiation	protected exterior joinery and framing	yes	yes	yes
3.2[a]	exterior, above ground not protected from weathering	unprotected exterior framing and joinery including cladding, vertical load bearing members, exposed unprotected culm ends	yes	yes	yes
4.1[b]	in contact with ground or in-ground	sole plates or columns at ground, columns built into ground, piles	yes	yes	yes
4.2[b]	in-ground severe, fresh water	piles	yes	yes	yes
5[b]	marine or brackish water	marine piles including splash zone	yes		

[a] Bamboo should not be used in use class 3.2 except for structures having a design life of less than 5 years.

[b] Bamboo shall not be used in this use class.

In ISO 22156 (2021), Service class is determined based on expected EMC (Figure 54). EMC can affect the strength and stiffness of bamboo. Service class 1 refers to bamboo whose EMC remains at or below 12%—the same basis for timber construction. Service class 2 addresses EMC up to 20% which should capture most indoor applications regardless of heating or cooling. Structures assigned to Service class 3 (in-service EMC exceeding 20%) require experimental determination of the adjustment factors C_{DF} and C_{DE}. The 20% threshold is based on the potential for fungal growth when EMC exceeds this value (Schmidt et al., 2013).

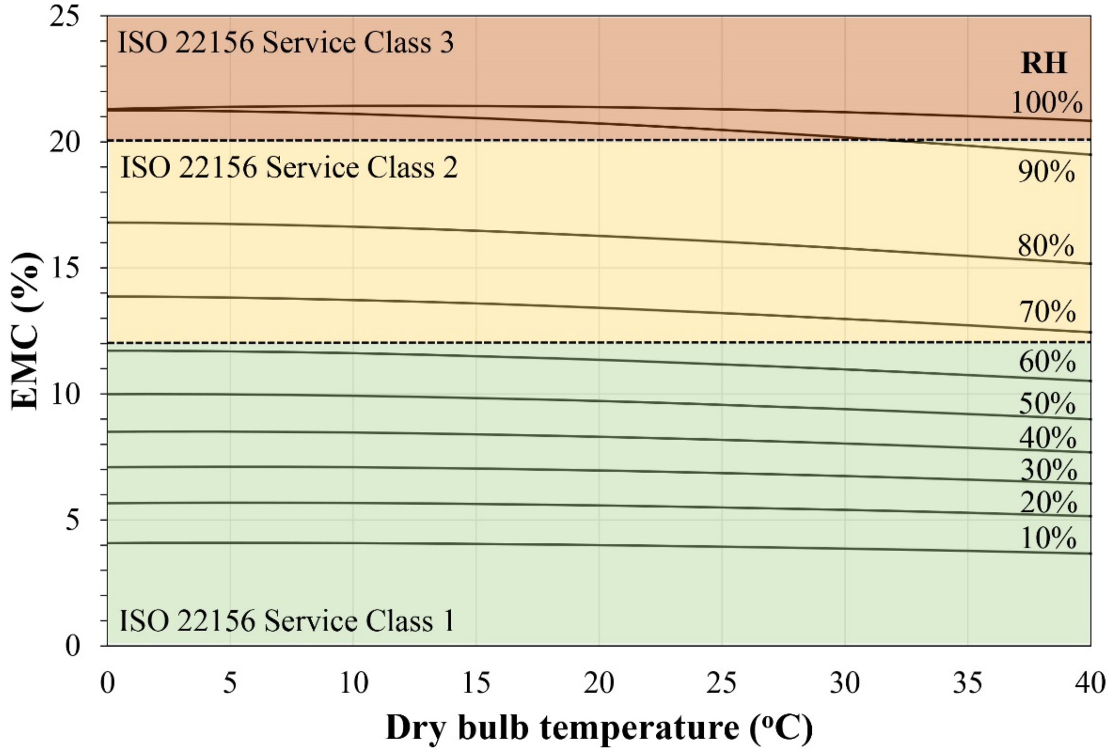

Figure 54: Hailwood-Horrobin (H-H) model showing the synergistic effects of relative humidity (RH) and ambient temperature on the expected equilibrium moisture content of bamboo (EMC) overlaid with Service class categorisation as defined in ISO 22156 (2021) and assigned colours.

In effect, Use class (Table 8) could be considered as the evaluation of the geometric or physical placement of a bamboo member in a structure, and Service class (Figure 54) could be considered the classification of the environmental context of each member in a structure.

3.4.9 Service class and modification factors for load bearing capacity

EMC, as indicated by Service class, can impact the load-bearing capacity and strength of bamboo structural members. Therefore, these values are adjusted by modification factors: C_{DF} (load bearing capacity, or strength), and C_{DE} (stiffness). Modification factor (C_{DF}) for Service class and load duration are given in Table 3 in ISO 22156 (2021), which is reproduced below in Table 9.

Table 9: Load duration factor for capacity and strength, C_{DF}. Table reproduced from ISO 22156 (2021).

load duration	Service Class defined in 5.6		
	1	2	3
permanent and long term applied load	0,60	0,55	see 5.6.3
transient loads	0,75	0,65	
instantaneous loads (wind and seismic)	1,00	0,85	

3.5 Durability: Elevated temperatures and fire

3.5.1 Elevated temperatures

When heated, the strength and stiffness of bamboo decreases (ISO 22156, 2021), and the parenchyma softens which allows the bamboo culms to bend more easily (Gutiérrez González, 2020; Gutiérrez González et al., 2018). Though not directly affecting the durability of the bamboo in the same ways as discussed in Section 3.4, elevated temperatures are something the design professionals should be aware of as this can affect the integrity of the bamboo structure. Liu et al. (2012) noted the glass transition of lignin (the point at which the solid lignin in the bamboo becomes "rubbery"), occurs at about 65 °C for the outer section of the bamboo, 83 °C for the middle section, and 75 °C for the inner section of the bamboo respectively. Therefore, prolonged exposure to temperature greater than 65 °C can cause significant and permanent loss of strength and stiffness in bamboo.

ISO 22156 (2021) Clause 5.8: Bamboo shall not be used for structures experiencing prolonged exposure to temperatures greater than 50 °C or short-term exposure to temperatures greater than 65 °C.

Therefore, any bamboo structural members exposed to sustained elevated temperatures up to 65 °C for more than three hours, have their load-bearing capacity modified by the factor shown in Table 10.

Table 10: Elevated service temperature factor (C_T). Table reproduced from ISO 22156 (2021).

	Service class defined in 5.6		
	1	2	3
$T \leq 38$ °C	1,00	1,00	see 5.6.3
38 °C < $T \leq 52$ °C	0,90	0,90	
52 °C < $T \leq 65$ °C	0,80	0,80	

3.5.2 Fire performance

The performance of bamboo structures in fire is an important research gap which needs to be addressed (Harries, Mofidi, et al., 2022). Though fire retardant treatments of bamboo could be employed, many are nonviable due to cost Janssen (2000), and lack of efficacy data. This future research need is discussed in Section 6.2.4. Elevated temperatures will affect the durability of the bamboo structure and result in a loss of load bearing capacity in the structure even significantly below a temperature which would most likely cause fire in the structure (Table 10) (Liu et al., 2012). When compared to timber, bamboo experiences a similar reduction in compressive strength (retains 20%) but a significantly lesser reduction in tensile strength (retains 42%) in relation to the measurements at ambient temperature conditions (Gutiérrez González & Maluk, 2020). Fire is a great danger to bamboo constructions.

It is important to note that the consideration of fire still hangs over any design for a bamboo structure. ISO 22156 (2021) notes that bamboo shall be assumed to have very little fire resistance by itself. If a national regulation requires bamboo to perform in fire, some form of fire protection or treatment will be required. Fire resistance ratings for bamboo structural assemblies (e.g., wall panels) shall be determined in accordance with applicable national standards for fire testing. Effects of fire are addressed in ISO 22156 (2021), which states that bamboo is, "assumed to have very little fire resistance by itself" (Clause 13). Fire performance is a primary factor for limiting the scope of ISO 22156 (2021) to two-storey structures. Fire is therefore only considered within this PhD thesis, as far as that outlined within ISO 22156 (2021).

3.6 Material and species availability

3.6.1 The impact of different bamboo species on durability

The choice of species can also have an impact on the durability of a bamboo structure and the aesthetic of the bamboo in the structure. No species of bamboo is known to have significant natural resistance to biological attack (ISO 22156, 2021). *B. vulgaris* is known as the most widely distributed species in the world being present in 123 countries (Canavan et al., 2017). This may be one reason this species is referred to as *common bamboo* (Rojas-Sandoval & Acevedo-Rodríguez, 2022). *Vulgaris* being Latin for *common*, or *popular*. *B. vulgaris* grows to a height of 8-20 m, with a diameter up to 10 cm, an internodal distance between 25 cm and 35 cm, and a culm wall thickness up to 1.5 cm (Ohrnberger, 1999a; Rao et al., 1998). This gives *B. vulgaris* the physical characteristics and distribution to make this good for structural applications and in many cases *B. vulgaris* is used in construction, with the author having first-hand experience of this in Haiti and Myanmar.

ISO 22156 (2021) Clause 5.7: No species of bamboo is known to have significant natural resistance to biological attack.

B. vulgaris has a higher starch content compared to other species of bamboo which provides relatively more susceptibility to beetle attack (Liese, 1998). Though not related to durability, the aesthetics of *B. vulgaris* impact societal attitudes to this species, and given its wide distribution, often bamboo in general. This species slightly crooks at the nodes creating a slight zigzag through the culm and the nodes are rather pronounced (Figure 55a). This can foster a negative aesthetic perception when used in construction as this makes columns and beams look slightly distorted when the *B. vulgaris* is used compared to more straight and uniform bamboo species such as *G. angustifolia* (Figure 55b).

Figure 55: (a) *B. vulgaris*, and (b) *G. angustifolia* growing in Kenscoff, Haiti. Photograph by author, 2012.

G. angustifolia can grow from 6-30 m in height, with a diameter at the base of 20 cm reducing to 7 cm, with a wall thickness between 0.8-2 cm (Akinlabi et al., 2017; Mena et al., 2012; Ohrnberger, 1999b; Pancel, 2015). The average internodal lengths are from 12-24 cm at the base, 40 cm in the middle and this reduces to roughly 30 cm at the top of the culm (Hidalgo-López, 2003). *G. angustifolia* has received a large amount of attention in codified bamboo construction as one of the most used species for construction in South America (Correal et al., 2021; Lou et al., 2010). Both the Colombian NSR code and the Ecuadorian *Norma Ecuatoriana de la Construccion* focus on this one species (Amede et al., 2021; NSR-10, 2010; NSR, 1998). This species grows at an altitude of 400 m to 1,500 m, especially along rivers and on hilly ground, and can tolerate temperatures as low as -2 °C (Kleinn & Morales-Hidalgo, 2006; Pancel, 2015; Rao et al., 1998). Hidalgo-López (2003) noted that this species can grow from sea level to 1800 m, with bamboo in Colombia displaying the best physical and mechanical properties at 1400 m. It is suggested not to use those poles harvested at sea level for structural purposes (Hidalgo-López, 2003). Therefore, even within one species the altitude at which the bamboo grows can have a determinate effect on the efficacy of use in a structure.

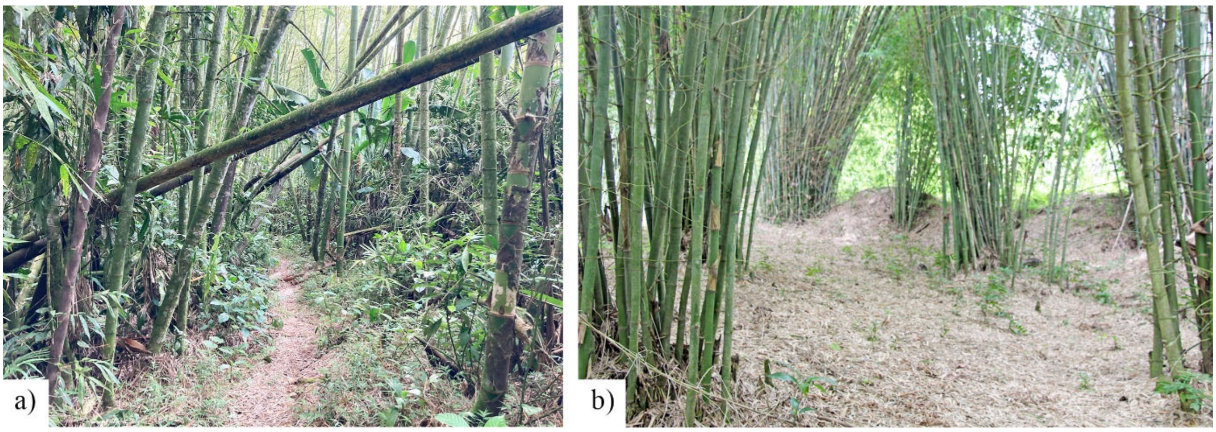

Figure 56: A comparison of biodiversity between: (a) the *G. angustifolia* forest (guadual) at *El Paraiso del Bambu y La Guadua*, outside of Armenia, Colombia (photo by author, 2022), and (b) the area around the growth of *B. oldhamii*, in Marmelade, Haiti (photo by author, 2016).

Another species *Bambusa oldhamii* exemplifies some different characteristics to *G. angustifolia*. This bamboo can grow 8-20 m in height, with a diameter of 5-10 cm (Akinlabi et al., 2017; DPIRD, 2014; Ohrnberger, 1999a; Rao et al., 1998). *B. oldhamii* has a more regular distance between nodes. There is not a concentration of nodes at the base of the culm and a greater regularity of distance between nodes can be an asset in construction. The impact a bamboo species can have on the ecology is important to consider when considering species use in construction. *B. oldhamii* may have certain characterises that make this a good species for construction, but a comparison of the forestry condition of *G. angustifolia* (Figure 56a) to *B. oldhamii* (Figure 56b) shows the impact on biodiversity. The *guadual* in northern South

America refers to a dense bamboo forest dominated by *G. angustifolia*. This is an important refuge for wildlife species from surrounding native hardwood forests that are being destroyed (Judziewicz et al., 1999). The long rhizomes *(long-necks)* of *G. angustifolia* also allow more light to get to the forest floor (Figure 56a) and the thinner leaves—Ohrnberger (1999b) noting the word *angustifolia* refers to the narrow leaves—may also reduce the extent to which the leaf litter covers the floor of the bamboo forest preventing other plants from thriving (Figure 56b). Without curving to find sunlight, the *G. angustifolia* culms can grow straighter.

Another species worth noting is *Dendrocalamus strictus* which is a thick walled sympodial species of bamboo (Sharma et al., 2014). Culms can grow from 6-20 m in height, with a diameter of 2.5-8 cm and internodal distances of 30-45 cm (Akinlabi et al., 2017; Ohrnberger, 1999a; Rao et al., 1998). Though the diameter may be less than that of other species listed in this chapter, the relatively thick culm walls make this species usable as a building material and for furniture (Ohrnberger, 1999a). This relatively small diameter species of bamboo with a larger wall thickness may appear solid, compared to a larger diameter species such as *Dendrocalamus latiflorus*. *D. latiflorus* species shows the potential for much greater height at 14-20 m and diameter at 8-20 cm (Ohrnberger, 1999a). However, the walls of this species are thin relative to the diameter meaning that the greater diameter does not necessarily correspond to structural qualities. This species can, however, be a useful species to make *esterilla*, an unfolded (unrolled) series of bamboo strips from the bamboo culm to make boards or mats.

ISO 22156 (2021) Annex A.3 (for information): The majority of available data on bamboo in load bearing structural applications is based on culms having a diameter, D, greater than 50 mm. Exceptions may be in bundled compressive load carrying members such as columns or truss chords. Appropriate determination of characteristic material properties for culms smaller than D = 50 mm may be impractical and only component properties may be determined. Full culm bamboo used in load bearing structural applications will typically have a diameter-to-wall thickness ratio (D/δ) [D/t] less than 12. Above this threshold, local buckling of the culm wall becomes a concern.

The wall thickness[15] (t) of the bamboo is important to consider. From a durability perspective a thin-walled species is more prone to the effects of decay and splitting. ISO 22156 (2021) provides guidance that bamboo which is of a diameter greater than 50mm with a diameter to culm wall ratio (D/t) of less than 12, is used.

Awareness of the locally available species will increase the likely success of an initial design with bamboo to be articulated, and support durability. Sourcing material locally also facilitates the checking of the material by the design professional during construction to ensure material quality. A knowledge of available species is important to the success of a project with bamboo (Zea Escamilla & Habert, 2015).

3.6.2 Grading of bamboo

As well as species characteristics, the design professional should be aware of physical characteristics of the bamboo that can be inspected visually or through touch to ensure a long service life. Design professionals can determine grading based on the available stock and define their own grades, as long as the bamboo within these grades is adequate for the intended use. For example, though bow is bad for columns, grading could be applied to the bow of bamboo poles for beams as bow could be good for this use. Such grading and selection are highlighted in Figure 107 in Section 4.5.3. The values which are derived from testing are derived in an environment which ISO 22157 (2019) states is where the bamboo culms are to be stored in a manner to minimise deterioration, following these guidelines: (1) no direct exposure to sunlight or rain, (2) no direct contact with soil or standing water, and (3) adequate air circulation to permit the equilibrium moisture content to be achieved for all stored culms (ISO 22157, 2019). Specimens shall be tested in air dry condition (12 ± 3% MC) or the EMC at the locality where the bamboo is to be used and subjected to the same preservation treatment that would be considered standard (ISO 22157, 2019). This is important as this accepts that in some environments it will be impossible to reach 12% EMC. The practicalities of a particular environment in which the bamboo is dried and used, may

[15] ISO 22156:2021, ISO 22157:2019 and ISO 19624:2018 use (δ) to denote wall thickness, however literature in this field more commonly notates wall thickness as (t) (Akinbade et al., 2020; Correal, 2016; Harries et al., 2022; Harries et al., 2022; Mouka et al.; Sharma et al., 2013; Trujillo & López, 2016). In this PhD research the symbol (t) will be used to align with a wider array of literature in this field.

make this higher, which both highlights the importance of local knowledge, and the importance of using bamboo locally from where the bamboo was harvested, treated and dried (discussed in Section 3.7.1). If the bamboo were over 12% this would be classified as Service class 2 (as per ISO 22156, 2021) as discussed in Section 3.4.8 and 3.4.9.

ISO 22156 (2021) Clause 15: Quality assessment and control is beyond the scope of this document. Nonetheless, appropriate quality assessment and control of materials, workmanship and construction methods should be specified. The adoption of a verifiable grading protocol (see [ISO 22156:2021] Clause 14) is evidence of appropriate quality control of bamboo culms supplied to a project.

ISO 19624 (2018) provides grading guidance design professionals should be aware of. There are two types of grading: (1) grading by machine to infer non-visible properties through non-destructive measurements, and (2) visual grading where the geometric properties and the physical condition of the bamboo can be checked. This could also be done by machines and examples of visually assessing the bamboo by machine are documented in work such as Lorenzo et al. (2017); Lorenzo and Mimendi (2020); Lorenzo, Mimendi, et al. (2020). Quality assessment and control is beyond the scope of ISO 22156 (2021), however design professionals should make themselves familiar with ISO 19624 (2018) and the information presented on correct grading based on physical properties. Machine grading requires tools and an infrastructure which are not in the scope of the design professional's capacity and most likely not available to the construction industries of LMICs. To the author's knowledge, there are also no known machine bamboo grading techniques out there, however machine learning has been used to establish the most appropriate geometrical and/or physical properties from a large data set to infer bamboo capacities (Correal et al., 2022). However, the skill to visually inspect the bamboo is a skill the design professional, contractor or builder can learn and use onsite to choose material or reject material to be used in the structure as undertaken by Interviewee D (Section 2.4.7). ISO 22156 (2021) is clear that bamboo should be graded in accordance with ISO 19624 (2018) but also presents a streamlined procedure. In the event that, "a grading protocol in accordance with ISO 19624 is not adopted" (Clause 14), the bamboo should still be graded in accordance with the intent of ISO 19624 (2018). If a grading protocol in accordance with ISO 19624 (2018) is not adopted, ISO 22156 (2021) outlines an alternative procedure. Methods of bamboo selection that meet the criteria established from the experience from previous generations are permitted, also termed *vernacular knowledge* (as discussed in Section 1.2.6 and 3.8.1).

3.7 Treatment methods and supply chain

3.7.1 Harvesting and drying

Bamboo harvesting occurs at an optimal age – typically 3-5 years, however in reality harvesting will take place somewhere between 2-4 years, which means 50% is not fully mature which can then cause severe cracking due to 5%-10% shrinkage. While the bamboo culm sprouts at its final diameter and reaches full height rapidly, the material must lignify (essentially a process of thickening the cell walls) over a few years to develop the optimal strength and stiffness of the culm (e.g., Lu et al., 1985). Although lignification ultimately slows, older culms (i.e., older than 6 years) become harder and due to cellulose breakdown, they become brittle, and prone to cracking and splitting (Stamm, 2022). As a plant, this micro-cracking also invites excessive moisture uptake, fungi, and rotting. It is important for the design professional to be aware of poor bamboo material quality. The weight of the bamboo per unit length can be an indicator. If one pole in a batch of cut poles weighs less than the others, this means some of the bamboo may have been attacked by beetles during growth. Another important observation is to ensure when the bamboo is cut and the branches removed, the silica skin has not been torn away. Bamboo has to be cut at the correct age to be used in construction. As the bamboo dries, the circumference of the inner wall will contract, whilst the outer strong silicate wall will remain as the same diameter. This can cause the bamboo to split when drying. This will cause internal cracking through the wall (Figure 57, Item 2), invisible to the outside but felt by touching the pole as *longitudinal indentation* (Figure 57, Item 1).

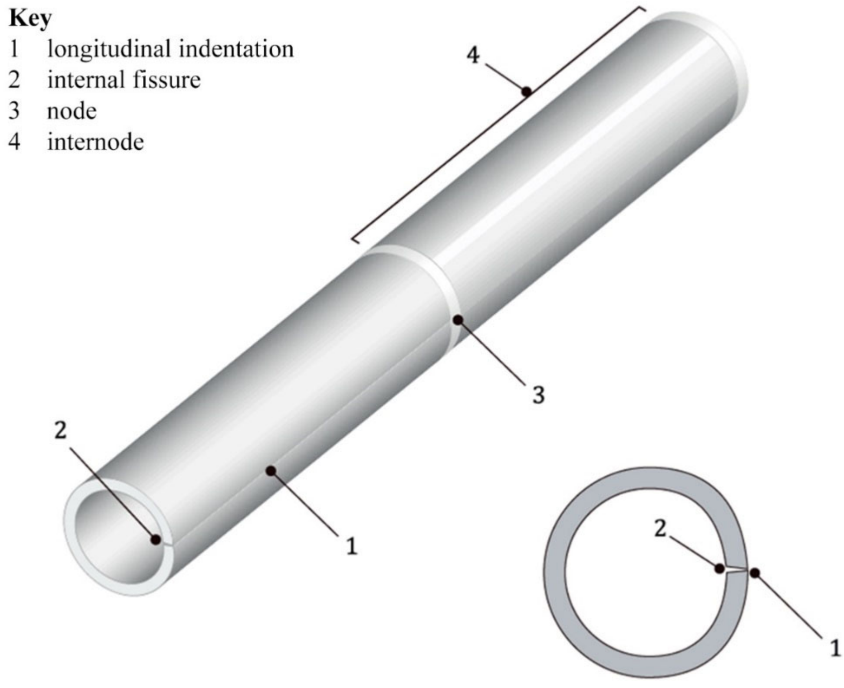

Figure 57: Manifestation of longitudinal indentation, cross-section through internal fissure, and associated indentation, reproduced from ISO 19624 (2018).

Additionally, even if bamboo has been cut at the correct age, the moisture content of the bamboo needs to reduce to be used in construction, which will be determined by the environmental context. Dried bamboo is that which has achieved the EMC in the context it is drying in which then makes sense that this is the context the bamboo is used for construction. Only bamboo which has been dried to a moisture content below 20% should be used in construction. Ideally this would be 12% or less as defined as Service class 1 in ISO 22156 (2021), however, in reality the environmental context could make this closer to 16%. This will designate the bamboo as Service class 2 following ISO 22156 (2021). At harvesting, the moisture content can vary amongst species and within culms of the same plant (Dunkelberg et al., 1985; Hidalgo-López, 2003). At harvesting, the moisture content decreases from bottom to top (Hidalgo-López, 2003). Hidalgo-López (2003) also recommends drying in the air outside as the method of drying, also referred to as *air seasoning*. Here, the bamboo responds to the RH and T of the environment. This has an advantage, over being rapidly dried in a kiln, as the rapid drying process can split the bamboo (Dunkelberg et al., 1985).

Figure 58: Air seasoning of bamboo poles drying in the open air and sun light. Photo by author, Ecobamboo bamboo treatment facility, outside Candelaria, Valle del Cauca, Colombia, 2022.

Minke (2012) states that air seasoning is the simplest method to dry also, erecting frames out of bamboo poles to rest other bamboo poles and exposing them to the sun and wind for a limited period of time while the moisture content is reduced (Table 11). Air seasoning outside in the sunlight on racks is also an important means to achieve the darker yellow hue of the bamboo (Figure 58). Through air drying in the sun, the UV light changes the green colour, to a reddish colour, then a brownish tone (Stamm, 2022). However, the directly UV exposed poles should be turned around daily at noon, as the direct sunlight also dries the surface very fast and will cause the same issues identified in Section 3.4.6. Leaving the same side exposed for a few days will lead to the pole cracking and bleaching.

Table 11: Three stages of the bamboo from harvesting to use, with the moisture content (MC) of bamboo at each of these stages.

Stage terminology	**MC**	**Description**
Harvest	> FSP	At harvesting, the moisture content of bamboo is greater than the fibre saturation point.
Drying	< FSP	As the bamboo is dried after harvesting the moisture content reduces below the fibre saturation point (FSP), which, if unknown may be assumed to be 30% in ISO 22156 (2021, Clause 5.7).
Curing or seasoning	≈ 12% or lower (determined by the environmental context of the site which may make this closer to 16%)	When the bamboo is cured following treatment the moisture content in the bamboo will reduce to an EMC which will be determined by the environmental context of the location the bamboo is dried in (RH and T).

Dunkelberg et al. (1985), Hidalgo-López (2003) and Kumar et al. (1994) note the air drying process can take from 6-12 weeks depending on the initial moisture content and wall thickness. However, Liese and Tang (2015a) highlight the variables this process can undergo and says this process can take from weeks to months given the uncertainties of weather conditions. Though not the reason the bamboo cracks, it is interesting to note the difference between longitudinal shrinkage of 0.3% compared to shrinkage of 8% in the tangential direction as noted in Yu et al. (2008). Therefore, the shrinking of culm section in the tangential direction (Figure 31) is what the design professional needs to be most aware of.

3.7.2 Treating the bamboo

Bamboo has to be adequately dried and stored, and the right treatment solutions must be used. It is important that the design professional is aware of the treatment procedures of the bamboo and can develop a relationship with bamboo suppliers. This facilities checking to ensure material quality as there can be limited alternatives to bamboo supplies in many regions where bamboo grows. No chemical treatment can protect against environmental factors such as exposure to rain (excess moisture) and sunlight (Janssen, 2000), and splitting also cannot be prevented by any chemical treatment (Liese & Tang, 2015a). Treatment can help mitigate the risk of attack by beetles and termites. A challenge of treating bamboo compared to the treatment of wood is that the penetration of chemicals into the bamboo culm tissue is more difficult than in wood. There are no ray cells which allow radial transportation of chemical solutions as with timbers, meaning treatment solutions on the bamboo run longitudinally (Correal, 2016). Methods address this such as soaking the bamboo in a bath, and the *Boucherie* method (Kaminski, Lawrence, Trujillo, & King, 2016), in which the treatment solution penetrates into the bamboo under pressure. Since the bamboo skin is also less permeable to moisture ingress the solution mostly enters bamboo through the culm wall and to a lesser extend the inner wall. Boron compounds such as borax and boric acid appear as the most appropriate chemical treatment for bamboo (Janssen, 2000; Liese & Tang, 2015a), and Kaminski (2013) notes a good track record of this treatment. Minke (2023) references Jörg Stamm in noting it is sufficient in industrial processes to use 2.5% borax and 2.5% boric acid. Bamboo should be treated with boron compounds following peer-reviewed guidance, such that the retention levels are greater or equal to 4 kg/m^3 or such retention level as determined through testing following BS EN 350 (2016).

Design professionals should ensure that firstly the bamboo is treated to make sure that what is built is durable. ISO 22156 (2021) specifies that treatment is required against biological agents for Use class 1-3.2, as shown in Table 8. There is little evidence that bamboo can perform reliably in Use classes 3.2-5. In these Use class, the bamboo is exposed as the result of the design decision. It should not be assumed that preservative treatments in these Use classes, will be effective for bamboo, unless demonstrated experimentally.

3.8 Locality and context of a project

3.8.1 Local and vernacular knowledge within ISO 22156 (2021)

The design professional should be informed of local vernacular knowledge. As introduced in Section 1.2.6, vernacular knowledge in this PhD research is defined as both historical knowledge passed down from generation to generation (also described as “tried and tested”), and contemporary practices and experiences not yet included in formal codes. Knowledge of the local context, site conditions, specific climate, local societal attitudes to bamboo, supply chain, transportation constraints and local construction skills, can improve durability in a project as well as de-risking the project for the clients and end users. Such knowledge, when embedded in a project, can then also be used to inform future projects in the local area, emit positive social attitudes to bamboo, or inform future iterations of code documents.

ISO 22156 (2021) Clause 5.11.2: Experience from previous generations (i.e., vernacular construction) that is well preserved in local tradition and dutifully transmitted to people living today can be considered to be an informal, noncodified "standard" provided all of the following criteria are met:

- the content shall be known and accepted to result in adequate or acceptable structural performance;
- the content shall be considered as an "old and pure tradition" or as "general wisdom";
- the community shall be characterised by a relatively undisturbed social structure having a recognised social pattern; and,
- the community understands the construction technique and are aware of and prepared to conduct required maintenance, which may be more significant than with other building materials.

The application of experience from previous generations is limited as follows:

- the content is only applicable to similar scenarios;
- the content is not extrapolated in terms of dimensional scale; and,
- after migration, the presence of this tradition is no longer self-evident.

Stamm (2022) notes that the Colombian NSR-10 (2010) Clause G (which relates to the use of bamboo) is conservative. The code assumes a lack of material quality in grading and selection within a real-world supply chain (e.g., unmature poles, poles harvested from low altitudes, etc.). This highlights that with better awareness in the design professional of local material supplies, and better selection and grading processes, the quality benchmarks could significantly improve, and thus over time, the code can become more progressive. The local nuances in all facets of bamboo construction—from design through material selection to construction practices—means that a globally applicable code, risks "parachuting" in a code that requires technology to also be parachuted in, potentially overwriting the nuances of this local knowledge and experience. ISO 22156 (2021) avoids this through two clauses: Clause 5.11.2 - *Experience from Previous Generations*, and Clause 5.11.3 - *Design by testing*. What these clauses facilitate is that, if the phenomena can be tested and the information exists and is valid, then it should be fully utilisable. ISO 22156 (2021) makes clear that these experiences should be, "well preserved in local tradition and dutifully transmitted to people living today"

(Clause 5.11.2). The design approach developed through this PhD research also endeavours to do this.

ISO 22156 (2021) Clause 5.11.3: Where the composition or configuration of structural members or systems is such that design by analysis cannot be performed in accordance with the provisions of this document, their structural performance and conformity with the intent of this document (5.1) shall be established from test results that are evaluated in accordance with the following:

- tests shall be full-scale and use bamboo culms representative – preferably of the same grade – as those to be used in the designed structure;
- tests shall be conducted to failure and the mode of failure reported in addition to all necessary applied forces, deformations and stresses; therefore "proof-testing" does not satisfy the requirements of this Section;
- evaluation of predicted capacity shall be made on the basis of the 10th percentile value of tests of at least ten (10) identical specimens; this value shall be the characteristic value, X_{ik} defined in [Clause] 6.2. No test result shall be eliminated without a written rationale; and,
- The testing shall be presented in a report suitable for peer-review. The report shall provide sufficient detail to permit the testing to be repeated.

For joints, the requirements of [Clause] 10.2 shall supersede those of this Section.

3.8.2 Natural hazards or extreme events: Earthquakes

Earthquakes and wind load from tropical cyclones (or hurricanes) can severely affect the service life of a bamboo structure and individual structural members. Numerous literature claims bamboo is earthquake "resistant" due to its lightweight nature and flexibility (Liese et al., 2015; Yadav & Mathur, 2021). In fact, as Hidalgo-López (2003) clearly outlines in *Bamboo: Gift of the Gods*, there are many design decisions that make a structure with bamboo "earthquake resistant" (pp. 356-363). However, bamboo frame structures exhibit only limited hysteric energy dissipation (ISO 22156, 2021; Sharma et al., 2013).

Bamboo is not inherently earthquake resistant (Sharma et al., 2013). Any benefits the strength to weight ratio of bamboo affords are irrelevant if the building is not well-designed, well-constructed, and well-maintained (Kaminski & Low, 2021). As discussed in van Drunen et al. (2016), earthquake and wind loads are similar in that they are considered to apply a horizontal load onto a building and this has to be transferred down to the foundations. In the case of an earthquake this load is proportional to the weight of the structure, and earthquake loads are also cyclical which can cause low cycle fatigue failures on connections. Therefore, the connections are important to the durability of a bamboo structure (and discussed in Section 2.4.9). Bamboo is not inherently earthquake resistant as a material, only the design can be earthquake resistant. Unlike steel, bamboo is not ductile and can split and crack. Even minor degradation in the bamboo structural elements or joints can stay hidden and only be revealed in an earthquake. In an earthquake the joints have an important role to play to act as ductile elements and absorb energy. If not able to play this role, even minor damage to the bamboo poles, or joinery could then create problems with the structure which could exacerbate other issues that could affect durability. Separation between the bamboo structure and any other material, such as masonry, is also important in a design due to out of phase motion. Separation makes sure there is enough space in an earthquake event to prevent pounding of one structure against the other.

The experience in Haiti shows that concrete buildings built adjacent to timber structures significantly damaged timber structures during the earthquake as both structural systems moved differently due to lateral forces and the impact of the concrete mass onto the timber frame damaged the timber frame. This is known as *pounding*. In isolation the timber frame would have performed well. Another challenge for earthquakes is *additions*. This is where the bamboo structure is part of an incremental structure. It is important to have local knowledge to think if there are strong local supply chains, cultural preferences for additions to the structure, and if these additions may be built from other materials such as masonry.

3.8.3 Natural hazards or extreme events: Hurricanes

In Haq (2007) the main cause of wind damage on the houses, particularly houses built with bamboo, is insufficient weight of these houses when they are subjected to external pressure and suction on the walls during a tropical cyclone[16]. This can be improved or even avoided by improving the anchoring of vertical supports firmly to the foundation. Using nails in roofing for example was observed in Haiti to result in the vibration of the sheet roofing against the nails used in the roof. Over time this vibration could pull the nail loose, which was not the

[16] Tropical cyclone is generally understood as the globally applicable term; however, the term *hurricane* would be used specifically for the Atlantic and Caribbean contexts.

case with screws which are less prone to withdrawal under the same circumstances. ISO 22156 (2021) notes that, “For applications in which vibration is likely, lock washers or some other means of ensuring the nut does not loosen shall be provided” (Clause 10.12.2). This situation would be exacerbated by rust forming on the nail and around the hole in metal roofing sheet. A screw with a rubber seal could mitigate this issue. However here, cost is the primary concern and therefore the relatively inexpensive metal nail would be chosen first. If nails are to be used to connect the sheet metal to bamboo rafters or purlins, this will make matters worse due to inevitable splitting in the bamboo through the nailing. This can include the ingress of moisture through wind driven rain (Haq, 2007).

3.9 Construction and workmanship

3.9.1 Lack of expertise in a local construction industry

Durability of the bamboo in a structure can be significantly affected by the quality of the workmanship (van Drunen et al., 2016). Therefore, it is important for the design professional to be aware of the workmanship available on site and design for this accordingly. The detailing of the bamboo project therefore should be considered based on this context. As (Ngab, 2001) notes, designs should be simple and easy to construct. In Ecuador, it was noted that bamboo structures are often built by bricklayers and carpenters with little training in bamboo. With increased complexity of execution comes increased potential for failure, as any puncturing of the culms can weaken them (Disén & Clouston, 2013). Often Hong Kong scaffolding is referenced as a quick means of scaffolding, and often looks informally constructed. However, this is underpinned by a code in place where years of experience are stipulated that “Proper workmanship, close supervision and frequent inspection are required to ensure the structural integrity of the bamboo scaffolds” (HKBD, 2006, p. 17).

The design professional should always consider a project using bamboo as an opportunity to capacity build construction skills (Janssen, 2000; van Drunen et al., 2016). Exposing joinery internally can be good to teach construction techniques in addition to the requirements of inspection and ventilation. The ability to see the joinery can influence other carpenters. During the construction process workers should be made aware that bamboo splits easily, particularly in the longitudinal direction, and that any load acting perpendicular to the fibre should be avoided during working (Dunkelberg et al., 1985).

Bamboo does not have radial cells like trees. Given the fact the majority of bamboos are hollow (other than at nodes), bamboo culms can split easily (Hidalgo-López, 2003). For the manufacture of esterilla or splits of bamboo this splitting can be an asset, however, when the bamboo is impacted on the outside this can cause splitting and cracking. Such impacts could be caused by a hammer and if a nail is also inserted into the bamboo wall, this can make splitting more likely. Species with thick walls are recorded by Liese and Tang (2015a) to tolerate nailing better than thin-walled species. However, avoiding nails and hammering in bamboo construction is important. This can be a challenge as the nail is by far the cheapest option for a connection system, however the requirement for regular maintenance negates this upfront saving. Nailing bamboo together can also be more difficult for maintenance of the structure. It is easier to withdraw and replace a bolt, than a nail, as this can also result in splitting. ISO 22156 (2021) forbids the use of driven nails or staples to connect structural bamboo members, unless it is in the nailing of small strips of bamboo or small diameter bamboos to create the matrix of a LCBF. The nail can split the bamboo if it has not been pre-drilled (Dunkelberg et al., 1985), and metal bolts should be used in joinery (ISO 22156, 2021).

Modularity, and designing for offsite manufacture and assembly (DfMA) can be a way to ensure construction quality and therefore durability. Building elements such as trusses or sections of LCBF walls can all potentially be prefabricated and used in a modular means of construction. Designing in this manner can provide standardisation and efficiency of cost, time and materials, as well as the potential for off-site construction. This improves safety and can support a construction economy close to where the bamboo is grown and harvested.

3.10 Design for inspection, maintenance, and replacement

There is the chance that even in a structure which is protected from moisture or UV light, an incident could occur which could compromise a bamboo pole through damage or longitudinal splitting. Therefore, the bamboo in a structure will need to be inspected and maintained through the service life of the building.

ISO 22156 (2021) Clause 5.9: For a variety of reasons, bamboo culms may split longitudinally or be otherwise damaged when in service. To the extent possible, provision should be made to permit maintenance and inspection of bamboo load-bearing members; particularly members forming part of a non-redundant load path. To the extent possible, consideration of the future need to replace individual culms in a member or structure should be made.

As highlighted above from ISO 22156 (2021), there are a series of considerations that the design professional will need to take into account to design for durability. This is where the design professional has to separate the service life of the building from the service life of the material. The design which involves bamboo will have to be designed so that bamboo structural members, specifically load-bearing members (particularly members forming part of a non-redundant load path), can be: (1) inspected without significant effort, (2) can be removed, and (3) new replacement structural members can be inserted. If the bamboo structure is visually accessible for inspection this can be coupled within a design concept to provide ventilation to the bamboo members also. For example, the bamboo structural members in one of the buildings of the *Universidad Tecnológica Pereira* (UTP) as shown in Figure 59, show bamboo structural members internally and externally visible. Here they have the ability to be well ventilated and visually inspected.

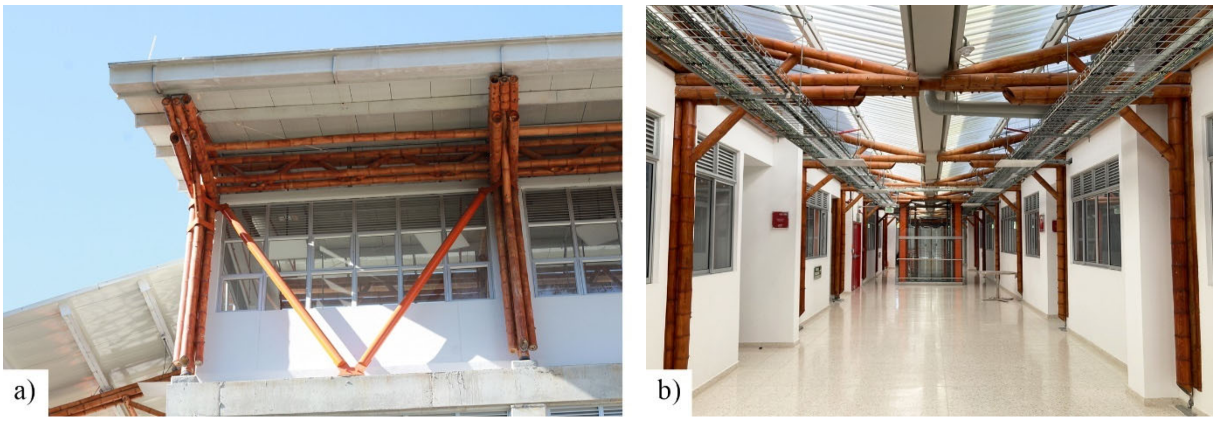

Figure 59: Some campus buildings at UTP, Pereira, Colombia. Photo by author, 2022.

An example of a project in which replacement could be possible is the *piaje* (toll gate), just outside Manizales, Colombia (Figure 60). On speaking with a local resident, they mentioned that 40% of the bamboo members had been replaced seven years prior, and every few years the structure is re-varnished.

ISO 22156 (2021) describes the structural members that should be able to be inspected and replaced. These are, “bamboo load-bearing members; particularly members forming part of a non-redundant load path” (Clause 5.9). Design professionals when designing bamboo structures should consider the future need to replace individual culms. However, if a single culm was used as a load bearing column, this would not facilitate replacement since the structure would collapse if this were compromised or removed. Design professionals should therefore design considering multiple culms within the structure so that if a bamboo pole is damaged it can be replaced without compromising the structural member. These can all be considered as structural members, with a specific category for flexural members (or beams).

Figure 60: *Piaje* (toll-gate) by Simón Hosie, outside of Manizales, Colombia. Photo by author, 2022.

ISO 22156 (2021) Clause 5.4: To the extent possible, non-redundant structures and/or structural members or components should not be used.

Non-redundant structural members in ISO 22156 (2021) are load-bearing members that fit either one of two categories. Firstly, if the removal of a load-bearing member results in the failure of the structure then this will be considered a non-redundant structural member.

Secondly, a non-redundant structural member could be a load bearing member made of multiple poles of bamboo where if one of these poles was removed, the structure would fail. Therefore, design professionals should design with redundancy in mind and design structural members to have multiple poles (Figure 60). Redundant structural members are defined in ISO 22156 (2021) as four or more structural members of the same stiffness which are connected to a continuous load distribution path (such as may be the case with floor joists, rafters, purlins, and trusses). In addition, either the continuous load distribution path is capable of redistribution of loads, or the structural members are no more than 600 mm apart, the load distribution members are continuous over at least two spans, and any joints in the load distribution members are staggered. This means that at least four poles should be used to form a column (Figure 61). Therefore, when one is compromised, there would be three of the four (75%) of the capacity of the column remaining.

Figure 61: A four pole column, shown on the ground prior to erection. Photo by author, 2022.

Any maintenance requirements must also align with the clients and end-users financial situation and they need to be bought into the maintenance requirements making this important information to be shared throughout the design process. No matter how good the design code and the design methods used, it is not possible to produce safe and durable structures unless buildings are built properly, under excellent construction techniques, and good supervision

(Ngab, 2001). A key element to reduce the need for maintenance is also by focussing on the supply chain, and using mature, well selected poles which are checked for their quality before construction.

3.11 Joinery and connection detailing

As noted in the interviews, joinery and connection detailing are important to ensure durability. Inappropriate joinery can of course damage the bamboo in the structure, but without knowledge of joining bamboo, the design professional will be unable to control the design and influence the final outcome. Robustness in joinery was designed into improved low-cost housing in El Salvador through the use of steel plates for the connections which would increase strength and ductility of the connections, but create a more forgiving structure if errors were made (Kaminski, Lawrence, Coates, et al., 2016).

ISO 22156 (2021) Clause 10.12.2: Dowels, other than wood screws, shall be inserted through predrilled holes having a diameter not greater than 110 percent of the inserted dowel diameter and not less than the inserted dowel diameter except as required for press fit dowels described below. The dowel diameter shall not exceed D/8. Wood screws or sheet metal screws, with the exception of self-tapping screws shall be inserted in predrilled holes having a diameter between one quarter and one half the nominal screw diameter. Self-tapping screws and auger-tip wood screws are permitted to be installed without predrilling. Driven nails or staples shall not be used to connect structural bamboo members except as permitted in E.2. Bolt, or threaded-rod dowels shall be secured with washers and nuts. Nuts shall not be tightened more than “finger tight”.

ISO 22156 (2021) notes that, “joints in bamboo structures shall be assumed to be pinned (hinged) unless otherwise permitted” (Clause 7). This is important for the design professional to be aware of as this has implications on the design and construction of a project which conforms with ISO 22156 (2021). Using stainless steel or hot dip galvanised bolts is important to ensure Clause 10.12.2 is adhered to. This is especially necessary in coastal sites where the saline moisture will increase the degradation of metal joinery.

ISO 22156 (2021) Clause 5.7.2: Metal fasteners and other structural connections shall be either inherently corrosion resistant or protected from corrosion.

Figure 62: A mortar filled joint with the ends of the cut bamboo culm filled with mortar which prevents insects and moisture penetrating the bamboo culm. Photo by author, Ecobamboo bamboo treatment facility, outside Candelaria, Valle del Cauca, Colombia, 2022.

ISO 22156 (2021) Annex B.3 (for information): Special attention should be given to treatment of saw cuts, drill holes or other intrusions into or through the bamboo section. These may require additional post-assembly treatment to prevent local degradation.

An example of Clause B.3 of ISO 22156 (2021) being adhered to can be seen in Figure 62, in which the exposed ends of the bamboo poles have been treated to seal the inside of the bamboo from moisture or insect ingress. The quality of the bamboo around the joint can be compared to Figure 39.

Figure 63: Bolting near to a node. Photo by author, 2019.

Joinery is a big unknown for codification in bamboo structures, yet, as a contrast, there are whole code documents on just one type of connection in steel construction. For full-culm bamboo in ISO 22156 (2021) there is a non-mandatory annex (Annex D). The design professional should be aware of the need to bolt near to nodes (Figure 63), and there are a series of connection types (Figure 64) they should be aware of based on the research of Widyowijatnoko (2012). When evaluating the design, they should consider these types in the design, and leave the detail of these joints to construction professionals who will be able to supply support in this area.

ISO 22156 (2021) Clause 10.7: Joints shall be designed to mitigate the risk of longitudinal culm splitting as described in [Clause] 5.3. To mitigate splitting at joints near the ends of culms, to the extent possible, at least one node should be located between a joint and the end of a culm.

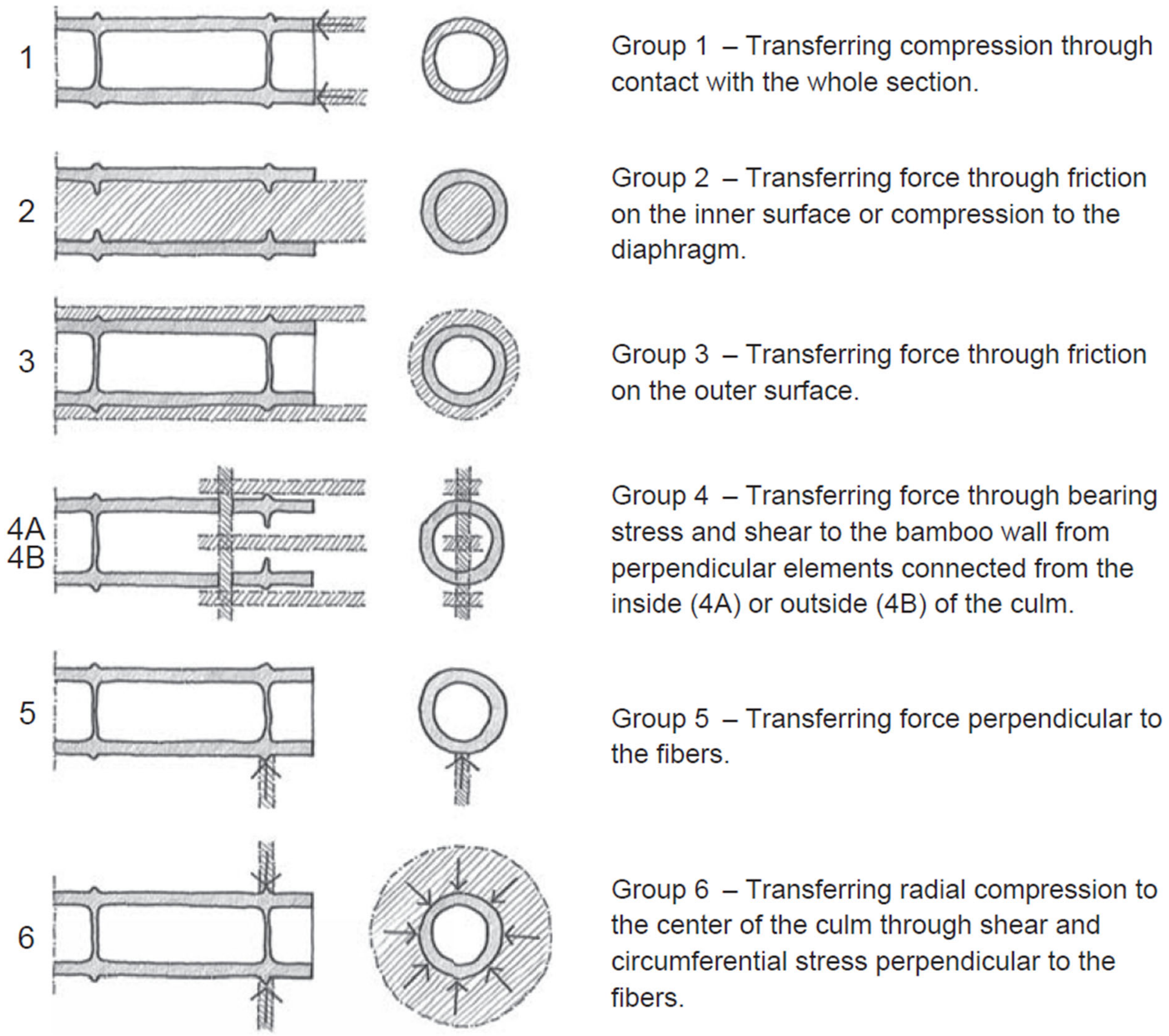

Figure 64: Proposed bamboo joint classification developed by Widyowijatnoko (2012). Image reproduced from Widyowijatnoko and Harries (2020).

When the term cross sectional area (*A*) is used, this is the area of the net section perpendicular to the direction of the longitudinal axis of the culm[17] (ISO 22157, 2019). When constructing one needs to be familiar with the net section requirements which is the sectional area, less any holes in the culm (Kaminski et al., 2017).

[17] ISO 22156:2021 defines cross sectional area without reference to a gross or net value for sectional area. Therefore, net section has be assumed in this research to align with ISO 22157 (2019).

3.12 Concluding comments and lessons for a design approach

Examining instances of bamboo deterioration in reference projects and literature reveals that environmental factors, particularly abiotic factors and insect damage, are the principal catalysts of durability challenges which are exacerbated through design decisions by design professionals. Though there are many other factors that design professionals should be aware of, such as material quality, site and environmental conditions and available workmanship quality that will impact durability. These issues are amplified when bad material or incorrect joinery is exposed to excessive moisture, direct sunlight, or elevated temperatures.

This chapter also highlighted the importance of vernacular knowledge to inform code documents such as ISO 22156 (2021). This chapter may have a negative aura but when the principles of durability are correctly achieved, bamboo becomes a material which achieves a long service life for a wide spectrum of uses from non-structural application in the *Leipzig Zoo car park* (Figure 51), to a 100-year old structural bahareque house in Kaminski and Low (2021) (Figure 65). With more information and testing it will be possible to generate more positive and realistic information and reduce the conservative nature of codes (e.g., Colombian NSR-10, 2010).

Figure 65: 100 year old traditional bahareque house in Colombia. Image reproduced from Kaminski and Low (2021), https://www.betterbamboobuildings.com/home/3rn12lawxv5ouxu9gzzyy3ftdhv051 .

Design professionals have a crucial role in taking on board the principles of durability and protecting bamboo in their designs from environmental factors such as rain (excess moisture), UV light, and ensuring the bamboo is raised above the ground in a structure. Therefore, the design approach developed through this research should support design professionals though the guidance in ISO 22156 (2021), which defines the Use class and Service class of bamboo structural elements. This quantitative guidance can assist design professionals in classifying the durability of their emerging designs. While such a guide is valuable, it should complement, not replace, established design methods and tools. The following chapter will explore how a design approach should integrate with existing processes and tools available to design professionals.

4 Chapter 4. Design methods, tools, and algorithmic design for full-culm bamboo

"Architecture is defined by physical components that are materials."

Edwin Viray (2011, p. 8)

4.1 Chapter overview

To ensure a long service life for a bamboo structure, the position of bamboo structural members within a structure need to be considered to protect bamboo from environmental factors. As introduced in Chapter 1 and discussed in Chapter 3, this is more important than in a design for manufactured materials such as steel and concrete. In Liu et al. (2022), the majority of bamboo pavilion design entries, for the *2019 International Bamboo Construction Competition* including the three finalists, fail to abide by the principles of protection by design (protecting the bamboo from rain, excess moisture and sunlight), despite long-term durability specified in the brief (Figure 66).

Figure 66: *2019 International Bamboo Construction Competition* top three realised finalist projects. Image reproduced from Liu et al. (2022).

This is not intended as a criticism of the competition or entrants, but a comment of a contemporary process of design, accustomed to manufacturing materials to clothe carved, stacked architectural *mass* and *form*, rather than designing architectural form around the performance requirements and assemblage of a material. In order to define a separation between these two ways of approaching design, a stereotomic (primarily form-making) /

tectonic (primarily material and structural considerations) distinction has been applied in this chapter, based on the descriptions in Frampton (1995) which theorises buildings are "first and foremost a construction and only later an abstract discourse" (p. 2). Designers use a range of tools to conceive and visualise new building designs (Carpo, 2003; Di Mari & Yoo, 2012; Schilling, 2018). The easiest way to design for durability is to consider the material from the earliest stages in the design process. Those designing for bamboo with little experience of the material—without proactive research—can easily make basic durability errors inconsequential to most standardised man-made materials. A design which exposes bamboo to environmental degradation will reinforce negative societal attitudes as the material understandably deteriorates. Without material consideration from the beginning, the design tools and methods used by design professionals at the earliest design stages in the conception of architectural design foster abstraction in design. The precision of digital tools can compound this condition.

The design approach developed through this research aims to take the understanding of protection by design and apply this in a practical manner. This chapter provides an overview of design tools and looks at how these are, and could be, applied to design for full-culm bamboo. This chapter endeavours to define a mixed media approach to design for bamboo, together with AD tools, to understand which tools could be used in a design approach for bamboo durability.

Not all design professionals may recognise the design process laid out in Section 4.2, or agree with the magnitude at which abstraction in the design process may impact the use of bio-based materials. This chapter presents this argument as a major factor, and the references are compounded by the author's own over a decade long experience in practice and education in Europe, Southeast Asia, China, Central America, and the Caribbean. Different professions will no doubt have different perspectives and opinions. This chapter concludes with the position that the use of algorithmic thinking to apply qualitative guidance to existing design methods can position the design professional to better support durability considerations and apply digital tools to this process.

4.2 Massing, form-making, and materiality

4.2.1 Defining the early stages of the architectural design process

It is important to understand contemporary architectural design processes before establishing how design tools can be applied within this process to design for bamboo durability. This is a similar starting point to the article by Greenberg (1974) where it is important for him to locate computational tools in an architectural design process. In Greenberg (1974), the design process involves: (1) rough sketching of an initial design or schematic design which includes a rough plan layout, (2) more detailed elements of the plan are assembled into a preliminary design with representation of the completed building, and (3) working drawings and models. This can be after numerous conversations with other disciplines, end users, and clients. In some cases, a building may not in fact be the answer to a client's needs and there is much to be said about such an approach. The most "sustainable" building is the one which was not built in the first place where the response to a client's brief is to deliver what the client needs without the resource, time, labour, and cost of a building.

At some point in the design process, if a building is to be built, there will be the initial step in the design process to develop an initial idea. Prior to a concept emerging there is a "primary generator" which Darke (1979) explains, this is "a broad initial objective or small set of objectives, self-imposed by the architect [or design professional], a value judgement rather than the product of rationality" (p. 36). There will be early tentative inconclusive ideas, but avenues and options will be left open for as long as possible (Cross, 2011). This broadly aligns with the first step in Greenberg (1974). Considering the observations of Lee and Ostwald (2022), the primary generator could also be termed *ideation.* Ching (2015) notes that "Designers [in the architectural design process] inevitably and instinctively prefigure solutions to the problems they are confronted with", continuing to state that "Form and space are not presented as ends in themselves but as means to solve a problem in response to conditions of function, purpose, and context" (p. ix). Cross (2000), notes that designers who were successful—therefore producing better quality solutions—distinguished between initial stages where information, constraints and project requirements led to "first solution ideas", before entering "conceptual design stages" (p. 27). Though designers do refer back to the initial ideas, there is an important detachment between these two stages. The initial idea could also be the establishment of a conceptual framework—similar to the one articulated by DeLanda (2015). Considering the multiple design constraints—or opportunities—presented by full-culm bamboo as a material (e.g., supply chain challenges, variable material characteristics, etc.), this notion of a framework rather than a single *idea* and the subsequent "forcing" of a form (p. 21), seems more fitting where the *idea* of the material's potential acts as a framework for the design to emerge. Jones (1992, p. 24), breaks down the architectural design process into four stages. The first three of these cover the process of developing a design, with the fourth the production of construction information, construction, and hand-over:

- **Stage 1:** Inception, feasibility, and outline proposals.
- **Stage 2:** Scheme design.
- **Stage 3:** Detail design.
- **Stage 4:** Production information, bills of quantities, tender action, project planning, operation on site, completion, and feedback.

Considering the advent of AD in architecture, Chokhachian and Atun (2014) proposed a *Parametric design thinking* model which comprising of four Sub-systems as design stages, each with a design activity:

- **(1) Representational:** Data collection, analysis and ideation.
- **(2) Proportional:** Conceptualisation and synthesising of information.
- **(3) Indexical:** Evaluation and detailing.
- **(4) Operational:** Drafting and presentation.

Stages 1-3 as proposed by Chokhachian and Atun (2014) and Jones (1992), overlay with the three stages already outlined by Greenberg (1974). Though some references date back to the 1970's through this outline review of design methods (e.g., Greenberg, 1974; and Darke, 1979), these do have contemporary relevance. When Greenberg (1974) is looking to situate the computer within the architecture design process, it requires a deconstruction of the design process in a similar manner as is required in this PhD research. It is important to understand the design steps to see where a design approach can be integrated within. If we look at contemporary examples of the design process, these steps are still evident within contemporary design processes in which the material has been at the forefront of design. Menges (2015) challenges the linearity of the design process, suggesting a process neither linear or vertical. Here the process of making (or fabrication) can inform the architectural design process itself. However, a “design intent” is present shown the initial input of an idea into the process to steer the development of the *Cyber-physical fabrication and assembly system* to produce a design and then fabrication.

The goal of this section is to conceptualise the early design stages that the design approach proposed in this thesis can engage within. This requires a level of simplification, and therefore the design stages are defined as (Figure 67):

- **Stage 1 – An initial idea (primary generator or ideation):** This develops through rough drawings or models.
- **Stage 2 – Concept design, or design concept:** This establishes more resolution and represents the design intent for the completed building.
- **Stage 3 – Construction details (detailed design and construction documentation):** This is a broader range but at this point overall design decisions are largely finalised, and the specificities of the design are developed towards and through construction.

Figure 67: Conceptual diagram showing the design stages: (1) an initial idea, (2) a design concept, and (3) detailed design and construction documentation.

Architectural design is an iterative process. It is a process of constant questions and answers that often lead to new questions (Sheil, 2005). Design includes a process of refinement, identified through feedback procedures within the process. This aspect of design is the iterative element. An evaluation that the emerging design is adequate for the needs of the brief. Cross (2000) uses the example of a bridge. Once an idea for the bridge design has been conceived, it will be checked to see if it can carry the required loads and adjustments will be made to the design based on results. A similar process of iterations, informed by information on bamboo—through the design process to inform a design professional—is what this PhD research can explore for bamboo durability. What seems crucially important is that for full-culm bamboo, the design cannot be conceived in the abstract and that the design idea—whether visual sketch ideas or initial massing studies—needs to be already infused with material information and considerations before the concept design is developed.

4.2.2 Architectural form-making and massing studies

This initial design idea often emerges with the study of the mass of the proposed building design. A massing study in architectural design is a preliminary design exploration that focuses on the overall form and volumetric composition of a building or a group of buildings within a site. It involves the study of the building's mass, scale, and spatial relationships without delving into finer details like materials or specific architectural elements. As well as the first step, it is one of the most important architectural design considerations establishing identity and impact (Akin & Moustapha, 2004; Dietsch, 2002; Fawcett, 1998; Leyton, 2003). The mass is the first in a series of design steps which opens *Towards a New Architecture* by Le Corbusier (1927/1946) stating, "Architecture is the masterly, correct and magnificent play of masses brought together in light…cubes, cones, spheres, cylinders or pyramids are the great primary forms which light reveals to advantage" (p. 31). This is the *massing study,* also known as *form-making* (Fawcett, 1998; Leyton, 2003). The term massing used in architectural practice is used to describe the visual impact the building would have. It is this massing, that will create the most visual impact from a distance, more so than the individual details (Charleson, 2014). The challenge of this process is the limited amount of detail embedded in the design from the earliest design stages. A focus on the form or volumetric qualities unchecked, can risk overlooking critical aspects which can impact sustainability, user experience, or material performance. Fawcett (1998) recounts the design process as a series of formal and typological steps, with the appropriate technologies, and the consideration of structure and material as the following steps, after form-making.

Massing studies are beneficial for the design professional as they provide fast means of developing, testing, and comparing designs without the need to invest time and resource to study structure, materials, or detail the design. Often these are explored through diagrams which are discussed in Section 4.2.3. By emphasising the architectural form, design professionals can develop a clear and compelling design concept to guide both the project as it develops and communicate ideas to a client or end user. Considering an abstracted building form can simplify massing studies, especially on an urban scale. This helps to understand how the form of buildings can be oriented or placed, to provide shade, take advantage of prevailing winds, or aesthetic considerations to understand how the building form will interact with, or impact the site context such as topography or neighbouring buildings. The overall building form can also convey symbolism or create an icon for a particular area or community. Though hard to quantify, this emotional response to the built environment is important for design professionals to consider and articulate. *Biomorphism* is an example of a type of design in which this is the case. This is an artistic style as an inspiration to form-making based on organic, abstract shapes inspired by natural forms to create visually appealing designs. This is not to be confused with *biomimicry* which is “not just in the abstraction of useful ideas from the living world but also in the process by which this is done” (Vincent, 2001, p. 2), and “design inspired by the way functional challenges have been solved in biology” (Pawlyn, 2016, p. 1). This involves emulating designs in nature beyond their aesthetics, to mimic systems which have evolved over time in nature with examples such as Weinstock (2006). Biomorphism as a formal exercise (Figure 68) influences architectural form-making by incorporating organic shapes, curves, such as seashells, or the patterns found in natural forms (Barandy, 2020; Frearson, 2014b; KKAA, 2022; Senosiain, 2007). Biomorphism fosters a sense of connection with nature and is important to the user experience. This formal approach is highlighted here as this is often referred to as natural, or ecological given the imitation of forms found in nature. However, sometimes imitating natural forms at the scale of a building can require substantial resources such as concrete and steel to achieve the same usable space for users than if it had been, for example, an orthogonal form.

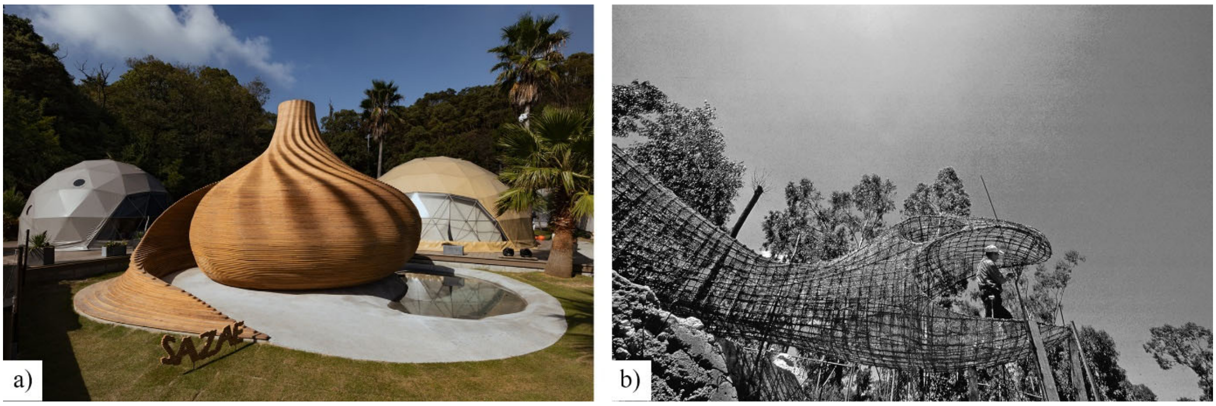

Figure 68: Biomorphic forms inspired by nature: (a) *Sana Mane Sauna Sazae*, Kengo Kuma and Associates, Naoshima, Japan, image reproduced from KKAA (2022), and (b) *El Nido de Quetzalcoatl* under construction, Javier Senosiain, north-west of Mexico City, Mexico, image reproduced from Senosiain (2007).

When considering form in the abstract, the relative freedom from force, material, and real-world constraints can allow ever more creative and unique designs to emerge. Such form-making can then drive forward material research and structural research in endeavouring to build ever more complex form. Examples of design professionals who appear to engage with this process are Studio Libeskind (Figure 69a), Morphosis Architects, and Bjarke Ingels Group (BIG) (Figure 69b) to name just a few (Ago, 2022; BIG, 2022; Studio Libeskind, 2010).

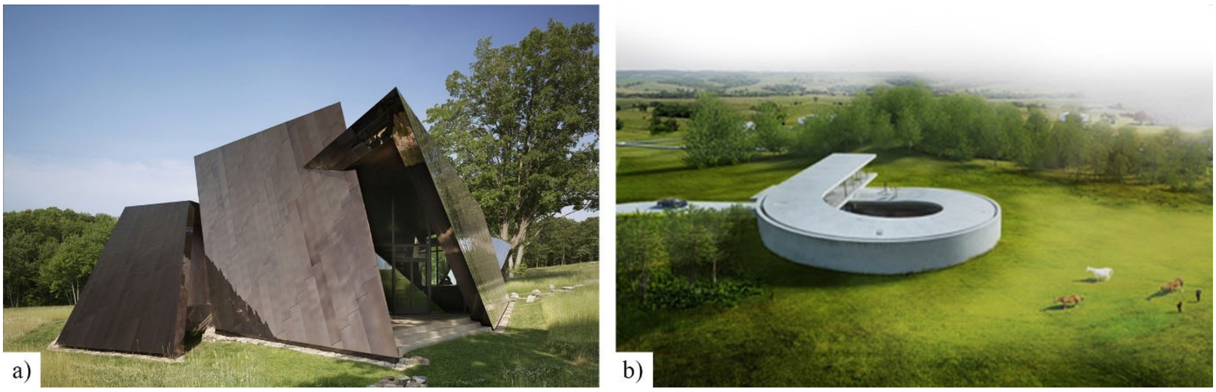

Figure 69: (a) *18.36.54*, Connecticut, USA, by Studio Libeskind, with image reproduced from Studio Libeskind (2010), and (b) a render of *Villa Gug*, by BIG, with image reproduced from BIG (2022).

4.2.3 Architectural diagrams in form-making

In the form-making process, design professionals often use diagrams to visualise the factors which influence architectural form, whether this is pedestrian flow, traffic, site context, sun orientation, or other environmental factors. Early in the design process, diagrams help the design professional—or design team—communicate ideas and understand the relationship of space within a design or the relationship to the context of the building.

Fraser and Henmi (1993) note that design professionals use diagrams to abstract and symbolise information for analysis. Design professionals sometimes present a design for a building as the diagram, without even designing anything formal. As John Young explains in Robbins (1997), the design for the *Lloyd's Building* in London was presented as a series of analytic and diagrammatic sketches that dealt with their future and flexible business needs. The benefits of using diagrams to inform the form-making process is the ability to make the design more user centric considering how end users will utilise the building and how circulation and spaces within the building should be related to each other, such as with the Möbius House by UN Studio as shown in Figure 70a, (UN Studio, 1998). The resultant form of the architectural design is formed around the diagram (Figure 70b).

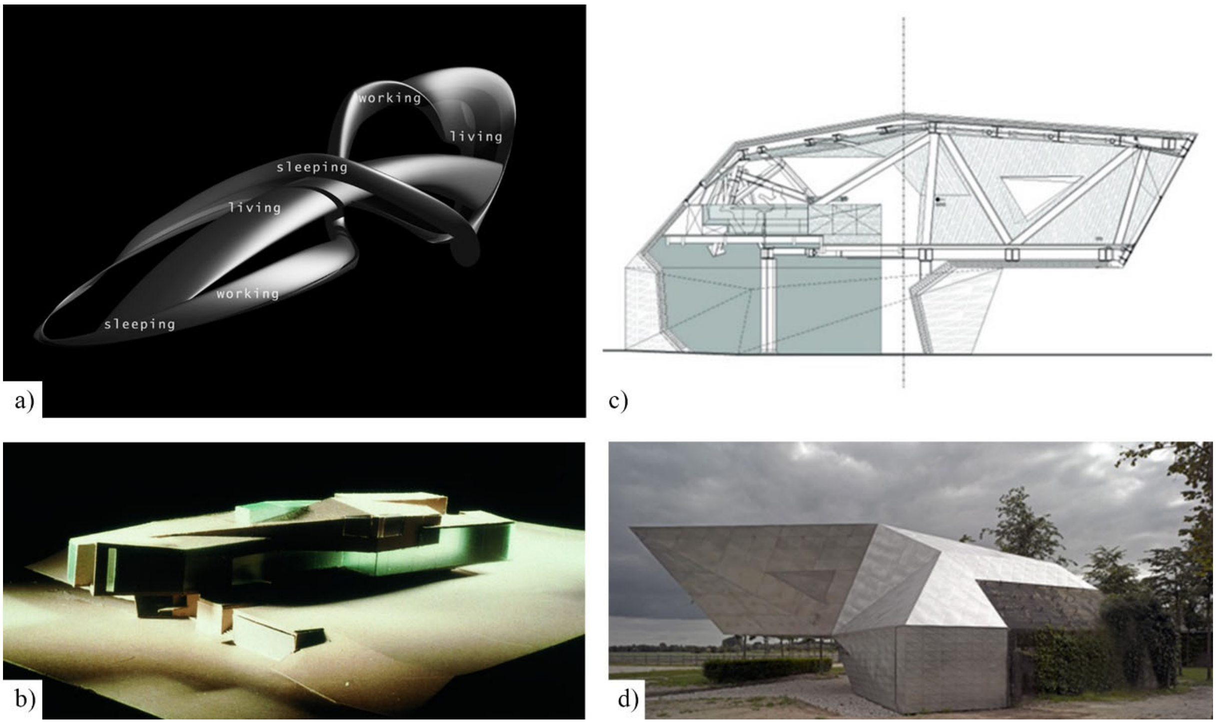

Figure 70: (a) The 3D diagram of the *Mobius house*, (b) a physical representational model using card of the *Mobius House*, images reproduced from UN Studio (1998), and (c - d) *The Tea house* by UN studio showing the building form and sectional drawing showing structure, images reproduced from Fairs (2007).

Other design professionals diagram their emphasis on the exploration of spatial and volumetric arrangements of the form. These are manipulated in the abstract in the initial design stages, prior to the technical aspects of structure or material (Figure 71).

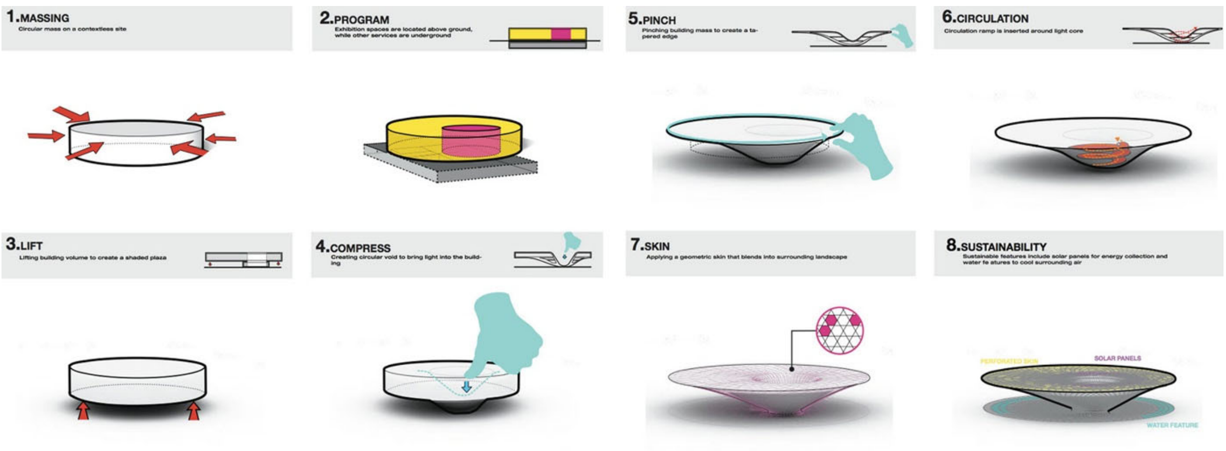

Figure 71: An example of one form-making design process which shows the design steps followed by the designers. Design for the *PH museum*, FR-EE 2019. Images FR-EE and reproduced from Butler (2013).

There is a broad range of international examples of the diagram being used by design professionals to explain the design process or the design concept. The Dutch studio Office for

Metropolitan Architecture (OMA) use diagrams as powerful tools for conceptual exploration and design analysis (OMA, 1991), as does the Mexican architecture studio Fernando Romero Enterprise (FR-EE). In the design for the *PH Museum* (Figure 71), FR-EE use form-making diagrams to demonstrate the sequential steps considered in this form-making (Butler, 2013). Massing studies and diagrams are used by MASS Design Studio in their proposal for the reconstruction of the *Hospital of the State University of Haiti* (Figure 72) (Porada, 2013) and in Japan, architecture studio SANAA use diagrams to express their minimalist design concepts and emphasise the relationships between space, light, and *void* in their work. An example of this is *Moriyama House*, to understand the *voids* between the forms and their impact on programme, as well as the overall form (Martín Domínguez & de Esteban Garbayo, 2018). Another example is Grace Farms in Connecticut, USA, in which SANAA conceived a 400 metre long single form which rests as a “wafer-thin strip” along the contours of the site (DETAIL, 2016, p. 903).

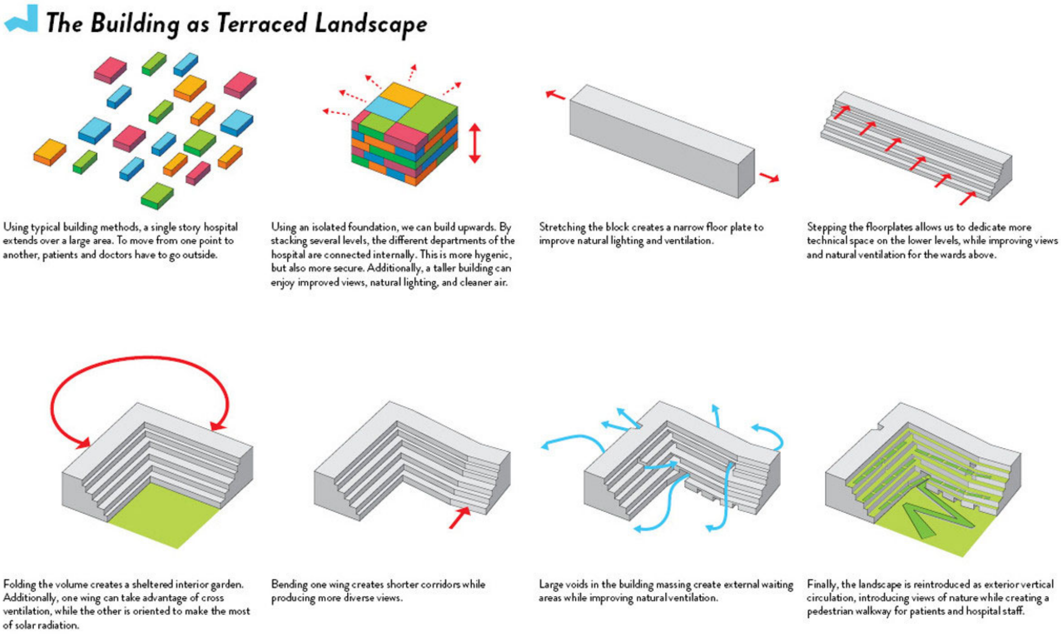

Figure 72: Massing studies and the use of diagrams to demonstrate the form-making process in the design for the reconstruction of the *Hospital of the State University of Haiti*, Haiti, Mass Design Studio, 2012. Images reproduced from Porada (2013), originally created by Mass Design Studio, 2012.

Another such prominent architectural design studio known for their abstract, pioneering and fluid architectural designs (Figure 73), Zaha Hadid Architects (ZHA), frequently use diagrams to explore complex geometries, spatial relationships, and circulation patterns (Garcia, 2010; Woods, 2008; ZHA, 2006).

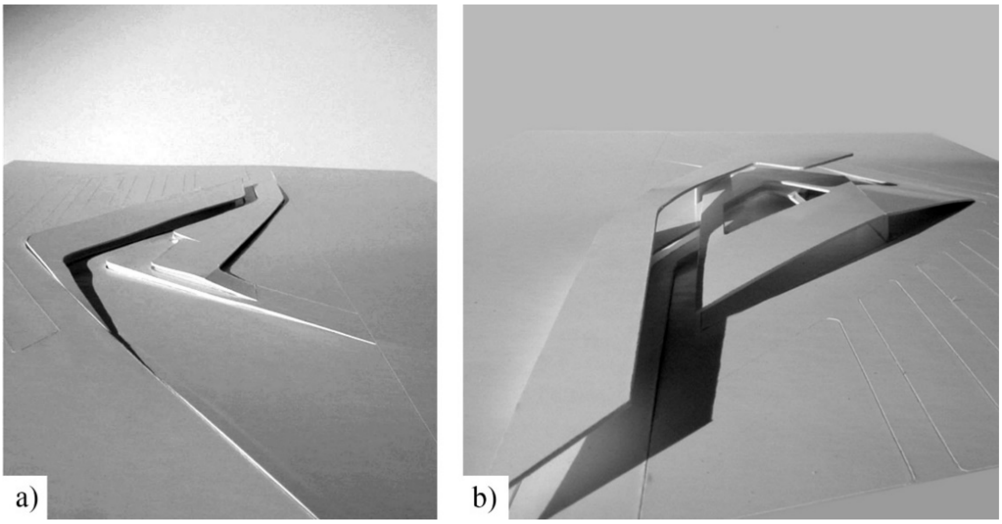

Figure 73: Concept design models for the *BMW Showroom* (2003-2006), Zaha Hadid Architects. Images reproduced from ZHA (2006).

Given the many elements of contextual information which are recorded, diagrammed and used to inform the form-making process, digital tools are often used to provide efficiencies. AD tools have allowed ZHA to create dynamic digital models which are linked to various design parameters (Bhooshan, 2017; Schumacher, 2009a). These tools enable ZHA to manipulate and iterate designs rapidly and explore numerous possibilities within a short time frame. The ability of the software to respond to changes in design variables facilitates an interactive design process, leading to a more interactive and iterative approach to form-making. Designing algorithms, into which contextual information is input into in order to output a form, then shifts the design process from form-making, to form-finding (Kolarevic, 2014). This shift and AD tools are discussed in section 4.3.6.

4.2.4 A move away from material considerations

Even though materiality is an important aspect of many projects whose design was instigated through a form-making process, subsequent choices of material may then be limited. Finding materials that can effectively articulate the desired architectural form without posing a challenge to structural integrity can be a challenge. When selecting materials to articulate the form—which has been designed in the abstract—an opportunity has been missed to ensure the form was designed to respond to the needs of material characteristics, whether this be structural or long-term durability requirements. The architectural form may be more easily realised through manufacturing materials to fit the design. Le Corbusier (1927/1946) describes man-made materials such as concrete and steel as providing the architect with a "genuine liberation from the constraints" of natural materials such as timber (p. 266). This "liberation" can be traced back to the industrial revolution in Europe where Benjamin (1968) states, "With iron, an artificial building material appeared for the first time in the history of architecture" (p. 78). The same was true with concrete, as recorded at the turn of the 20th Century in Scientific American (1906), "[Reinforced concrete] is now used for nearly every form of structure for which timber, steel, or masonry is suitable. Indeed, its greatest evil is that it has been crowded into uses for which there is small warrant for its adoption" (pp. 383, 387).

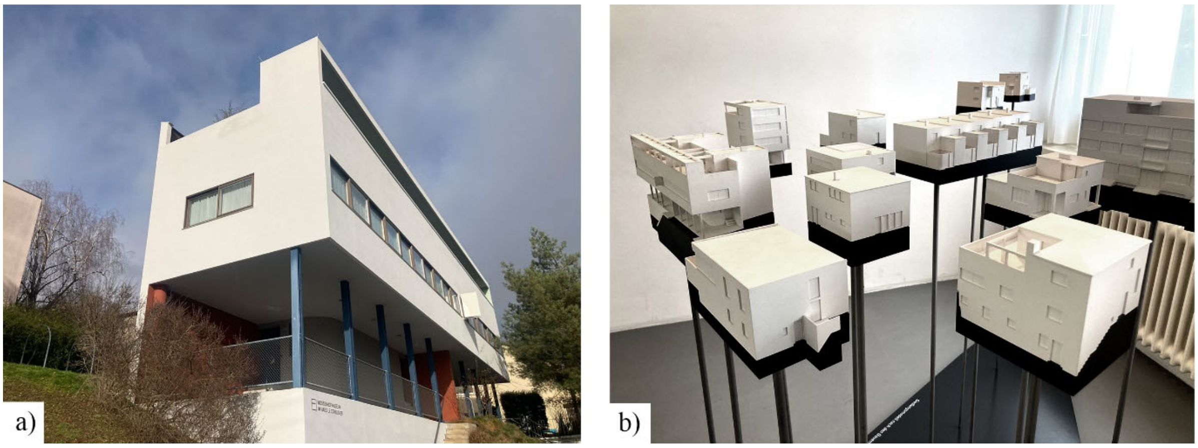

Figure 74: (a) *Le Corbusier house*, Weissenhof Estate, Stuttgart, Germany. Photo by author, 2023, and (b) Architectural models - Though these models are not study models, these are models to represent the built artefacts. The fact these models are all white shows the contrast between design can be described through form alone, not through material or textural differences. Photo from the *Weissenhof Estate*, Stuttgart, Germany. Photos by author, 2023.

Auguste Choisy's illustrations in *Histoire de l'Architecture* (1899) showed abstracted axonometric projections which revealed the essence of a type of form in a single graphic image, comprising plan, section and elevation (Frampton, 2020). As Fure (2011) notes, abstraction in design and the ability to manufacture materials to fit an abstracted design has taken the design professional away from needing to work with a found material, to one who can manufacture it. As stated by the British architect Andrew Waugh, known for his use of timber, "With timber, you need to think about how the building will stand up and the individual pieces that hold it together. That's what generates the form" (Frearson, 2023, para. 5). Manufactured materials could be produced to achieve the form instead of the form being a dialogue with the material. As Le Corbusier (1927/1946) states in *Towards a New Architecture*:

> The prime consequences of the industrial evolution in 'building' show themselves in this first stage; the replacing of natural materials by artificial ones, of heterogeneous and doubtful materials by homogeneous and artificial ones (tried and proved in the laboratory) and by products of fixed composition. *Natural materials, which are infinitely variable in composition, must be replaced by fixed ones.* [Emphasis added by author] On the other hand the laws of Economics demand their rights; steel girders and, more recently, reinforced concrete, are pure manifestations of calculation, using the material of which they are composed in its entirety and absolutely exactly; whereas in the old-world timber beam there may be lurking some treacherous knot, and the very way in which it is squared up by means a heavy loss in material. (p. 214)

Today, almost a century on from the influential projects (Figure 74) and writings of Le Corbusier, it appears the pendulum has now swung too far away from material as a primary driver in architectural design towards the architectural form as the primary consideration. A commentary on the prioritisation of form over material through the *Modern movement* needs to also respond to those who did consider material, such as Ludwig Mies van der Rohe. Even though he was the son of a stone craftsman—and himself had a great understanding of materials—that tectonic was predominantly one of manufactured materials (Hughes, 2003). Through the use of materials which were "industrially produced"—such as steel and glass—they were used in a way in which the structure becomes the "visual elements of the architecture" (Carter, 1999, pp. 9-10). This highlights the nuances of how materiality is employed to support a form-based approach to design.

A design process to practically use a material such as full-culm bamboo often contrasts with one in which the design professional has been, as claimed by Le Corbisier, "liberated" to focus on form, not needing to consider materials. As noted by the British architect Andrew Waugh, "When you design in concrete, often you come up with the building before you think about how you build it" (Frearson, 2023, para. 4). Lawson (1994) notes in the principles of the Modern Movement in architecture moved the architectural design process, "towards the abstract and a concentration on pure form and proportion" (p. 6). In fact Le Corbusier in *Towards a New Architecture* states in relation to massing studies, "Mass and surface are the elements by which architecture manifests itself" (Le Corbusier, 1927/1946, p. 45). Formal moves of carving or offsetting are conceived at the scale of the building as a mass, not the joint or material (Figure 75). Often when such forms are found, they do not consider the requirements of the materials.

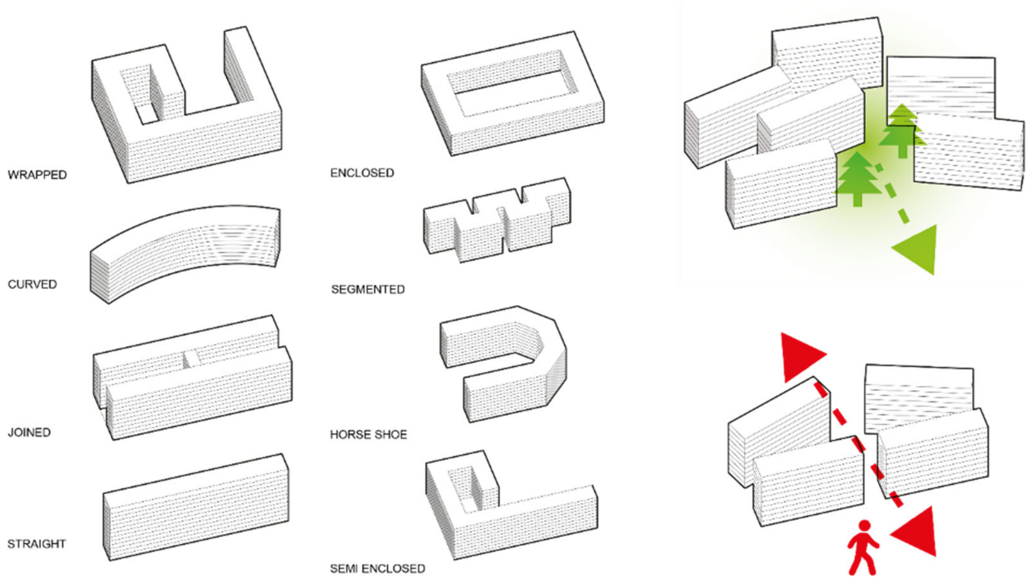

Figure 75: Example of massing studies and form-making explorations along with diagramming connections and concepts. Illustration by author, 2016.

When discussing a contemporary reluctance of design professionals to use bio-based materials in their projects in Hofmeister et al. (2021), the Austrian architect Herman Kaufmann who works with timber notes that this situation:

> Is partly an aftermath of modernism, because it forgot about timber construction. For many architects practicing today, timber construction was never addressed during their studies. Everyone was fascinated by modern building materials like concrete and steel. We weren't required to think about other materials…yet many architects and engineers still have a large information deficit in how to handle this not-entirely-simple building material. And this has prevented many projects in recent years. (p. 54)

4.2.5 Primacy of form

Crolla (2018b) observes the prioritisation of form noting contemporary digital practice should "not be based on design approaches that are characterised by a hierarchical relationship that prioritises the generation of form over its subsequent materialisation" (p. 39). This is a situation where a design can develop without "mundane inconveniences such as gravity, material resistance or building tolerance" (p. 34). The concentration on pure form and proportion as the first step of the design process is termed by Kotnik and Weinstock (2012) as the “primacy of form” (p. 106). They argue that in both architectural discourse and technique, the attention to material and the performance of material has been abandoned, with material considered for aesthetics and rarely for other factors. When designing for a material such as bamboo however, material properties both physical (e.g., diameter) and mechanical (e.g., exposure to environmental factors will reduce the load bearing capacity) are critical considerations. If a building mass is conceived as an abstract form without thinking of material then how this abstract form is protected from the environment becomes a later consideration. Le Corbusier (1927/1946) claims, “the task of the architect is to visualise the surfaces which clothe these masses, but in such a way that these surfaces do not become parasitical, eating up the mass and absorbing it to their own advantage” (p. 37). Contrary to this however with consideration of protection by design, the form of the building also has a role to play in proving protection to building elements and requires a different approach to design. Again drawing parallels to timber, the UK architect Waugh Thistleton notes in Frearson (2023) that there needs to be a different approach to design for cellulose materials, “At first, we were definitely making concrete buildings out of timber” (para. 9). Norman (2005) argues that the representation of materials in a digital form has focused the profession on an image of the material rather than the physical or mechanical properties. Menges (2010a) highlights the “increasing division between processes of design and making” in which there has been “increasing dependence on representational tools intended for explicit, scalar geometric descriptions that at the same time serve as instructions for the translation from drawing to building” (p. 44). He goes on to describe how the architectural design profession “has embraced design methods that epitomize the hierarchical separation of form definition from materialization” (p. 44).

With the advent of artificial intelligence (AI) and new technologies embedding themselves into contemporary architectural practice, one future direction for architectural design could be that AI exacerbates these issues of the image, or form, as the starting point for an architectural design, rather than material. AI and emerging platforms such as Midjourney (2023), SDXL (2023), and DALL·E (2023) have the potential to put more emphasis on form and images as the starting point of the design process and also enabling those from outside the design and engineering professions to develop initial design concepts with these visual tools (Dreith, 2022; Ennemoser & Mayrhofer-Hufnagl, 2023).

Vrachliotis (2022) explains that the use of computers in architecture is also an opportunity to bring material back into the concept design stages of architectural design. With new technologies in the architecture and engineering professions there is also the potential for more collaborative working and greater tools to understand and predict the performance of materials with natural variability such as bamboo (Correal et al., 2022; Mortice, 2023). This is an important direction for the use of digital tools in architectural design and one this PhD research will look to explore within a design approach to full-culm bamboo.

4.2.6 The unique design challenges for full-culm bamboo

There are many design professionals, and disciplines within the construction sector who do consider materials as a first step in the design process. For example, timber framing has been used in North America and Europe for a large number of residential dwellings. Taking a minimally processed natural material such as timber and cutting it down to size has facilitated the construction of 85% of Sweden's housing stock in 2015 (Schoof, 2018). This shows that minimally processed bio-based materials do have a significant presence already in construction sectors worldwide.

There are many shared challenges with using the minimally processed form of bamboo and timber. These include the anisotropy, transportation challenges, fire performance and susceptibility to environmental factors exemplified in the categorisation of Use class in ISO 22156 (2021) and ISO 21887 (2007) (discussed in Section 3.4.1 and 3.4.8). Exposing timber and bamboo to environmental factors—even with creosote-based preservatives—can result in degradation and failure. This is possibly the case with the 2022 Tretten Bridge collapse in Norway (Jessel, 2022) and numerous other challenges with durability of exposed timber members (Burkart, 2016). Differences between timber and bamboo lay in the lack of knowledge of material properties and workability of full-culm bamboo. Minimal tools can saw a tree trunk to a timber member of a specific depth, width and length within the maximum dimensions from the tree (Figure 76a). Solid timber for structural use can be sawn to precisely defined product characteristics, developed to meet the requirements of timber constructions (Lycken et al., 2020). They can be dried to a specified moisture content and available in various combinations of length and thickness (Figure 76c) (Teischinger et al., 2023).

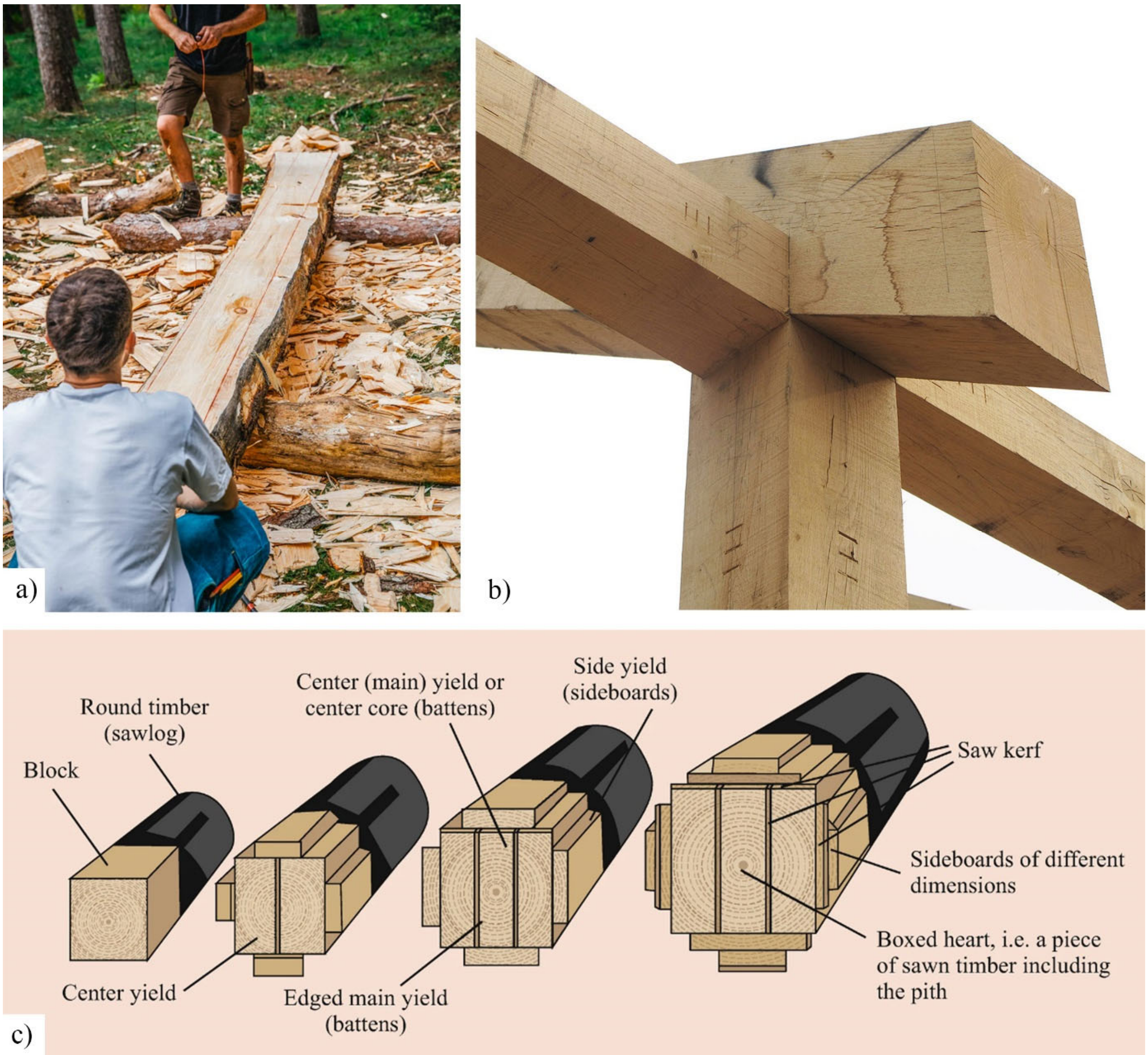

Figure 76: (a) Tree trunk being marked and sawn to required dimensions without the need for factories or heavy machinery, image reproduced from (Klein, 2022), (b) sawn timber joinery on the *Timber Frame House* by A-Zero Architects, where sections are removed from the timber elements so they slot together, image by James Whitaker and reproduced from ArchDaily (2014), and (c) different sawing patterns typically applied to softwood and assortments of sawn timber based on their sawing patterns and dimensions, image and caption reproduced from Teischinger et al. (2023).

Nature provides bamboo in a natural form and circular cross section which is structurally efficient. With bamboo the diameter is fixed from harvesting and will be different at each end of the bamboo pole. Therefore, only the length of a pole can be cut—not the width or depth of a pole—which would compromise the structural performance and durability of the pole. Making bamboo orthogonal requires engineered bamboo and processing, similar to CLT for timber. Therefore, only the length of a bamboo pole can be changed and even then, proximity to nodes needs to be considered. A way around this is through using multiple bamboo poles to define a size of column or beam (additions), rather than sawing a pole to a specific dimension (subtraction). This solution follows ISO 22156 (2021) Clause 5.4.2 guidance and allows for redundancy in this structural member. Given the orthogonal nature of timber and use of metal plates which can attach flush with a timber member, joinery for timber is better documented and simplified (Figure 76b).

Through either visual and/or machine grading, through a non-destructive assessment, timber is sorted into grades. The collective characteristic properties of the timber sorted into those grades determines the *Strength class* such as those in European standard *EN 338* (Ridley-Ellis et al., 2022). This simplification of timber grades such as C16 or C24 (the C refers to the type of tree) make timber a very accessible material for construction but this grading still underutilises the timber strength following the strength of the near minimum 5th percentile. Such a relationship for non-destructive machine grading has not yet been established for full-culm bamboo, however the main benefit for the design professional is that timber can be cut to a particular section size, which cannot be done with full-culm bamboo. In cutting timber to a specific size, knowledge of timber material properties can categorise that timber within a Strength class which can then be presented to design professionals in span tables to quickly determine the appropriate size and spacing of structural elements like beams and joists (e.g., Ranasinghe, 2014). Timber has been made accessible through classification of strength, span tables and non-destructive grading to determine characteristic properties. This simplification and accessible information have made timber a widely used material which has many similarities to bamboo, but full-culm bamboo is faced with a lack of knowledge in these areas and some unique challenges not faced by timber.

4.2.7 Contemporary material consideration in early design stages: Survey results (Q3 and Q4)

To investigate a contemporary tension between form as a primary consideration in the general architectural design processes or material, Q3 and Q4 of the survey detailed in Section 2.3.1, were asked. The demographic of respondents is detailed in Section 2.3.2. Q3 and Q4, along with the offered format of the responses are presented in Table 12.

Table 12: Survey questions Q3 and Q4 to provide an insight into the design process by architectural design and engineering professionals/practitioners and students.

Number	Question	Response format
Q3	In your design process in your architectural education which would usually come first?	Multiple choice allowing only one response: • Conception of form • Choice of material • N/A
Q4	In your design process in professional practice, which would usually come first?	Multiple choice allowing only one response: • Conception of form • Choice of material • N/A

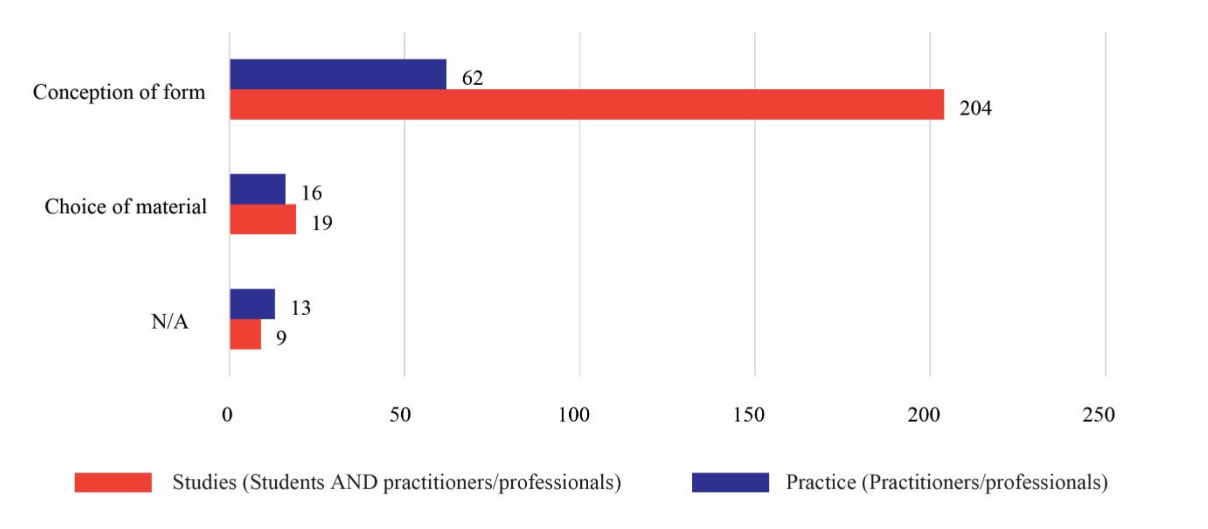

Figure 77: Results of Q3 and Q4 showing the "choice of material" or "conception of form" as the primary consideration in an architectural design process. Results broken down by students (responses for Q3) and architectural design and engineering practitioners/professionals (responses to Q4).

When asked in their design process which is considered first, either the "conception of form", or "choice of material", the overwhelming majority of current students of architecture noted that the conception of form was the first consideration in their design process in their architectural studies, and though to a less extent, still was also the case with those who answered in their professional practice (Figure 77). There is possibly positive response bias here, however given this response bias may mean respondents are more likely to be aware of bamboo, this may indicate that without this bias there may be more responses for "conception of form".

These simplified questions do hide many nuances. For example, one would expect stakeholders such as clients are more concerned about floor area, space, and aesthetics, and planners are more concerned about the volume of the building on a site. However, without asking clients or planners, this is only a hypothesis. It is apparent that the primary consideration in the architectural design processes of students and practicing design professionals alike are largely form driven. Such lack of early material consideration results in barriers to the use of bio-based non-standard materials such as structural considerations (i.e., achievable spans, allowance for the size of structural elements, etc.) or environmental factors.

4.3 Design tools in architectural design

As Sheil (2008) writes about contemporary practice, "how we design has become as important as what we design" (p. 7). This section provides an overview of architectural design tools and looks at how they are used in the architectural design process, to consider how a design approach to full-culm bamboo can be applied within the design toolset of design professionals. Given the need to consider the material of bamboo more so than with standardised man-made materials such as concrete and steel, it may be important that a design approach to full-culm bamboo should consider some tools more than others at certain times in a design process. To paraphrase Yi-Luen Do (2005), design professionals should be aware of the "right tool" at the "right time" (p. 383).

4.3.1 Sketching and drawing

Sketching and drawing are the most immediate means of getting an idea onto paper, and communicating the design of a building (Sachse et al., 2001). Since most design professionals do not participate in the construction of a building, it is not the buildings which they create, but the information for that building (Sheil, 2005). Drawing gives the first visualisations of ideas (Scheer, 2014). The design process is one that is difficult to be a purely internal mental process, but there needs to be an interaction with some sort of external representation by the designer (Cross, 2011). Lawson (1994) interviewed ten well-known architectural design professionals to study their methods, noting that for them "it is difficult to think and talk about design matters without holding the pencil" (p. 66), and noted these immediate drawings often make no sense in isolation outside the explanation of the designer. Cross (2011) describes a *cognitive limit* to the complexity a designer can handle and therefore there is a requirement for some sort of external store for temporary ideas to test what could be described as *primary generators* and develop a concept design through a dialogue between the brief and how the emerging design solves these challenges. Sketching supports such a dialogue. From the very beginning of the architecture profession, as noted by Vitruvius[18], it has been expected that drawing and sketching will be inherent in the process and an essential skill for a design professional. The format of drawings can vary from detailed drawings to quick concept design sketches to express an idea (Schilling, 2018). Drawings are not just communication tools, but representing the project through 2D visual media is also a tool for the design professional to help them think about the design, the form, and the spatial qualities (Edwards, 2013). The benefit of sketching is the lack of complexity (Sachse et al., 2001), which opens this medium to convey ideas which may not be bound by real world realities. What informs the sketched design is the mind and knowledge of the design professional (Figure 78). This process as Schon (1984) describes is a conversation the designer has with the drawing—as Denise Scott Brown terms—"a facility between hand and mind" (Lawson, 1994, p. 98).

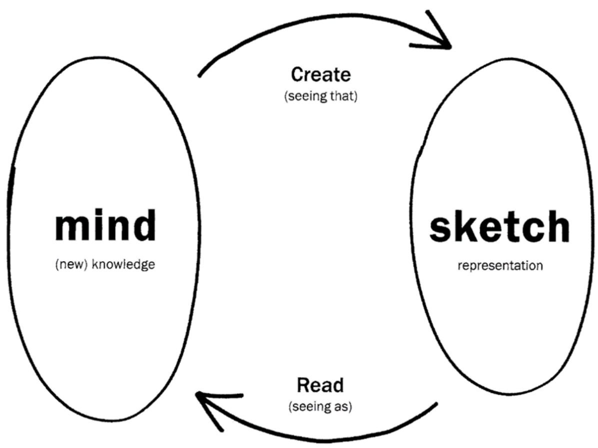

Figure 78: A sketch of a dialogue with a sketch presented by Buxton (2007), or as Schon (1984) terms a *conversation*. Image reproduced from Buxton (2007).

This is a feedback loop which requires the oversight and knowledge of the design professional. When designing for bamboo, material information or design guidance is only

[18] Vitruvius wrote De Architectura (On Architecture), c. 20 BCE (Cartwright, 2015).

inherent in the sketch if the design professional has considered this in the drawing. This is a paradox described by Chard (2005) in that the pencil and paper offer the most immediate and widest means of expressing an idea, but at the same time there is a lack of information which makes these quite restricting. Sketching helps us think through design questions and it is a key tool required by designers (Sachse et al., 2001). With the use of drawing techniques and drawing tools such as set squares, drawings become accurate means of representing construction information (Chard, 2005), and it is possible to produce detailed fabrication drawings by hand.

4.3.2 Digital 2D drafting tools

In recent decades architectural design has seen the emergence of digital tools and Computer Aided Design (CAD) in the initial architectural design stages (Aish & Bredella, 2017; Wintour, 2018). The use of digital tools has, in some cases, replaced established analogue tools of design (Fakhry et al., 2021), allowing the design professional to visualise ideas so they can be modified and analysed interactively (Jabi, 2013). The first two dimensional (2D) CAD software was Ivan Sutherland's Sketchpad in 1963 (Sutherland, 1963/2003). This was a tool to draw in 2D and through an inbuilt relaxation procedure it was possible to analyse the force distribution in the members of a pin connected truss (Sutherland, 1963/2003). This marked a departure in architectural design from the free hand sketching or physical models, replacing these tactile experiences with "clicking, pushing, pulling, or pressing" referring to the physical manner in which design instructions are communicated to a computer (Vrachliotis, 2022, p. 168). 2D CAD software allows for the drawing to be informed with greater precision and the hand drawing of multiple repetitive elements can be replaced by a *copy* function. This saves time but removes the iterative consideration of the design being repeated which occurred when having to manually repeat a task. One is no longer *refining*, but simply *copying*. Drawings could be measured, and details could be drawn, shared and copied into drawings. Even with the use of digital tools and 2D CAD software, it is apparent that pen and paper sketching techniques are still employed by even the most digitally literate while generating early design concepts (Gulay & Lucero, 2021).

4.3.3 Physical model making

Drawing is often the first in a sequence of tools because lines are possible to construct on paper in contrast to physical 3D forms. It can however be difficult to visualise forms in drawings which involve complex geometries, and this is where physical model making emerges. As the architect became designer as separate from builder, the model as a representation medium emerged to visualise the idea in three dimensions (Schilling, 2018), and physical modelling can help design professionals and students to reconnect with gravity and materiality (Agkathidis, 2016a). Modelling can perform two functions: (1) miniature representations of a building design or part of a building design, and (2) dynamic models to inform the design and communicate forces, and material information into the process of design (Gulay & Lucero, 2021), or "method prototypes" (West, 2008, p. 52).

In this second function, models inform the design with forces, material, and structure, exemplified by designers such as Antoni Gaudí, Heinz Isler, and Frei Otto. Their models were used to explore new and innovative designs found through responses to the structural stability. In effect this process of designing through models can simultaneously "resolve form, the structuring of form, and the formation of form" (Ahlquist & Menges, 2012, p. 62). The suspended catenary models of Antoni Gaudi were inverted to give the most efficient structural form for that particular loading case (Larsen, 2022). Gaudi would work with craftsmen to apply material properties and understand the load cases to make such unique forms practical (Larsen, 2022). The modelling techniques of Frei Otto to develop membrane structures—as described by Goldsmith (2016)—would start by stretching membranes which would act similarly to the woven materials that would ultimately be used in the final construction. Over time this method of design would see different modelling techniques layering new materials such as fixed woven membranes to simulate a construction method. This method would employ gravity and other forces of nature to "inform rather than plan" the design (Burry, 2016, p. 34). The design itself would be defined by the forces acting on it and "make the invisible measurable and the visible calculable" (Vrachliotis, 2020, p. 15). Many different materials would be used to allow the natural forces and the performance of different materials inform the architectural design. These included soap film models, hanging chain models, tensile fabric models made of stretch fabrics, inflatable forms, cable nets, and deployable models (Goldsmith, 2016). These are all used not as representational models but as stages of an interactive design process where "crude elements" become "sophisticated analytical tools" (Goldsmith, 2016, p. 26).

With Heinz Isler, models were used as exploratory models to ensure forces are evenly distributed and the form is structurally sound, and test the weights of different materials (Chilton, 2010). This method allows for materials and forces to inform the design output. Designing through model making teaches the designer much about structure and the effect on the form. Depending on the material used to build physical models, these models can also inform the designer how material will perform through design decisions. For example, an isotropic plastic straw may be a similar cylindrical form as bamboo poles, however the anisotropic nature of the bamboo skewer will feedback to the designer the impact of design decisions in a manner isotropic plastic cannot. This process of designing through models can be expensive in material costs and time. As Chilton (2010) notes with the models of Heinz Isler, to find an optimal design solution there could be an almost infinite number of iterations, and what works structurally may not be the most aesthetically pleasing design. This can limit their widespread application to the process of design. The soap bubble models of Frei Otto, the draped membranes of Heinz Isler, or the catenary chains of Antoni Gaudi are an initial step in understanding how forces would inform the design. This is not informing the design with material but only the forces acting on the design, or informing the design though "matter" (Ahlquist & Menges, 2012, p. 62). *Matter*[19] represents the fundamental principles, both physical and atmospheric (Ahlquist & Menges, 2012).

Using physical models to design for full-culm bamboo is using bamboo skewers and the material of bamboo, and not through matter. The cylindrical, flexible but non-ductile nature of bamboo is brought into the design process. Elastic bands as joints allow rotation similar to the performance of bolted joints, a connection technique stipulated in ISO 22156 (2021). A challenge of using physical models for anything more than representation is similitude, which needs to be considered by the design professional. Geometric dimensions, volume, the force of gravity, deadloads, and material stiffness are such examples of criteria found to scale differently from a scale model to a building scale. So, it is important that an experienced professional is involved between the model and building. The modelling medium of bamboo skewers and elastic bands, suggests form but also structure, and construction (Figure 79). Here models are tools for design, representation is a simultaneous by-product.

[19] In this PhD research the term *matter* follows the definition in Ahlquist & Menges, 2012, though it should be noted there are alternate uses within this field (e.g., that used in Lloyd Thomas, 2007).

Figure 79: Physical model making with bamboo skewers and small circumference elastic bands. Photos by author.

Physical models are also able to communicate to a client in a manner that 2D drawings often cannot. Physical modelling appears to show a way of communicating forces and material information in a hands on and accessible way where forces are not some mathematical calculation, but become obvious to everyone (Larsen, 2022).

4.3.4 Full-scale building

To understand the construction logic and material at the scale of the building requires building at full-scale. Full-scale construction is a common practice in the construction profession where *mock-ups* are produced as representation and communication tools, a means of training construction professionals, and to study weathering. It is important to note that if it is done, it is usually only a small component of the building (i.e., a small panel of brickwork, example joinery, etc.). This provides tactility, the feel of the material. Such a process can be termed *design and build*, as defined in Storonov (2017) as, "the act of physically making what is designed at full scale" (p. 1). This process can generate intuition in design professionals of material and construction processes. Full-scale building contacts the ground, it endures gravity. It informs—with tolerances in the material—the connections in a hands on way (Nicholas & Oak, 2020). With full-scale construction, a physical object is produced which can also demonstrate the impact of time. This dimension is crucially important to experience the environmental factors which can affect the material. For a material like bamboo with poor natural durability (Liese & Tang, 2015a), experiencing this performance, along with the variabilities, and the eccentricities first hand is important. As Storonov (2017) notes, without a "Ctrl+Z" (p. 3), a PC users' means to *undo*, the act of physically making teaches the importance of craft, care and responsibility.

4.3.5 Digital 3D explicit modelling and building information modelling (BIM)

Eastman (1975) hypothesised the most obvious advantage of using computers in the architectural design process. They offer the "ideal representation" of an architectural design (digital drawings and models), producing "infinite" drawings, whilst centralising all design changes (p. 46). When describing the "ideal representation", Eastman (1975) is describing three-dimensional (3D) modelling, or explicit modelling. This is the process by which each geometric object is modelled based on explicit coordinates and adding or subtracting parts to the models (Burger, 2012; Woodbury, 2014), with an early example of this being described by Greenberg (1974). The prevalence of digital representations in architecture has meant that new formats of media generated by computers have replaced drawings as the medium by which design intent is conveyed to those who build (Bernstein, 2018). Itsuko Hasegawa, interviewed in Robbins (1997) explains, computers provide an "exciting way to stimulate and accelerate the development of a design" and therefore, "we are better able to discuss the problem of the design process" (p. 201). Digital tools to represent explicit architectural models have potentially exacerbated challenges for design professionals to consider material. As Menges (2010a) asserts:

> In today's practice digital tools are still mainly employed to create design schemes through a range of design criteria that leave the inherent morphological and performative capacities of the employed material systems largely unconsidered. Ways of materialization, production and construction are strategized only after a form has been elaborated, leading to top-town engineered, material solutions that often juxtapose unfitting logics. (p. 44)

As Kotnik and Weinstock (2012) contend, contemporary design methods—such as *non-uniform rational B-spline* (NURBS) modelling—tends only to shift the consideration of materiality to the later phases of the architectural design project.

Computers could be considered more than a representational tool to be a platform for innovation with a profound impact. In the UK as an example, the UK Government has a commitment to a concept known as *Digital Built Britain* to enable the construction sector to fully utilise the benefits of digital tools (RIBA, 2018). In a RIBA survey almost 90% of survey respondents said digital technologies are transforming the way that they work, in particular, the embedding of Building Information Modelling (BIM) into the culture and processes of architecture practice (RIBA, 2018). BIM is a process, facilitating the creation of the building design as a 3D model and the management of information on a construction project across the project life cycle (RIBA, 2018). The premise behind BIM is the availability of precise digital information describing the properties of all project components (Lorenzo et al., 2017). Like 2D drawing, 3D explicit modelling and AD, BIM can be considered another paradigm in the use of computers in architecture (Wintour, 2018). Autodesk (2002) noted three main objectives of BIM. To: (1) create and operate on digital databases for collaboration, (2) manage change throughout those databases so that a change to any part of the database is coordinated in all other parts, and (3) capture and preserve information for reuse by additional industry-specific applications.

Following the definition of *parametric* in Caetano et al. (2020), BIM can be considered as a parametric. The design in a BIM platform can be adapted as a result of "intelligent coordinated parametric objects that can be changed and manipulated yet…remain consistent and correct" (Ingram, 2020, p. 9). One of the dominant pieces of software in this paradigm of modelling is *Autodesk Revit* (Autodesk, 2022b). This software is a BIM platform which allows users to design a building and structure and its components in 3D, annotate the model with 2D drafting elements, and access building information from the building model's database. As explained by Dr Robert Aish in Aish and Bredella (2017), BIM has a series of limitations. "[BIM] reverses the natural order of the architect's design process and forces the architect to think about the design or the selection of the components before the overall form of the building" (p. 66). As discussed previously, design professionals often abstract design through form-making studies in the early concept design stages. This *component* assumption forces the design professional to think about micro-ideas (the components) before macro-ideas (the building form) (Aish, 2013). The hard code functionality of the built-in system components is orientated towards conventional construction. When considering a material like bamboo, this is a limitation. BIM tools are becoming ever more integral in architectural design practice. There is growing dominance in UK architecture practice (NBS, 2021), in streamlining practice and potentially providing more agency to design professionals over the design and communication of complex buildings. In the symposium to establish a context for the application of this research (Section 1.7.5), in Haiti, BIM software was noted by practicing design professionals as important for time efficiency, productivity and the 3D aspect of the software being an important communication tool. BIM software facilitates communication with and reassures clients of the design progress. Therefore, it appears here that any design approach developed within this PhD research and utilises digital tools should work within a BIM environment or provide some compatibility.

4.3.6 Algorithmic design

Terzidis (2003) argues the use of the computer as an exploratory formal tool and the increasing use of computers in architectural practice is generating an increasing dependency in architectural design on computational methods. Lin (2001) records that explicit 3D modelling can represent the designers' vision though this use of computers in the architectural design process and can be inadequate to solve complex design problems. Jabi (2013) and Woodbury (2014) note however these changes can be time-consuming when each small design change could require a total remodelling, and effectively restrict design freedom, prohibiting design change later in the design process. 2D CAD drawing and 3D explicit modelling also focus design attention on the representation of the architectural design (Ahlquist & Menges, 2011; Aish & Woodbury, 2005). As Menges (2010b) notes:

> The point is that the increasingly exuberant form-making while relying on relatively conventional methods of design leads to an artificial complexity of the geometry and the construction of architecture, which we can observe in many of today's projects. Whereas the result of *a design approach that is truly suited to the potential of the computer is characterized by a reciprocity of material, form and structure, leading to a morphological differentiation and performativity* [Emphasis by author] – an uncomplicated complexity. (p. 142)

Kwinter (2003) explains that "the computer offers the possibility of apprehending developmental patterns of extraordinary and unprecedented depth and abstraction, offering tantalising glimpses of the very freeform structure of time itself" (p. 92). In the 1970's this scope for digital tools was proposed by establishments such as *ABACUS (Architecture and Building Aids Computer Unit Strathclyde)* proposing building design be directly and actively supported by a range of integrated performance appraisal aids running on a computer system which could assist the designer in finding the optimal solution (Maver, 1971). This was known as *PACE (Package for Architectural Computer Evaluation)*.

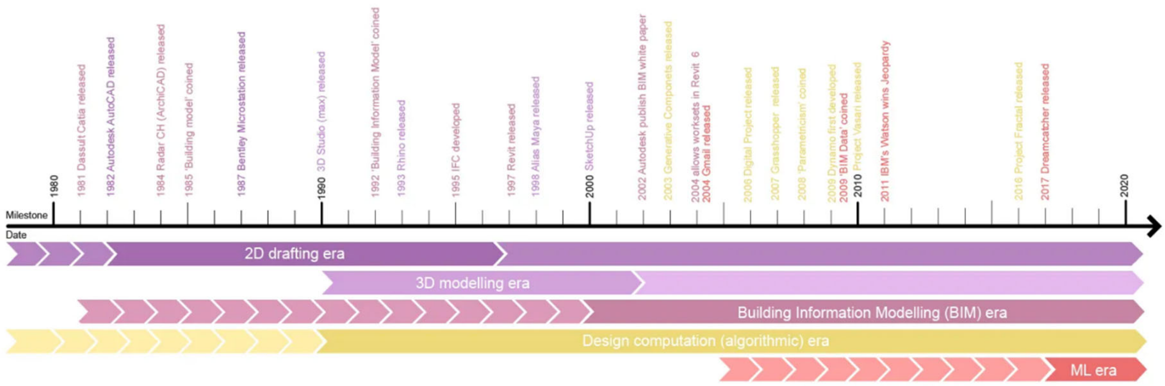

Figure 80: A timeline reproduced from Wintour (2018), which shows how each of the digital software can be considered as a series of five distinct eras with a series of milestone dates and events along the top and each software platform can fit into one or more of these. Algorithmic design (AD) is referred to as *Design computation (algorithmic)*. Image reproduced from Wintour (2018).

Algorithmic design (AD) is a way of thinking about a process of design which can be considered a new paradigm (or *era* as demonstrated by Wintour (2018) in Figure 80) of design in architecture (Oxman & Oxman, 2014b), based on algorithms (Castelo-Branco, Caetano, Pereira, et al., 2022). As shown in Figure 81, parameters are input into an algorithm and the adjustment of these, through established rules, can generate different outcomes considering a large number of competing constraints simultaneously, and test many more options than may have been economically feasible with physical methods (Bessa, 2009). Such digital simulations can facilitate "more full-size trials than a traditional craftsman would have made and broken in a lifetime" (Carpo, 2015, p. 26).

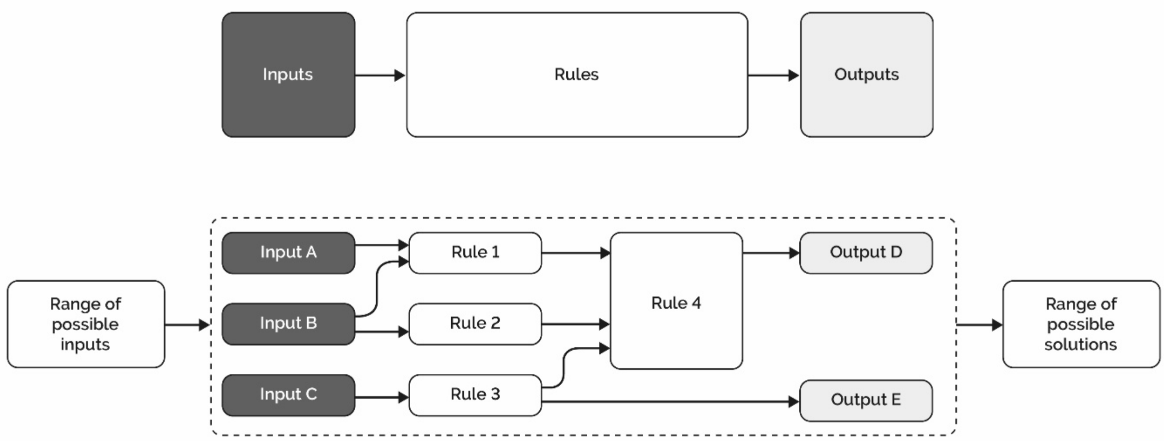

Figure 81: Inputs, rules and outputs in an example *parametric system*. Diagram redrawn based on that in de Boissieu (2022).

Algorithmic design (AD) and parametric design (PD) are often imprecisely used interchangeably. This research uses the term AD, following the definition outlined in Caetano et al. (2020), since this research endeavours to understand the computational thinking (or algorithmic thinking) of the process behind AD, and not specifically a PD design process in which the "use of parameters to describe sets of designs" (p. 297). An algorithm will have input parameters, but the parameters themselves may not always influence a design through an AD process. An AD process is one "characterized by an identifiable correlation between the algorithm and its outcome" with an "explicit use of an algorithm" (Caetano et al., 2020, p. 296). Therefore, in this research the AD term is used in order to focus more widely on the use of algorithms—and the construction of algorithms—in the design process, rather than a focus on a design output described through a series of parameters. This focus on the construction of the algorithm in an AD process is important. The designer becomes the designer of the algorithm which generates the design, or as Alexander (1968) terms this the "The designer becomes a designer of generating systems-each capable of generating many objects-rather than a designer of individual objects" (p. 610).

AD processes determine a form not by a "series of drawing and modelling steps, but by generating it using defined, rule-based procedures and parametrically described relationships" (Menges, 2010b, p. 142). To use a relevant quote Goldsmith (2016) recalls from Frei Otto, "The architect is acting more as a midwife than God the creator" (p. 26). To generate practical design options or objects from a generating system, requires a suitable definition of the design problem, which focuses upon, "a logic of associative and dependency relationships between objects and their parts-and-whole relationships" (Oxman & Oxman, 2014a, p. 3). This may sound cumbersome, but it is no different to how designers use diagrammatic sketching to conceive design relationships or how certain factors may have an effect on other parts of the project (Section 4.2.3). In AD, Ahlquist and Menges (2011) notes that the design process consists of two states which are the: (1) input parameters themselves, and (2) the influences which will activate these.

AD is not a style and AD tools do not in themselves drive the generation of form (Frazer, 2016). Often terms such as parametric design are perceived as a style, one associated with curvilinearity, double curved topology and a term promoted by Schumacher (2009b), *Parametricism.* These are often termed parametric not algorithmic, given the use of parameters to describe the design outputs. Gage (2016) points out Parametricism is neither a style nor a movement, but the tool coupled with a stylistic preference of the design professional. As Carpo (2014) writes, "Computers per se do not impose shapes, nor do they articulate aesthetic preferences” (p. 41). Picon (2014) states that though there has been a use of these tools to explore the geometries of form, the focus on form should not lead to the reduction of these tools to a mere “stylistic obsession” (p. 49). Such processes predate the computer with examples of the design process of Antoni Gaudi and Frei Otto highlighting this (Burry, 2016; Menges & Knippers, 2021; Oxman, 2017).

The first major application for a digital tool following an AD approach was *Waterloo Terminal* by Grimshaw Architects in London. This is a difficult site with a length of 400 metres with a tapering span that gradually shrinks from 50-35 m. To achieve this design and maintain the operational requirements of the stations each arch is required to be different. The solution was to design a series of 36 trusses (Figure 82) which follow a common set of design rules, but the dimensions of each are different (Aish & Bredella, 2017; Kolarevic, 2013).

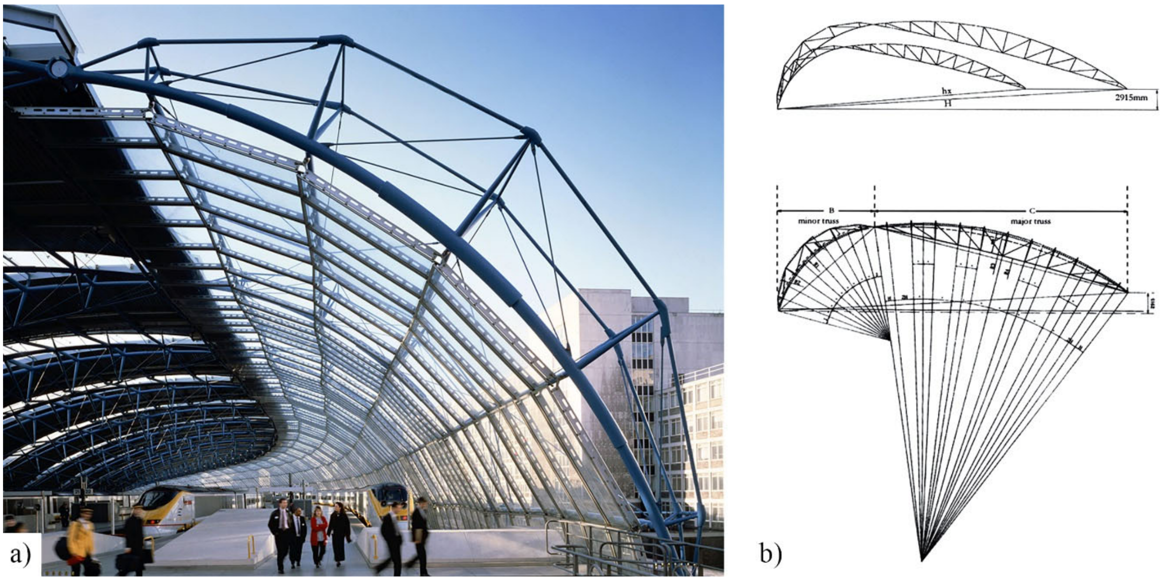

Figure 82: (a) *London Waterloo Terminal*, by Grimshaw Architects, 1993, image by Grimshaw Architects, and (b) Parametric definition of the scaling factor for the truss geometry, image reproduced from Kolarevic (2003).

The kit-of-parts system for *Waterloo Station* was not developed based on explicit measurements, but instead on a collection of implicit rules and relationships between parts (Burger, 2012). The project demonstrated the conceptual and developmental benefits afforded by an AD approach to design. The overall form is a result of the configuration of each arch. In the words of Oxman and Oxman (2014a), “Formation precedes form, and design becomes the thinking of architectural generation through the logic of the algorithm” (p. 3). By establishing the internal logic of the design, AD offers the ability to digitally sketch. As Woodbury (2014) notes, “Once made, they can be rapidly changed to answer ‘what if?’ questions and an algorithm through the moving of just a few variables can produce a repertoire of sketch models which replaces pages of manual concept sketches" (p. 164). The advantage of such approaches is that through the manipulation of only a few variables, designers can automatically generate many possibilities and move towards an optimal design solution (Brown & Mueller, 2018; Jabi, 2013). Kolarevic (2003) notes the opening up of the emergent and adaptive properties of form through this approach shifting the emphasis from the making of form to the finding of form, where form is no longer stable or fixed, but is replaced by the variable (Ahlquist & Menges, 2012). In writing algorithms, design intentions or parameters become encoded (Rocker, 2006), and form is therefore no longer *made*, but *found*, based on a set of rules which are set by the designer (Agkathidis, 2016b). The process of form finding emerges from analysis with the output exclusively determined by function (Laiserin, 2008), or in response to the environment (Oxman & Oxman, 2014d). To use a quote attributed to Frei Otto described in Goldsmith (2016), where computers are likened to cows, "you feed them good grass and you get good milk" (p. 29).

4.3.7 Challenges of digital tools in architectural design

It is important when considering a design approach for full-culm bamboo durability, that opportunities are presented from the use of digital tools, whether this be 2D CAD, 3D explicit modelling, BIM, or AD. Before studying references in which AD has been used to design for full-culm bamboo it is important to be aware of the limitations of digital tools (not just AD) in the design process and bear this in mind when considering a design approach for full-culm bamboo durability and the possible use of digital tools within this. The integration of computers into architectural design has been likened to the significance of the invention of concrete (Berkel, 2012). At the outset of these tools' use, this digital transformation was met with questions such as, "The computer – friend or enemy to architects?" (RIBA/AJ, 1970, p. 472). In practice design professionals have explored digital tools while constantly noting it is "essential, to maintain a critical mind towards what the computer can do" (Berkel, 2012, p. 74). Denari (2012) remarks on the "excitement" of NURBS[20] modelling in generating complex geometry (p. 29). Nevertheless, computational tools offer avenues for

[20] NURBS stands for *Non-Uniform Rational B-Splines*, and are mathematical representations of 3D geometry, a type of modelling used on platforms such as *Rhinoceros*.

comprehending complexity and achieving efficiency within architectural design (Berkel, 2012).

Sheil (2012) emphasised that built architecture is not just digital components, but material and space with greater complexities. Frascari (2009) critiqued the uncritical transition of architectural drawings to the digital realm, a position supported by Berkel (2012). In prioritising digital techniques over others, “a bizarre condition develops where just because something can be modelled on the computer, it can get built” (Berkel, 2012, pp. 78-79), where Denari (2012) adds the risk that in design “what could be done” has become more important than “what should be done” (p. 29). Rahim and Jamelle (2020) observe digital architecture has become “detached” from its materiality (p. 8), where, as described by Kwinter (1996), mainstream architectural design operates on “reduced matter-models” (p. 70). Without such a consideration of material, as Sheil (2012) writes, the building becomes just a “physical render of a projected image where the exploration of its performance as a construct ceased at the point of simulation” (p. 138). How material can be included into digital processes is a major challenge, but in Gramazio and Kohler (2008) the concept of “digital materiality” positions design within the methods of construction (Willmann et al., 2013). Fure (2011) adds to this with the term “digital materiallurgy”, to describe the relinquishing of design control to materials and accommodating their variations as part of the design process, contrary to materials “cast as inert matter waiting to be formed” (p. 92). Instead there should emerge a “productive slack between materials…and digital form” (p. 92). This opportunity to define the design by material performance and local construction (materialisation) techniques is discussed in depth by Crolla (2018b) noting, “today’s design and manufacturing tools, digital design and construction systems have the potential to expand the incorporation of onsite materialisation realities as productive and constructive components” (p. 41). He adds that digital tools can be “reconfigured” to manage the imprecision of non-standard materials (p. 305). Crolla (2018b) also explains that the design output should shift from an abstract form that regulates materials to form “co-defined by matter, material systems, and materialisation processes” (p. 305). Construction logic informing the design through digital tools is termed by Yuan (2016) and Yuan and Wang (2018) as “Parametric regionalism” where computational approaches allow inputs to be influenced by regional factors such as available materials and culture. Zarzycki (2014) highlighted the historical oversight, or obscuring of design tolerances in computational models, while Crolla (2017) and Qi, Zhong, Kaiser, Nguyen, et al. (2021) demonstrate the gap between digital and real-world environments when it comes to designing and building with bamboo.

There are authorship challenges when algorithms—and the designs those algorithms produce—are by different authors (Eskenazi, 2015; Terzidis, 2008). Immediate digital iterations may overlook factors like material behaviour and environmental impact (Gulay & Lucero, 2021), as Goldsmith (2016) notes when discussing the work of Frei Otto, the finding of form was not an immediate process, but hours and days may go by as the form is found and the structure unfolds. Haptic feedback from physical modelling conveys forces and material properties better than digital tools (Larsen, 2022), as with a loss of immediacy noted by design professionals interviewed in Lawson (1994) when comparing analogue and digital methods. The haptic feedback does not just inform the design professional about forces, but as noted by Zarzycki (2014), the digital realm removes the levels of material resistance to deformation, joint friction, and material fatigue. These are thoughts echoed by Norman (2005) who explains that digital tools have removed the design professional from the material to a virtual space. In bamboo growing regions this can be an even greater gap. Bechthold (2004) notes that digital design and fabrication research has taken place in the so-called Global North because skilled labour is expensive, and automation is a financial necessity. In the so-called Global South, skilled labour is less expensive and therefore digital tools have not been used in the fabrication process. Therefore here, skilled labour can be engaged to address the issues of construction tolerances. Cost and cultural change are also challenges to the applicability of digital tools in architectural design. Costs include hardware, software, and training (RIBA, 2018). Access to software was a significant barrier to maintained use of the digital tools that were taught on the AAVS Haiti workshops (and documented in Section 1.7.5 and Appendix D). Cultural shifts demand adopting new tools and ways of thinking, which senior staff are recorded in cases to resist (RIBA, 2018). In developing a design approach that utilises digital tools, it is important to constantly re-assess the tool appropriateness, their challenges and relevance. These should be remembered as it is apparent digital tools are incredibly powerful but there are challenges that need to be considered when designing for full-culm bamboo.

4.4 Reference projects for algorithmic design and full-culm bamboo

The challenge of materiality within digital processes within architectural design are well documented (e.g., Crolla, 2018b; Gramazio and Kohler, 2008; Qi, Zhong, Kaiser, Nguyen, et al., 2021). In recent years there have been a range of theoretical and built examples of digital (and AD) tools applied to the design and construction of full-culm bamboo structures. It is important to review these to learn lessons for a design approach to durability but also ensure a design approach is contextualised within this wider research field and emerging patterns.

4.4.1 Search methodology

A literature review was conducted systematically. This was limited to an English language search; however, the location of the projects and papers show a global spectrum of projects and research. The search terms were: “bamboo AND design AND algorith*”; and “bamboo AND design AND paramet*”. This was due to the interchangeable use of algorithmic and parametric when describing an AD approach. The platforms searched were: CumInCAD, Taylor & Francis, Sage Journals, Wiley Online Library, Springer, Science Direct (Elsevier), Newcastle University Library online search engine, and a search on *Google.com* using the same search terms. For CumInCAD[21] and the *International Journal of Architectural Computing (IJAC)* on the Sage platform, another search term of just “bamboo” was used, given the CumInCAD platform and *IJAC* already discuss the use of digital tools in architectural design practice, education and research. This would provide results which may not necessarily involve an AD approach to the design for full-culm bamboo, however this would provide results that may also be relevant. Therefore, where digital analysis tools have been applied within the design process for bamboo, these have also been included. This is because these would follow a computational process such as: (1) the use of finite element analysis (FEA) software ANSYS in Weinstock (2006) to simulate the response to various stresses and loadings, or (2) where a digital mapping has taken place of bamboo poles to suggest how the structure can be informed based on the bamboo digital data (e.g., Lorenzo et al. (2017); Lorenzo and Mimendi (2020), etc.). This widens the scope of the references to assist in understanding how digital tools and computational processes have been involved with the design for full-culm bamboo. Within many of the platforms searched for—where research was outside the scope of architectural design (e.g., where digital scanning had been undertaken within the discipline of plant science)—these have not been included. Within results for bamboo in architectural design, only results that pertained to the use of the round pole form of bamboo, full-culm bamboo, were used. Also if there was design research where bamboo had been referenced as inspiration in a biomorphic way (e.g., Busse and Empelmann,

[21] CumInCAD is an index of publications in Computer Aided Architectural Design supported by the associations ACADIA, CAADRIA, eCAADe, SIGraDi, ASCAAD and CAAD futures. Research presented in these conferences is documented and published on the CumInCAD platform. https://papers.cumincad.org/

2015; Woroniecki, 2021, etc.), or as a reinforcing material, this was also not included. The results from each platform are presented in Table 13.

Table 13: Reference projects for the application of digital design tools with an emphasis on an AD approach to design for full-culm bamboo, based on search terms: “bamboo AND design AND algorith*”; and “bamboo AND design AND paramet*”.

Platform	**Found research**
CumInCAD	Aditra and Widyowijatnoko (2016); Amtsberg et al. (2022); Amtsberg and Raspall (2018); Chen and Hou (2016); Crolla and Fingrut (2016); Crolla and Garvin (2020); Datta et al. (2009); Erdine (2015); Espinosa Trujillo and Wang (2015); Goepel and Crolla (2020); Goepel and Crolla (2021); Huang (2017); Kamath (2013); Klemmt et al. (2018); Łochnicki et al. (2021); Ma et al. (2021); MacDonald et al. (2019); Matson and Sweet (2016); Qi, Zhong, Kaiser, Nguyen, et al. (2021); Qi, Zhong, Kaiser, Tahouni, et al. (2021); Sun et al. (2022); Suzuki et al. (2020); Wang et al. (2017); Wu et al. (2019); Yang and Xu (2021)
Taylor & Francis	Crolla (2018a)
Sage Journals	Datta et al. (2009)*; Wang et al. (2017)*
Wiley Online Library	García (2019); Weinstock (2006)
Springer	Crolla (2017); Di Paola and Mercurio (2023); Espinosa Trujillo and Wang (2015)*; Suzuki et al. (2020)*
Science Direct	Lorenzo and Mimendi (2020); Lorenzo et al. (2021)
University Library Search Google search (in addition to papers found on other platforms)	CO-LAB (2019); Lorenzo et al. (2017); Lorenzo and Mimendi (2019); Michiels et al. (2017); Mimendi et al. (2022);Estrada Meza et al. (2022); Gonzalez et al. (2021); Matson and Sweet (2016)*;
* denotes that paper, article or chapter is also included on another platform.	

4.4.2 Description of reference projects

There has been work to map the variability of bamboo and input this into a design process using computational design tools. In Lorenzo et al. (2017) and Mimendi et al. (2022) a framework and workflow are suggested in which digital modelling and robotic fabrication are used. This is to enfranchise bamboo poles through the individual mapping of each pole and then designing for each distinct characteristic. Here the eccentricities of bamboo are mapped and embedded as design parameters. In a similar vein the paper *Digital analysis of the geometric variability of Guadua, Moso and Oldhamii bamboo* by Lorenzo, Godina, et al. (2020) proposes a reverse engineering methodology. This would be used to quantify and manage the geometric variability of bamboo culms which could then support the development of new formal design and fabrication processes for bamboo (Lorenzo, Mimendi, et al., 2020). *Digital Fabrication of Standardless Materials* by MacDonald et al. (2019) proposes an integrated digital fabrication method for bamboo which scans, identifies a best fit of the material element within an assembly, and provides feedback so the available material can affect the design of an assembly.

The *ZCB Pavilion* (Figure 83) by the Chinese University of Hong Kong built in October 2015 in Kowloon Bay, Hong Kong (Crolla, 2017), exemplifies the mixed media used within the design process and this project and workflow are also discussed in the paper *Protocol of Error* by Crolla and Fingrut (2016).

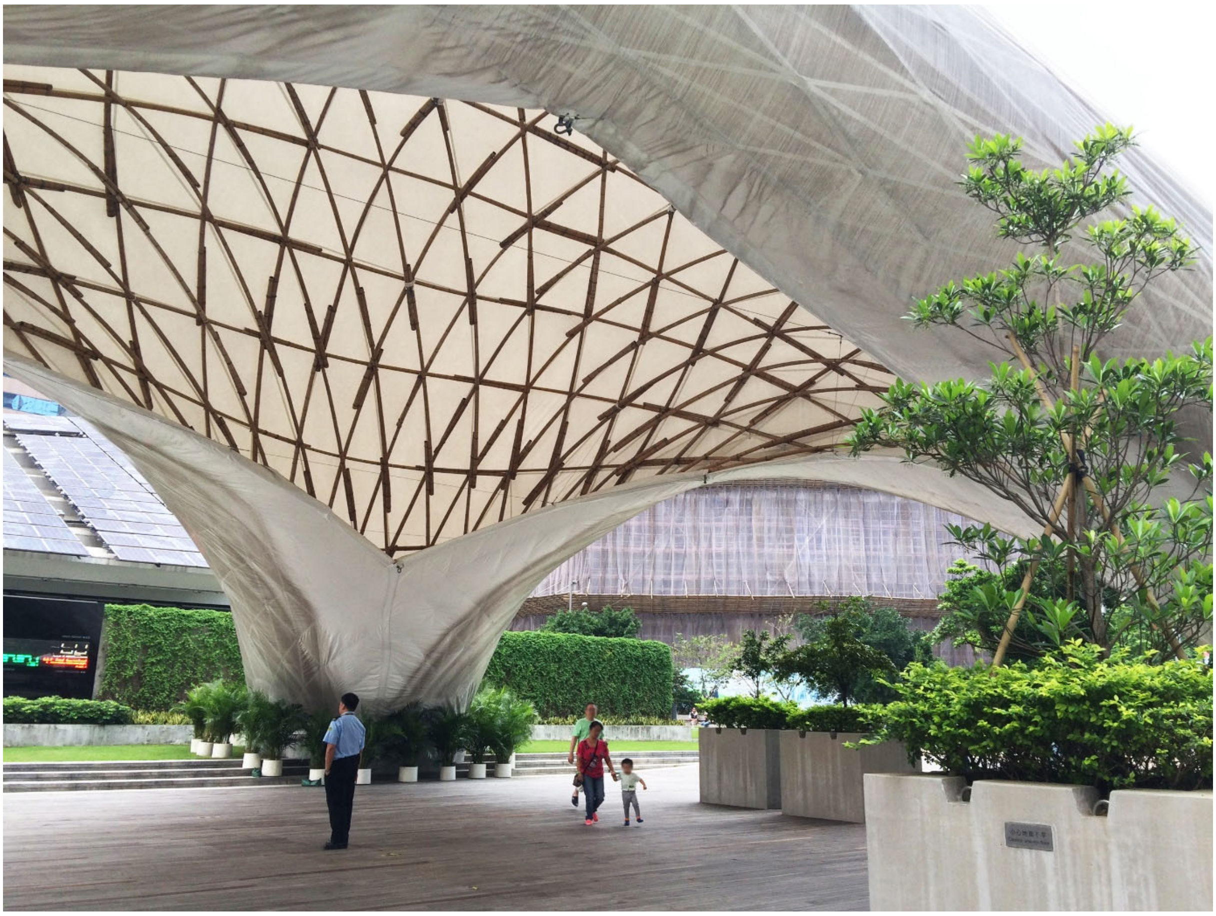

Figure 83: *ZCB Pavilion* by the Chinese University of Hong Kong, Hong Kong (Crolla, 2017). Photo by author, 2016.

This was an event space for the *Zero Carbon Building (ZCB)* with a span just under 40m (Crolla, 2018a). Bending forces present in the physical model were applied as vector forces on a discretised curve network to find its force equilibrium, followed by FEA analysis (Crolla, 2017). The *ZCB Pavilion* workflow produced a digital model which is described as an "open system" which would also act as a dialogue between digital simulation and visualisation on the one hand, and analogue testing and physical prototyping on the other (Crolla, 2017, p. 6). The interplay between the digital model and the physical model was used to refine the design through three iterations of each with digital scanning used but not to map the pole, but map a 1:20 scale model to compare this to the digital model and identify any deviations between the physical and digital. Given the relevance of this workflow to this research this is discussed in more detail in Section 4.4.3. In a similar vein as the *ZCB Pavilion* project, in the paper *Designing With Uncertainty: Objectile vibrancy in the TOROO bamboo pavilion*, Crolla and Garvin (2020) focus away from precision and control toward an embrace of the natural variability of bamboo and construction logic to inform the design process. This design and build project was a light-weight bending-active bamboo shell structure, built in Hsinchu, Taiwan, in June 2019. Precise design output, is replaced by one of a practical realisation which embraces the changes associated with the bamboo material, or site specificities (Crolla & Garvin, 2020). This project uses a live physics engine to apply forces within the model, and the term *objectile* is used which is a term to describe the laws of change of an *object* which will have an infinite number of functions (Carpo, 2014). Using live physics within an algorithm to design for bamboo is also employed by *BamX*, which is a pavilion constructed using bamboo splits (EPFL, 2022). In this project the splits are connected into cylindrical elements which can be compacted for transport and storage due to their scissor linkage mechanisms. These cylinders are then joined to create a bending-active structural frame termed an "X-Shell" (EPFL, 2022). AD is employed to provide physics-based simulation and advanced numerical optimisation to facilitate the design of intricate freeform surfaces. Live physics plug-ins within an algorithm are also used in Huang (2017) where AD tools are used to find the force equilibrium. This is modelled as a shell structure with a grid shell taken from this surface. The grid shell pattern is analysed under gravity using FEA tools within the algorithm. It is not clear if the bamboo mechanical properties were inserted into this process or the grid shell was modelled abstractly. The output is the construction information which is intended to be handed to craftsmen who can then bend the bamboo poles to match the curvature of the elements in the digital model. Huang (2017) observes the afterthought that is given to material in the design process usually following a formal process of design, echoing the comments of Kotnik and Weinstock (2012).

Bending active grid shells emerge as a favoured structural approach for integrating AD tools with bamboo material (e.g., Ma et al., 2021; Suzuki et al., 2020). Suzuki et al. (2020) examines a grid shell formation through a two-week workshop in Quito, Ecuador. This study underscores the efficiency of bending active grid shells and cites "curved compression", a term used by Frei Otto and documented in Dunkelberg et al. (1985) to depict structures moulded from elastically bent bamboo (pp. 302-367). The authors employ digital tools to reimagine bamboo bending while aligning with vernacular design principles of Ecuador. Live physics modelling, facilitated by the *ElasticSpace* software integrated as a plug-in within an AD platform, refines structure geometry. Hand bending of bamboo and empirical data collection during a short workshop period, contributes to an intuitive calibration of design tools. The construction of the bamboo-jute chord structure by students exemplifies the concept termed *digital vernacular* (Suzuki & Knippers, 2018).

Similarly, Chen and Hou (2016) evaluate bamboo's elastic properties through hand bending and digital analysis, tracing bamboo curvature in CAD. In Ma et al. (2021), the exploration of active grid shells includes digital simulations alongside a 1:20 scale physical model. Notably, CO-LAB Design Office and Arquitectura Mixta's pavilion at *Luum Zamá*, Tulum, Mexico (Figure 84a) exemplifies a built application through AD tools, enabling precise attachment point locations for bamboo strips in the structural grid (Figure 84b) (CO-LAB, 2019; Cogley, 2019). These studies collectively demonstrate the potential of AD tools to design and provide construction information efficiently.

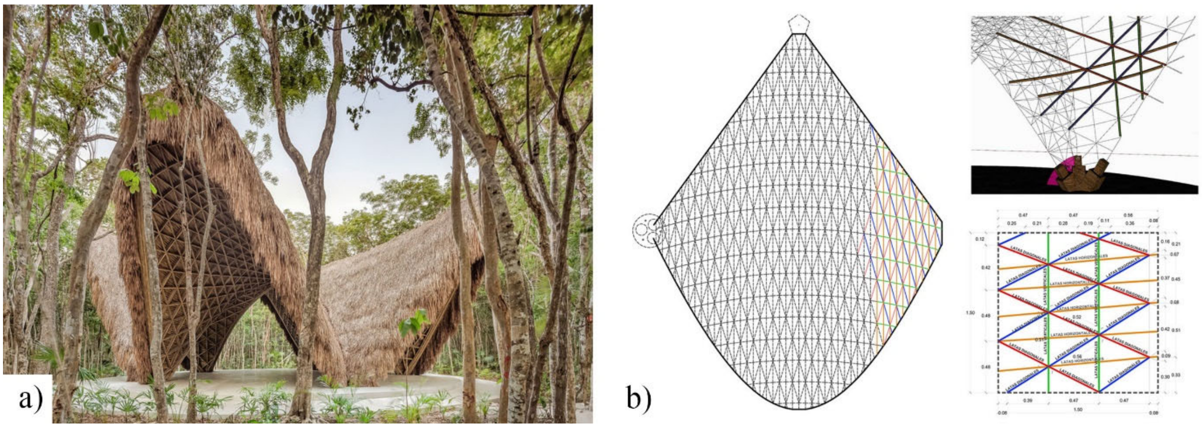

Figure 84: *Luum Zamá*, in Tulum, Mexico by CO-LAB Design Office and Arquitectura Mixta: (a) photograph of the completed structure, and (b) the graphical output of the digital model showing the configuration of structural members and connection locations. Images reproduced from CO-LAB (2019), https://www.co-labdesignoffice.com/luum-temple

More examples of construction and fabrication information as output of an AD process is seen in Qi, Zhong, Kaiser, Nguyen, et al. (2021) who demonstrate the use of vision augmentation to respond to deviations between the bamboo as-built and designed form in real-time so as to compensate for cumulative deviations caused by material uncertainties through the addition of non-bamboo elements. If the cost of licences of software are a barrier to use in tropical LMICs (as documented in Section 1.7.5), then this would be a challenge for widespread applicability of such systems.

Joinery is constructed on a joint by joint basis in the work reported by Amtsberg and Raspall (2018). Here the bamboo is mapped at the ends of the pole which have been cut to design bespoke joinery which can be 3D printed. The physical properties are analysed to inform the digital model with "individual material information" (Amtsberg & Raspall, 2018, p. 253). Using FEA within the algorithm, specific load cases are applied to determine the required bamboo diameter for each structural member. The goal of this research is "to bridge the gap between the former unknown individuality of this construction material [bamboo] and to combine it with the versatile and adaptable fabrication strategy of 3D-printing" (Amtsberg &

Raspall, 2018, p. 253). Again, the requirement for the equipment to facilitate this can be a challenge for widespread applicability in tropical LMIC contexts.

In Sun et al. (2022), the material characteristics of bamboo are proposed to be scanned as part of a proposed workflow. A catalogue would be created which includes the mapped variances in diameter, straightness, and cross-sectional area of the poles using a 3D scanning system developed by MacDonald et al. (2019). The challenge however that still exists is the translation from the precision of the digital model to the realities of the bamboo construction site and the skill of the craftsmen. This challenge is addressed through the use of an augmented reality (AR) model. Through headsets those constructing the structure can be assisted in the positioning and installation of the bamboo (Sun et al., 2022). In a similar vein, Kamath (2013) questions the scope of digital tools in the context of bamboo growing regions. Though not using an AD platform, the paper is worth studying as it reinforces some of the issues addressed in Sun et al. (2022). The research presents a methodology whereby the digital tools are employed in the design stages, before a physical 1:25 scale model is constructed to study the construction logic, and then information is conveyed so the roof design can be built manually (Kamath, 2013). Similar to Huang (2017), the software creates a surface from which curves are taken which form the grid of bamboo poles. In this case no live physics analysis is used as the design driver, the form is manually manipulated. The locations of the intersection points of the grid are read from the digital model and used to progress the design process to physical model, and then to full scale construction (Kamath, 2013). In Wang et al. (2017) AD is employed to address the bamboo material variability for bamboo joints. The algorithm takes a catalogue of bamboo physical properties and then identifies the best fit from this catalogue to be applied to the design. At the intersection points of the bamboo elements the length of the elements are reduced to provide the necessary space for joints to be placed. These multi-angular joints are also developed into a catalogue and the area given to these joints within the design which can be adapted based on the joint type chosen (Wang et al., 2017). This can assist with quickly updating the design based on the fabrication needs of the joints, but also the physical properties of the bamboo.

In Datta et al. (2009), computational fluid dynamics (CFD) analysis has been used in the process of design, though this again was in the finding of form. Here a stochastic wind motion model resulted in the subdivision of façade elements. The environmental analysis in this case was used to develop the design of the façade, not study the environmental effects on material.

4.4.3 Lessons for a design approach from reference projects

As seen in these examples, in many cases, employing AD tools to design with bamboo does not always consider bamboo in the design process. For example in many cases AD is applied either: (1) after a form has been established and then addressing the challenges incorporating bamboo creates through AD, or (2) to take advantage of the ability of bamboo to bend and, therefore, establishing a range that the bamboo can bend and these limits within live physics engines within an AD platform.

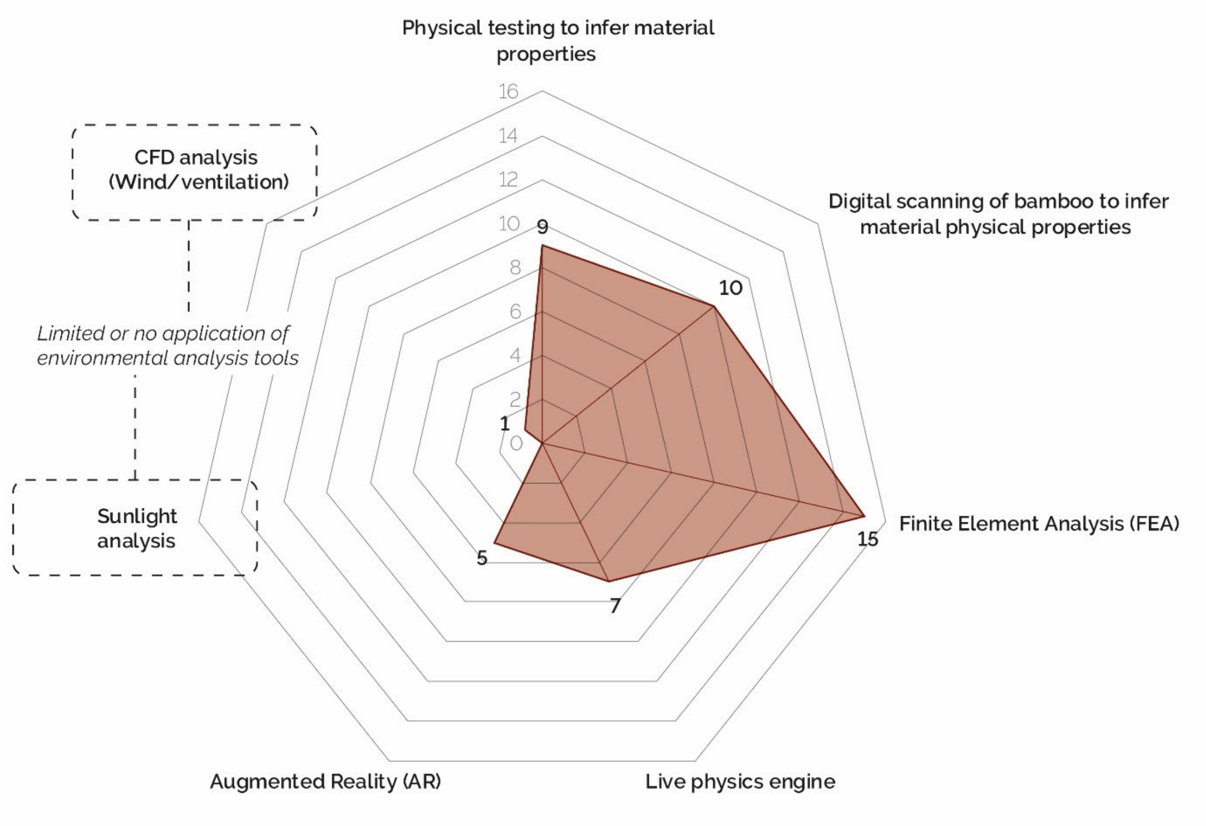

Figure 85: A study of which type of analysis, testing or mapping took place in the reviewed reference projects which demonstrates limited use of environmental analysis when using AD tools to design for full-culm bamboo.

Manufacture of 3D printed joints such as in Amtsberg et al. (2022); Amtsberg and Raspall (2018); Di Paola and Mercurio (2023), take into account the fact that bamboo is hollow, however in many cases bamboo is modelled as simplified geometry (e.g., Amtsberg et al., 2022; Datta et al., 2009). When mechanical properties are included and bamboo is modelled as an orthotropic material, FEA tools will not allow the incorporation of nodes, instead modelling bamboo as a hollow tube without solid nodes at a constant diameter such as in Gonzalez et al. (2021).

Environmental analysis tools are underutilised (as shown in Figure 85), in a process of design for a material which due to the poor natural durability, could benefit from environmental analysis in the design process. Maver (1988) called for the development of design tools which would provide technical evaluation in the early conceptual stages of a project. There can be multiple performance requirements in a design, and each may influence the other. For example, a roof design will most likely have the performance requirement to be as large enough to shade the bamboo from sunlight (as discussed in Section 3.4.6). However, the design can also have the performance requirement to be as small as necessary to reduce material costs (the need for value in material costs was established in Section 1.7.6), as well as the performance requirement to reduce overhangs to mitigate wind load. These performance requirements are not sequential in a hierarchical list but are required to be considered simultaneously. As Kolarevic (2014) argues, these performance requirements should be engaged early in the conceptual design stages of the project (Figure 86).

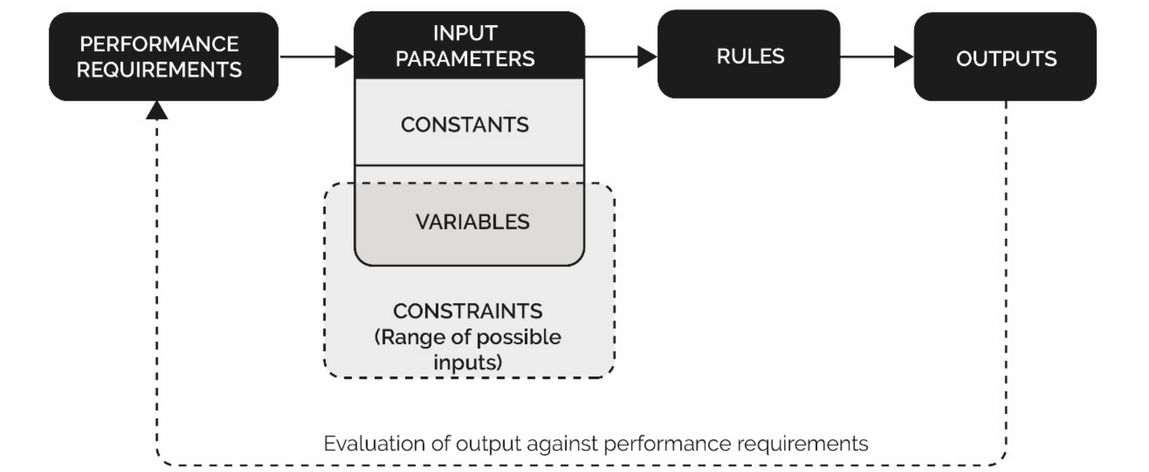

Figure 86: The process of establishing performance requirements, input parameters and outputs.

This gives the design professional information as to the meeting of these requirements throughout the design process, to inform the design professional as to the impact of design decisions. An example of this is discussed in Section 4.5.2 (and Appendix B), where an algorithm is developed to use sunlight analysis as an environmental input parameter to define the roof form. The examples of wind and sunlight show how the environmental context may inform complex processes of design synthesis (Oxman & Oxman, 2014c), and the design—or form—of a roof becomes a "subsidiary component of the environment" (Ahlquist & Menges, 2011, p. 10). As Crolla (2017) writes, incorporating the natural variability in the digital environment "is not possible with conventional tools but would be a requirement if we want to use raw materials that don't undergo extensive industrial standardisation" (p. 10).

In only half of these examples, mechanical properties are studied but in many cases they are too precise given the nature of bamboo or the likely construction process, and tolerances. The FEA tools used do not take into account the physical properties of the material such as nodes and their distribution (instead modelling bamboo as a constant hollow tube), tapering, or material length constraints, therefore requiring joints to extend the poles. In the majority of examples the physical properties are taken into account, however still abstracting the bamboo as a cylinder. Where digital scanning took place, a realistic physical representation of the bamboo is recorded and mechanical properties are occasionally inferred.

Roughly one fifth of the examples reference a code document. These include the safety factors in ISO 22156 (2004) referenced in Michiels et al. (2017), ISO 22157 (2004 and 2019) referenced in Lorenzo and Mimendi (2020) and Lorenzo et al. (2021), ISO 19624 (2018) in Mimendi et al. (2022), Colombian NSR-10 and ISO 22156 (2021) such as in Estrada Meza et al. (2022) and the Chinese bamboo testing standard MCBI (2017) such as in Lorenzo et al. (2017). Where ISO 22156 (2021) is referenced it relates only to how *bow* is defined in Lorenzo et al. (2021) and the process of structural modelling which is followed by Estrada Meza et al. (2022). The LUUM Temple, given this was a structure which would be occupied, followed a range of Mexican building codes (e.g., NMX-R-079-SCFI, 2015) and international bamboo design standards including Colombian NSR-10 and ISO 22156 (2004). In no cases is ISO 22156 (2021) Clause 5, Use class, or durability referenced. Therefore, a gap is identified in translating the design guidance for durability in ISO 22156 (2021) and apply this to an AD approach.

The examples which use AR to support construction, such as Goepel and Crolla (2020); Goepel and Crolla (2021); Qi, Zhong, Kaiser, Tahouni, et al. (2021), are interesting. There is an interface which supports the constructor. A similar output of evaluation would be useful to the design professional to support design decisions which could extend to a visual interface to provide durability guidance while designing for bamboo.

In roughly half the reference projects, it is interesting to note that even in a digital process, in order to understand the material characteristics or inform the digital tools with material information, physical modelling or prototypical construction with one-to-one scale connections or poles are used. This also supports the findings from Section 2.4.6 which observed the use of physical models by professionals in this field through the design process for bamboo structures.

In the cases of Chen and Hou (2016); Lorenzo et al. (2017); Lorenzo and Mimendi (2020), and Lorenzo et al. (2021), physical bamboo poles are digitally mapped, or bamboo is manually subjected to forces to generate 3D models of the bamboo poles which input material characteristics whether mechanical, or physical. Another example of the use of physical models in the design process is in the interplay between the digital and the physical information to support the design for bamboo structures which is seen in both Crolla (2017) and Crolla and Fingrut (2016). When discussing the design process for the *ZCB Pavilion* by the Chinese University of Hong Kong built in October 2015 in Kowloon Bay, Hong Kong, they note the mixed media used within the design process and this project and workflow.

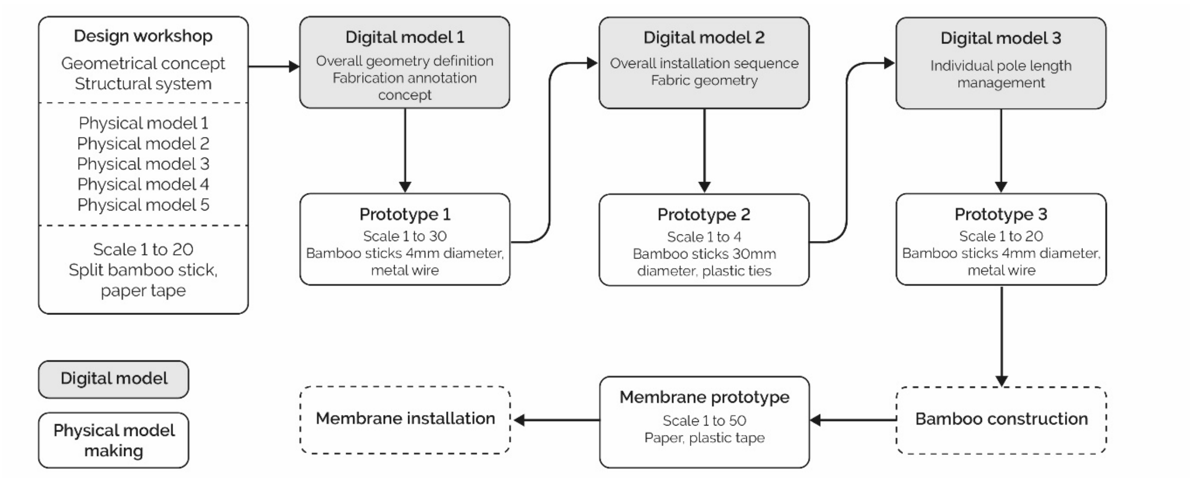

Figure 87: Diagram from Crolla and Fingrut (2016) and Crolla (2017) showing their design process "flexible design model" for full-culm bamboo (Crolla, 2017, p. 2), which comprises of a constant exchange between digital and physical design tools used through the project design sequence. Redrawn based on the diagram in Crolla and Fingrut (2016) and Crolla (2017).

As shown in Figure 87, the initial design concepts emerged from physical modelling and a series of iterations between the digital and physical models at different scales informed both the design, construction logic and material catalogue. The digital model could provide representation, testing and information management. This is described as a "flexible design model that encompassed both the digital and physical" (Crolla, 2017, p. 2), which acts as a dialogue between digital simulation and visualisation on the one hand, and analogue testing and physical prototyping on the other (Crolla, 2017). This is continued throughout the construction and assembly process. Aspects of the physical model which emerged were at some connections of up to six poles which were meeting, and this had to be resolved. The realities of road transportation meant there was a limit on the length of poles which could be used onsite to 7.2 m. Therefore, this had to be fed into the digital model to work out where the poles would overlap to be extended. A final 1:20 scale physical model was constructed based on the design at that stage of the process and was digitally scanned so this could be compared to the digital model. This was a means of bridging the gap between the physical and digital so any issues in the design could be assessed and rectified if needs be. In this case there were only minor discrepancies between the two.

In conclusion, there are some lessons from the reference projects relevant to develop a design approach, which is presented in Chapter 5:

- They are used to provide visual support to designers as they design.
- There is an opportunity to apply environmental analysis to a design. None of the references do this for the purposes of assessing durability.
- AD tools should interface within a mixed media of other design tools (analogue and digital). This is a practice followed by the majority of references.
- AD tools can align with the design standard ISO 22156 (2021) to provide design information. None of the references use this guidance to apply principles of environmental durability.

The utilisation of AD tools for full-culm bamboo has exhibited both opportunities and challenges due to bamboo's inherent variability. Studies have demonstrated how AD can embrace the eccentricities (mostly physical) of bamboo, as seen in the works of Lorenzo et al. (2017), Mimendi et al. (2022), and Lorenzo, Mimendi, et al. (2020), which emphasise the individual mapping of poles and incorporation into design parameters. However, the integration of environmental analysis tools in this context remains limited. The parallels with timber design showcase the advances made in AD tools. Notable examples such as *Reindeer*, which simplifies timber structure design and detailing (NTNU & Nikken Sekkei, 2019), highlight the potential for similar advancements for bamboo. The emergence of tools like *Beaver* (Beaver, 2022) and *GluLamb* (Svilans, 2021) underscores the capacity to analyse and design timber structures using codes such as *Eurocode 5*, providing reference for advancing AD tools for bamboo (Svilans et al., 2019). However, the challenges for full-culm bamboo remains (as discussed in Section 4.2.6). These AD tools for timber reply on sawing, grading—and in the case of GluLamb—engineering the material. For full-culm bamboo, the material properties have a much more significant impact on the design decisions of a design professional.

4.4.4 *Software toolset from reference projects*

In the review of reference projects in Table 13, a series of softwares were identified. There are also some alternative platforms which could be used for similar performance. These are discussed:

- The 3D explicit modelling platform is *Rhinoceros 3D.* This is a 3D computer graphics and computer-aided design software which uses NURBS, to build geometry as opposed to a polygon mesh-based system (Robert McNeel & Associates, 2023). Rhinoceros follows a three-dimensional cartesian coordinate system. Rhinoceros is widely used in the architecture profession (Stavric et al., 2013).

- *Grasshopper* is a visual programming environment which runs within the Rhinoceros platform (Robert McNeel & Associates, 2020). The main interface for algorithm design in Grasshopper is the node-based editor. Algorithms are scripted by dragging components with inputs and outputs onto a canvas. A collection of components forms an algorithm, and the output of these commands is displayed in the Rhinoceros window. The initial input geometry can either be assigned from Rhinoceros or generated in Grasshopper. A benefit of Grasshopper is the ability to integrate custom plug-ins (Preisinger, 2013), such as environmental (Sadeghipour Roudsari & Pak, 2013) and live physics engines (Piker, 2013).

- *Ladybug* is one of a number of plug-ins for Grasshopper which are all part of a wider family of environmental simulation tools known as *Ladybug Tools* (Ladybug Tools LLC, 2020). Ladybug allows the designer to explore the direct relationship between site specific environmental data through the importation of standard *EnergyPlus Weather* (EPW) files, and the generation of graphical data outputs which can also act as inputs into the geometry and design process (Sadeghipour Roudsari & Pak, 2013).

- *Kangaroo* is a plug-in which can apply forces to the model, known as a live physics engine (Piker, 2013). This can be used for interactive simulation and form-finding directly within Grasshopper. An example of the use of Kangaroo to design with full-culm bamboo is seen in Crolla (2017) where it is used to produce a digital model based on previous physical models which would find its force equilibrium and produce design geometry. One drawback of some physics engines can be that they are limited to the elastic behaviour. Unable to address nonlinear, bi-modular, or quasi-brittle behaviour, the last two characteristic of bamboo.

- *Karamba 3D* is a parametric structural engineering tool which provides analysis of spatial trusses, frames, and shells (Karamba3D, 2020). It provides FEA for predicting the behaviour of structures under external loads (Preisinger, 2013). Structural properties such as deflections, natural vibrations, and force flow lines can be viewed and this performance information can then be used as analysis, or fed back into the design process as a design driver (Preisinger, 2013).

- *Autodesk Robot*, as exemplified in the study by Mimendi et al. (2022), functions as a BIM structural analysis software within a BIM platform that enables evaluation of building structures (Autodesk, 2023).

- *ElasticSpac*e for Grasshopper, as demonstrated in its application to a bamboo based project by Suzuki et al. (2020), serves as a form-finding tool for building bending-active components by defining material properties and the number of particles in the bending elements (Suzuki & Knippers, 2017).

- Weinstock (2006) performs FEA using *ANSYS*, a widely used engineering simulation software (Ansys, 2023). In Weinstock (2006) a digital model was constructed which links the general form of the bamboo to a digital model of the internal structure. Structural studies such as deflection analysis were tested at various scales, taking into account the fibres and surrounding matrix, so that simulations of the response to various stresses and loadings could be carried out using ANSYS.

- Optimisation software is a process of "identifying the best element from a set of alternatives in terms of a specified criterion" (Wortmann & Nannicini, 2017, p. 1). One example which comes pre-installed within Grasshopper is *Galapagos* which is a heuristic solver used when there are a large number of variables to consider and an exact solution cannot be found, so a best fit to the problem is sought (Rutten, 2013). It is employed to find a best fitness outcome based on testing a variety of input variables. Another platform is a plug-in for Grasshopper named *Opossum* which was developed to address problems that involve time-intensive performance simulations such as building energy simulation (Wortmann, 2017).

AD has been integrated within BIM with software such as *Dynamo* (Autodesk, 2019). In recent years BIM tools have also seen greater interoperability with 3D explicit modelling and AD platforms, through the release of *Rhino.Inside*. This software has been developed by Robert McNeel & Associates to embed into other software. *Rhino.Inside.Revit* is a specific application of this into the Autodesk Revit platform (Robert McNeel & Associates, 2022), that allows Rhinoceros to be loaded into the memory of Revit just like other Revit add-ons. In real-time, the modelling in Rhinoceros or Grasshopper can be visible in Revit. This affords the graphical and documentation capabilities of BIM, with the modelling capabilities of AD. Most 3D explicit modelling applications and BIM platforms have some means of scripting algorithms to efficiently perform design and analysis tasks, whether this is built in or through additional pieces of software which can be plugged in[22] to a scripting platform (Stavric et al., 2013).

[22] Such pieces of software are known as *plug-in software* or more commonly, *plug-ins*.

4.5 Application of AD in design for full-culm bamboo

Learning from the research documented so far in this thesis, three applied examples of how AD can be applied to the design and construction for full-culm bamboo are explored (Figure 88). Each of these three cases has been presented at conferences by the author and they have been peer-reviewed, and published. These conference papers are documented in Appendices A-C. These examples use the design principles for full-culm bamboo established through Chapter 3 and apply these through the process and toolset established so far in Chapter 4, in order to calibrate how a design approach for full-culm bamboo can be developed. Together they explore a range of design, analysis and construction for full-culm bamboo to inform a design approach.

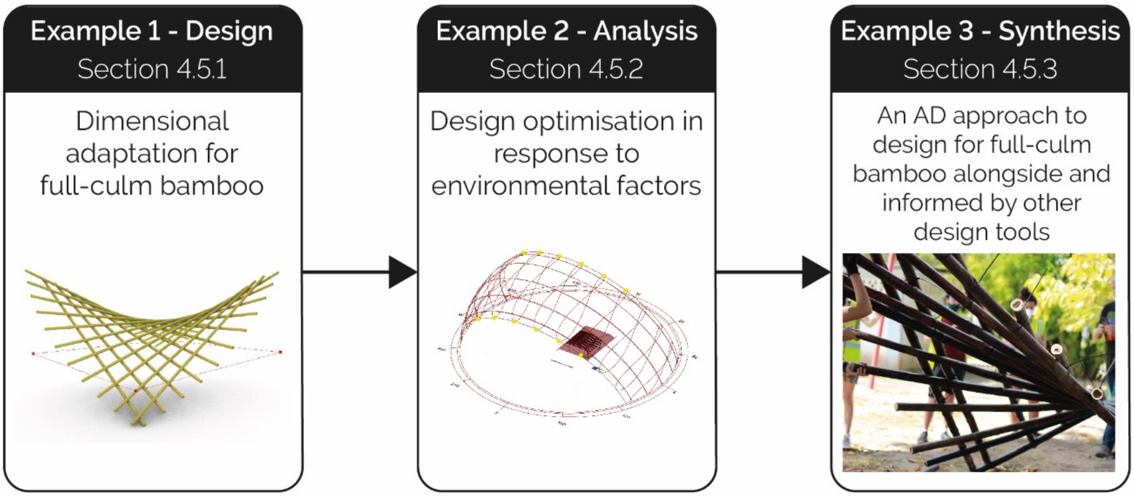

Figure 88: Overview of three applied examples of the application of AD tools and algorithmic thinking to the design of full-culm bamboo structures, undertaken as part of this research.

4.5.1 Example 1: Adapting dimensions and geometry of a design for full-culm bamboo

This example endeavours to apply AD tools to the design of a hyperbolic paraboloid constructed of straight bamboo poles. The hyperbolic paraboloid form is an anticlastic saddle shaped surface (Figure 89), as when the surface is cut, it reveals hyperbolas and parabolas. Although straight lines exist on the surface this is a doubly curved surface (known as a ruled surface) and though it appears complex, the surface can be relatively easily constructed (Booth, 1997).

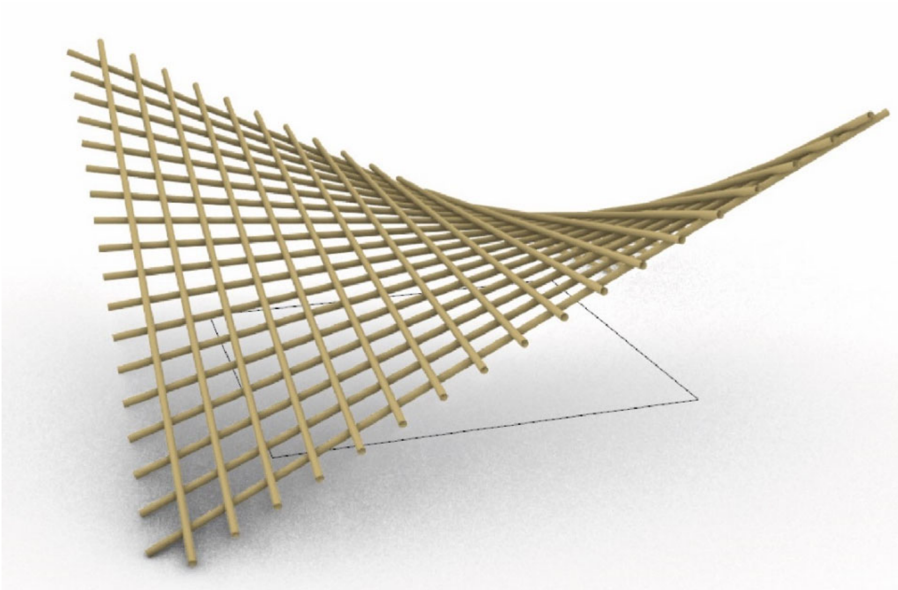

Figure 89: Idealised 3D explicit model of a hyperbolic paraboloid from the digital model developed through an AD process.

In this example, Rhinoceros and Grasshopper are the software which are used (Figure 90). Two assumptions have been made in the algorithm to negate effects of variability: (1) in the bamboo poles are modelled as a straight line, or a cylinder, and (2) the diameter of the bamboo culm input into the algorithm is a single value where as in reality a bamboo culm will have a diameter greater at the base than the top. This is not taken into account in this algorithm as depending on the species or specific plant the tapering can vary in extremity.

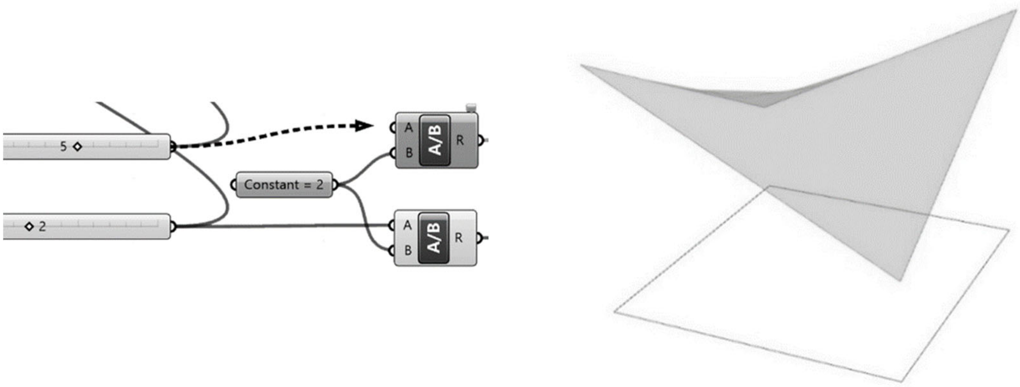

Figure 90: Example of nodes, inputs and outputs on the Grasshopper graphical algorithm editing canvas (left); a screenshot of Rhinoceros interface showing the polygonal outline which defines the area for the surface to cover, and the hyperbolic paraboloid (right).

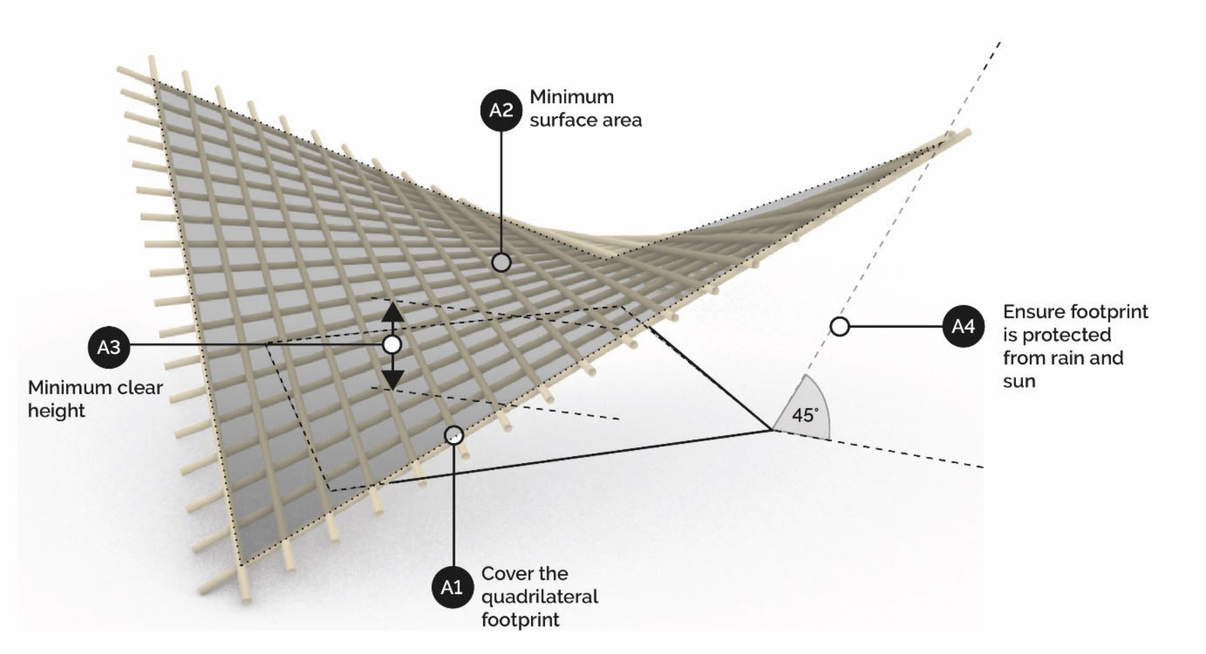

Figure 91: Performance requirements in the AD process for the hyperbolic paraboloid model considering the use of full-culm bamboo material.

With these construction elements (Figure 91), clear performance requirements of the design of the hyperbolic paraboloid and the bamboo material are required. The surface is to cover a defined footprint therefore there is a quadrilateral area in plan to be covered (Figure 91, A1) and protected from rain and sunlight (Figure 91, A4), based on a 45° angle rule of thumb (Kaminski, Lawrence, & Trujillo, 2016a), as well as minimising the surface area of the hyperbolic paraboloid surface (Figure 91, A2), and a clear height required at the centre of the footprint (Figure 91, A3). These would be informed by a client and/or an end user briefing requirements.

The next step is to identify the constant parameters, as shown in Figure 92. In the case of Figure 92, these are the footing locations (B1), which are the vertices of the building footprint defined in (Figure 91, A1), which is drawn in Rhinoceros as a *Closed polyline*. It is not required to be planar which accounts for the possibility that the site may not be flat.

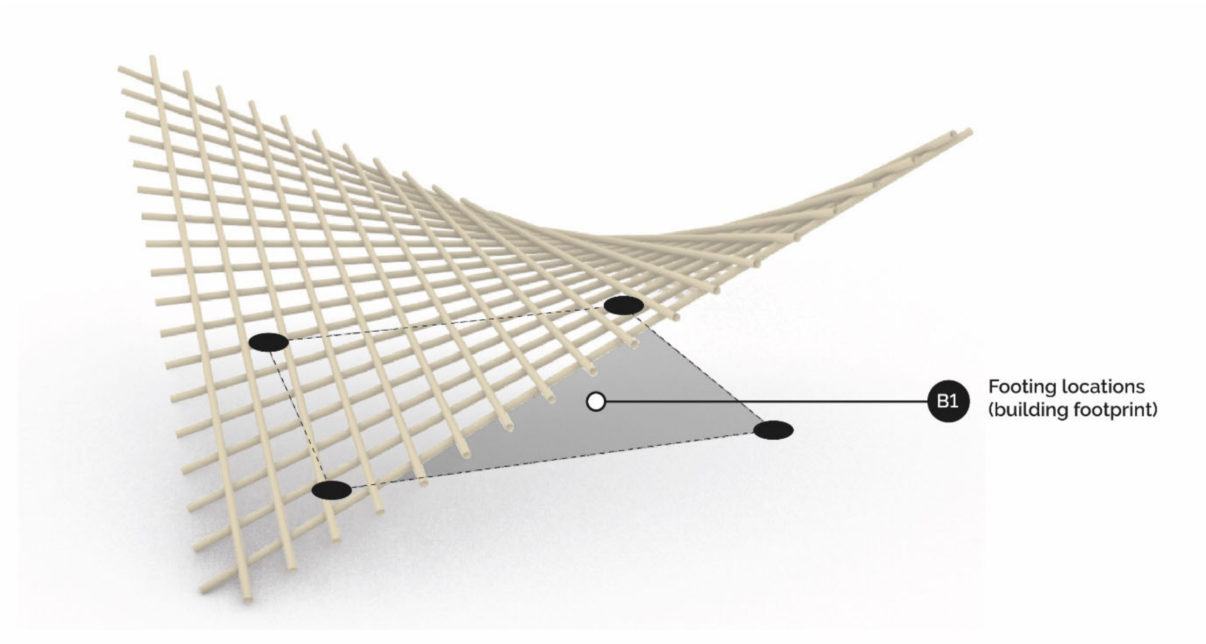

Figure 92: Constant values for input parameters in the AD process for the hyperbolic paraboloid model considering the use of full-culm bamboo material.

Next there is the identification of the variable input parameters. In the case of Figure 93, these are: (C1) The diameter of bamboo, (C2) the length of the bamboo poles to be used, (C3) the peak heights of the hyperbolic paraboloid, and (C4) the eave height.

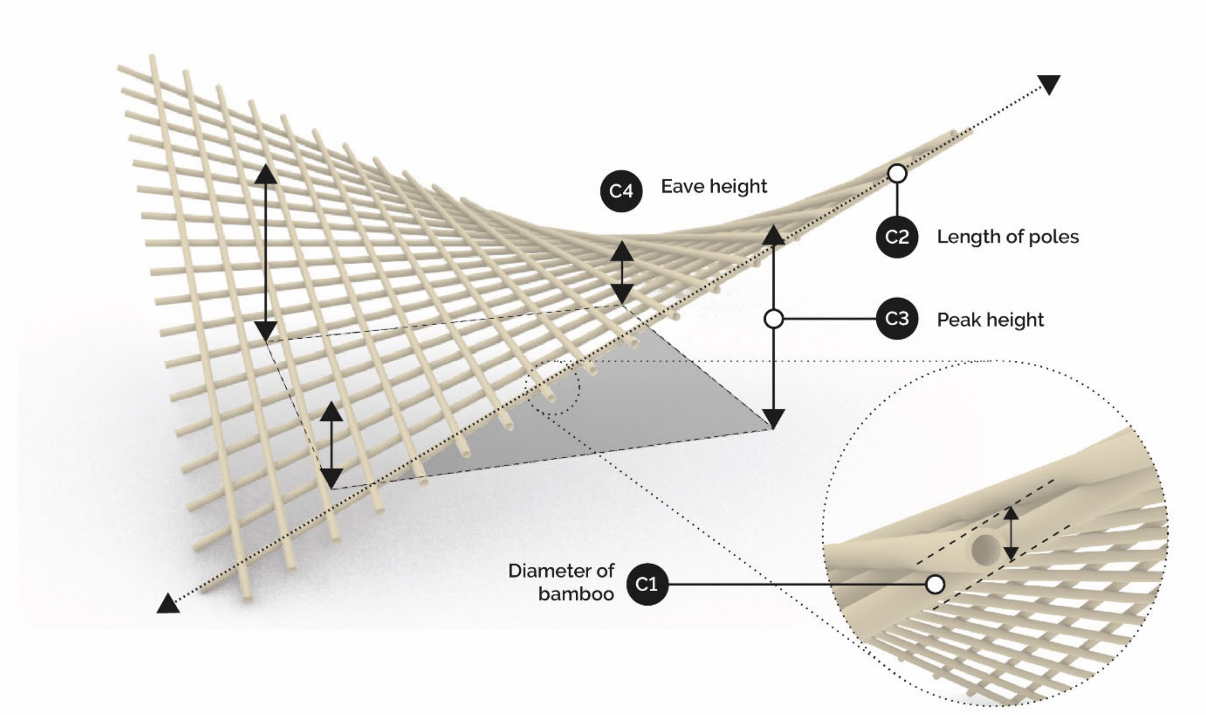

Figure 93: Variable input parameters in the AD process for the hyperbolic paraboloid model considering the use of full-culm bamboo material.

The algorithm will generate a hyperbolic paraboloid from this initial building footprint (Figure 91, A1). The algorithm for generating the hyperbolic paraboloid will extract the nodes at each corner of the quadrilateral, move the nodes vertically (Z-axis) to a point defined by the user which correspond to the intended peak (Figure 93, C3) and eave heights (Figure 93, C4) of the roof. Poles can be extended beyond the required 45° angle overhang requirement (Figure 93, C2).

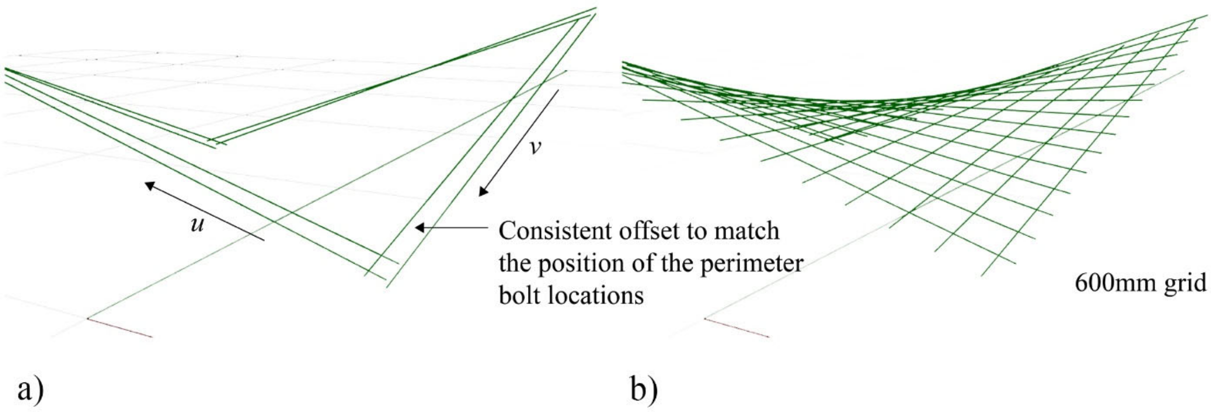

Figure 94: Graphical display in the Rhinoceros viewport showing geometry representations from Grasshopper, with: (a) The edge curves offset from one another to represent the different levels of the grid of bamboo poles showing the *u* direction and *v* direction offset above by the diameter of the bamboo pole to be used, and (b) the grid applied based on the distance (also represented in Figure 95, D3).

The roof will be constructed from straight bamboo poles with a series of longitudinal poles and a series of latitudinal poles placed above (Figure 94b). This distance is input into the algorithm by the user and is the diameter of the bamboo poles to be used in construction. This distance is used to offset a second upper surface from the original. Longitudinal members (*u*) are extracted from the lower surface, and latitudinal members (*v*) are extracted from the upper surface (Figure 94a). The offset distance of the roof is connected to the diameter of the bamboo (*D*) to be used (Figure 93, C1). This will save a lot of time for the design professional as this algorithm will adapt the design if alternative bamboo species, alternative sites, or new suppliers of bamboo, are required. As also shown in Figure 94a, a constant offset is applied inwards of the edge to define the position of the perimeter bolt locations.

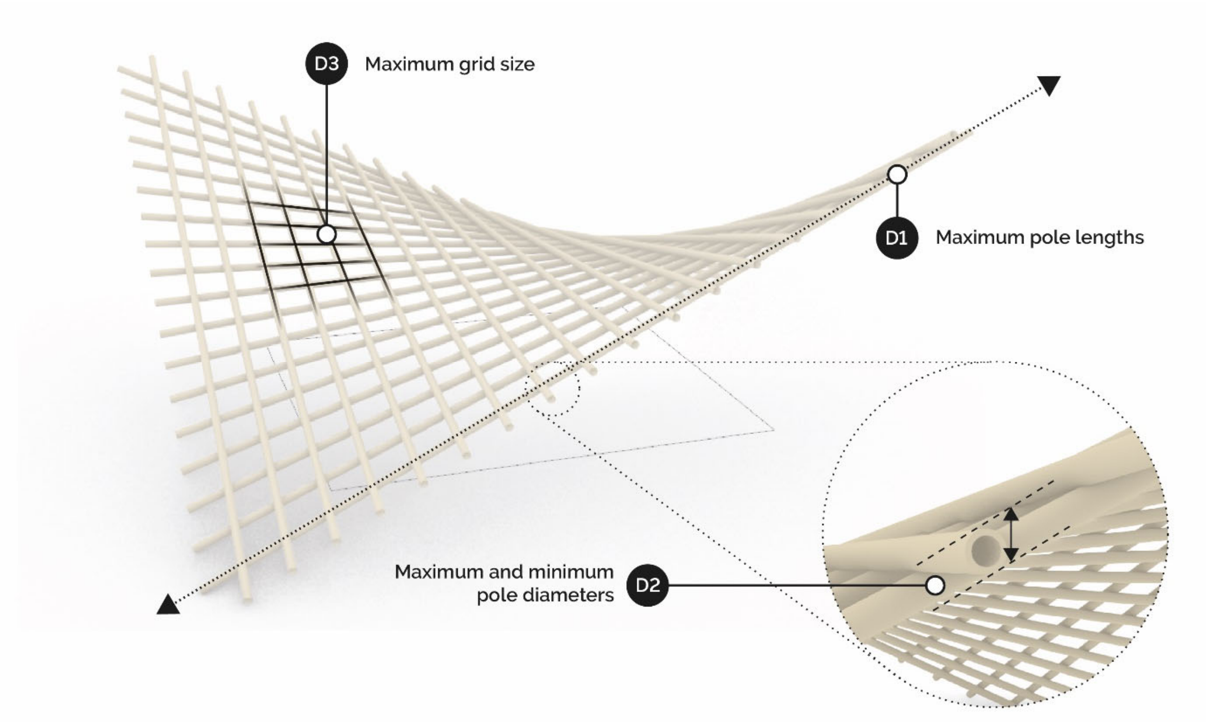

Figure 95: Design constraints to be applied to input parameters in the AD process for the hyperbolic paraboloid model considering the use of full-culm bamboo material.

Once the variable input parameters have been identified, then it is a question of identifying which of these have constraints informed by the seven factors a design professional needs to consider for durability (Section 2.5). In the case of Figure 95, these are: (D1) The maximum lengths of poles to be used, which will be informed by the supply chain of the bamboo material (performance requirements established in Section 3.7), (D2) The minimum/maximum diameter of the available bamboo, which is again informed by the supply chain, the geography and available bamboo species (performance requirements established in Section 3.7 and 3.8), as well as (D3) the minimum grid size, which is informed by the instruction of an engineering or construction professional, or necessity of local code (e.g., ISO 22156, 2021).

The final step is then to identify which of the variables may be linked (Figure 96). To address durability, the roof has an important role to play in protecting the bamboo used in the structure from driving rain and a large roof overhang is often required to shelter the walls and structure also known as protection by design (established in Section 3.4.3). The algorithm is designed to extend each line in the roof grid, by a length which is the height above the ground plane of the roof at that location. In the case of Figure 96, this is the extension of the bamboo poles at the peak height relative to the peak heights distance above the ground plane.

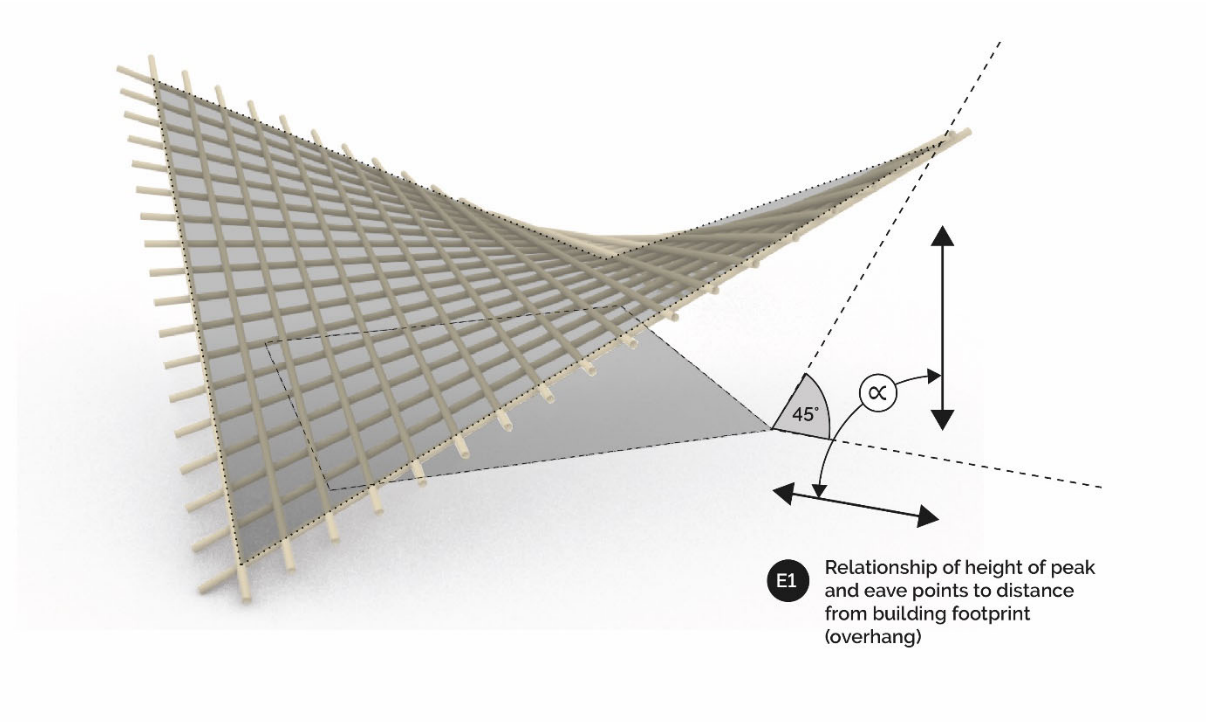

Figure 96: Input variables which are linked to one another in the AD process for the hyperbolic paraboloid model considering the use of full-culm bamboo material.

The relationship established in Figure 96, E1, ensures the 45° angle rule is adhered to in the design and, therefore, embed the consideration of durability and protection from rain and sun into the algorithm and, therefore, the design (performance requirements for durability established in Section 3.4.3 and 3.4.6, and performance requirement A4 in Figure 91). The full list of performance requirements and input parameters is shown in Table 14.

Table 14: List of performance requirements and constraints in the AD process for the hyperbolic paraboloid model considering the use of full-culm bamboo material.

Category	**Annotation**	**Description**
Performance requirements	A1	Cover the quadrilateral footprint
	A2	Minimum surface area
	A3	Minimum height clearance
	A4	Ensure footprint is protected from rain and sun
Constant parameters	B1	Footing locations (building footprint)

Variable input parameters	C1	Diameter of bamboo
	C2	Length of poles
	C3	Distance from ground of peak point
	C4	Distance from ground of eave point
Design constraints to be associated with variable parameters	D1	Maximum and minimum pole lengths
	D2	Maximum and minimum pole diameters
	D3	Maximum grid size
Linked variables	E1	Relationship of height of peak and eave points to distance from building footprint (overhang)

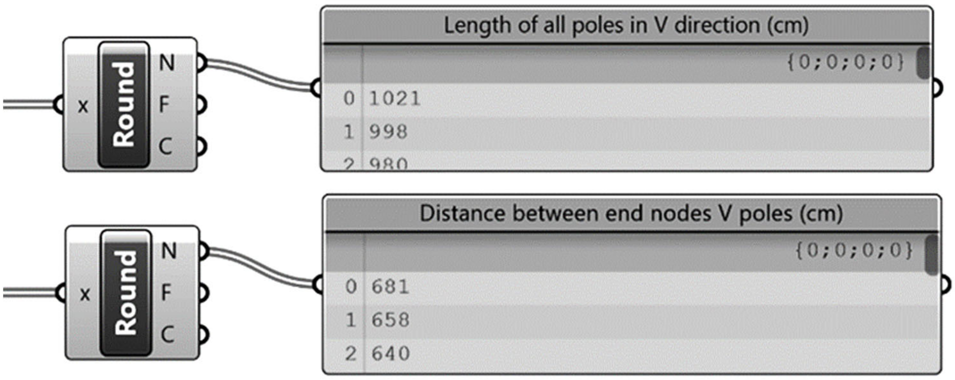

Figure 97: Grasshopper algorithm screenshot showing: lengths in cm of all the poles; and lengths between the first and last nodes to be bolted on each member, in the latitudinal (v) direction.

The output from the algorithm includes:

- The quantity of poles required to form the surface.

- The lengths of bamboo poles, rounded to the nearest cm[23] (Figure 97). This can assist the design professional or builder in determining the availability of bamboo culms, the limits of transportation to site, and the cut lengths.

- The required distances between first and last nodes for each pole (Figure 97), which will be useful when selecting poles from a stock to be used for specific roof members.

- Visual output of the massing in order to view the form in 3D (Figure 89).

- NURBS geometry output which can be used to produce diagrams, drawings and rapid prototyping.

- Locations of connections where bolts may be placed. These measurements can then be used to mark out the poles prior to construction to prevent having to drill in situ which can be more dangerous than a factory or workshop environment.

The challenges presented in this example are exemplified by the negation of the curvature and the tapering diameter of the bamboo poles. These characteristics could have structural and architectural significance which are not taken into account. A further challenge is in the translation from design to construction, and therefore such a digital process may need to add robustness or margin of error into the design to compensate. In order to compare the algorithmic model, it is important therefore to develop these algorithms in response to the queries which may emerge through the physical construction process and test the use of these tools with a group of students and professionals. An endeavour to identify these challenges and learn how to incorporate AD with other design tools and full-scale construction is documented in the third example in Section 4.5.3.

4.5.2 Example 2: Environmental analysis on a design for full-culm bamboo

This second applied example looks to apply AD tools to perform environmental analysis to design for durability in full-culm bamboo structures. This was a gap in the application of AD tools identified in Section 4.4.3. Here, a simple example of four columns (proposed to be full-

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[23] Centimetres are a unit of measurement aligned to the real-world precision and tolerance of bamboo construction.

culm bamboo) and a pitched roof cover are used. As this design develops, these can be four pole columns (presented in Chapter 3, Figure 61). The roof type along with the input parameters to define the geometry of the roof are shown in Figure 99. This example was presented as a peer reviewed conference paper and published as Naylor (2021) which is included as Appendix B.

The software used in this study are Rhinoceros, Grasshopper, Ladybug for the sunlight analysis and Galapagos. These pieces of software were discussed in Section 4.4.4.

This process starts by drawing a closed quadrilateral shape in Rhinoceros which should have sides no larger than 6m and this *Closed curve* is assigned in Grasshopper. This allows the roof geometry to be built over any quadrilateral site. The first edge of this quadrilateral will define the location of the planar truss and the truss will be constructed perpendicular to the base plane. The design of the planar truss (Figure 98) is based on a design in Minke (2012, p. 51).

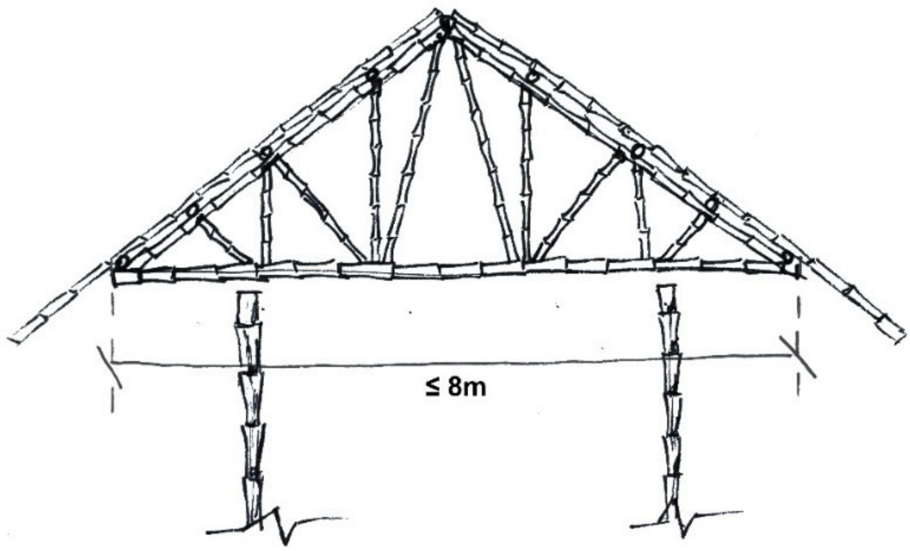


Figure 98: Planar truss spanning up to 8m. Sketch by author based on truss design referenced from Minke (2012, p. 51).

The truss is modelled within the algorithm generating secondary members. Producing the geometry for the individual poles in the truss will allow for drawings to be produced which show bamboo elements to cut, with node and bolt locations. This truss defines the transverse section of the roof geometry, where this truss will be replicated and arrayed along the length of the building.

The algorithm which generated the gablet roof geometry was built with a series of variable input parameters (Figure 99): (1) the peak height of the roof truss in meters, (2) the position of the ridge line as a percentage of the width of the building, (3) the height of the gable as a percentage of the height of the roof truss (Input parameter 1), (4) the width of the roof in meters, (5) the depth of the roof overhang in meters which is mirrored on the opposite edge, (6) the height of the arc segment as a percentage out of straightness which defines the curved rafters, and the additional length of the overhang (each opposite edge can be independently input). (7A) is the extension in meters of the straight rafters in Trial 1, and (7B) is the extension of the arc of the curved rafters used in Trial 2 and 3. Within the input parameter 7A and 7B, minimum values can be set to ensure that the 45° angle guideline roof overhang is maintained. Input parameter 2 allows the truss to become asymmetrical to assist in finding the optimal roof geometry and surface area. The formal model for this algorithmic process is shown in Figure 100.

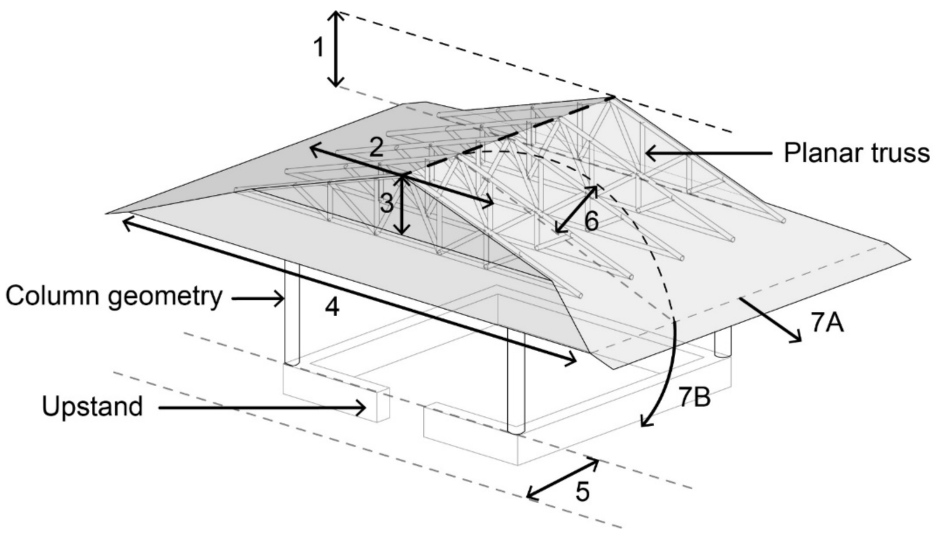


Figure 99: Parameters of the gablet roof design which are input into the algorithm to define the roof geometry.

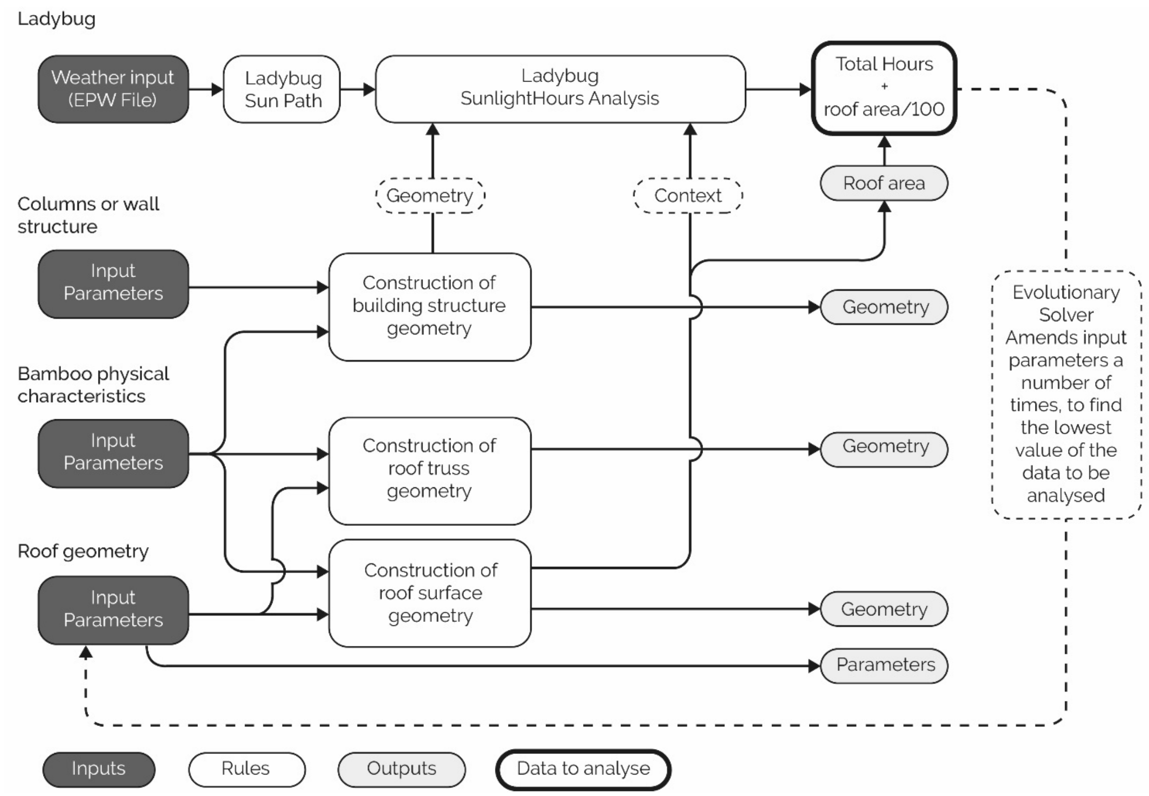


Figure 100: Conceptual representation of the AD process developed for the example in this section, based on Laiserin (2008) and Tedeschi (2014).

In Trial 1, the algorithm negates any curvature of the bamboo similar to the steps in the previous example (Section 4.5.1). Using curved poles as rafters is later implemented in the algorithm and in Trial 2 and 3, this is compared to the results of the Trial 1 environmental analysis. Trial 2, generates curved rafters with a bow of 5% out of straightness and Trial 3, connects the input parameters for the rafter curvature to the Galapagos evolutionary solver to let the algorithm suggest the optimal curvature of rafters which can reduce the surface area of the roof. Within this process it is possible for the algorithm to test different combinations of input parameters to produce an “optimal” design solution.

In order to run the solar hours study in Grasshopper a series of input geometry is needed along with components which are provided in Grasshopper through the Ladybug plug-in (Ladybug Tools LLC, 2020): (1) the geometry to be exposed to the solar study (the bamboo columns), (2) the geometry which will provide the shade, known as the *Context* (the roof), and (3) the locations of the Sun to test, which are available through the Ladybug component *Ladybug_SunPath.* This generates a 3D sun path in the Rhinoceros window (Figure 101b), with the sun path-oriented east to west as default. In all tests in this study the building is positioned north/south, however this can be easily changed by rotating the sun path as necessary. A file path container and the *ImportEPW* component is used to link this algorithm to an EPW file.

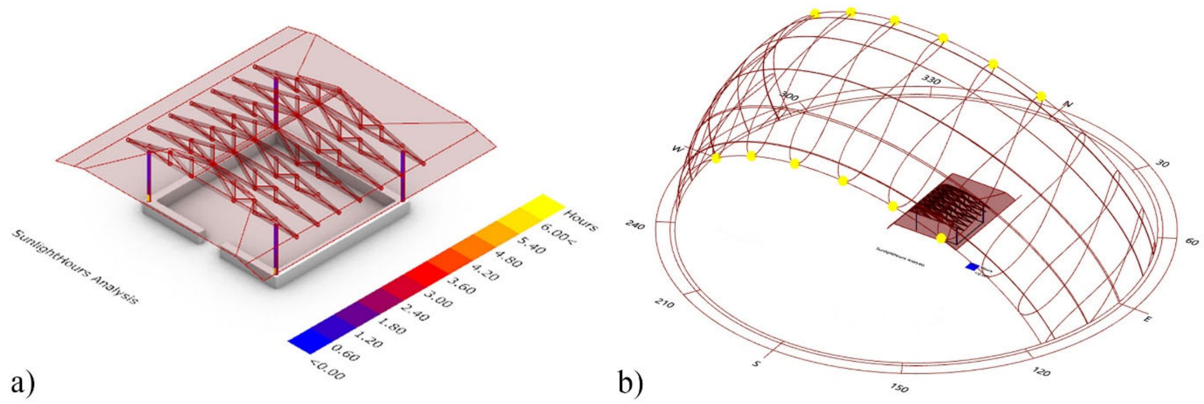


Figure 101: Sunlight analysis using Ladybug software with: (a) a scale showing the hours of sunlight hitting each area of the column geometry representing bamboo columns, and (b) an image of the sun path showing from which angles the direction of the sun was applied onto the model geometry.

Three sites were chosen to reflect a variety of geographies in which bamboo could be locally sourced and utilised. These were Kunming, China, which is north of the tropics, Bengaluru, India, situated between the Tropic of Cancer and the Equator, and La Libertad, Ecuador, which will be exposed to equatorial sunlight but is characterised by a local steppe climate with little rainfall throughout the year and proximity to local bamboo resources. For Kunming and Bengaluru, the 45° angle guideline roof overhang is set as a minimum value in input 7 given the protection required for rainfall. The script looks to validate or add to this to provide full protection from UV light. In La Libertad, given the steppe climate and lack of rainfall, the goal here is to optimise and potentially reduce the roof overhang therefore there is no minimum value set for input 7 (this step is further commented on later in this section). EPW weather files were used for each of these three locations. Hourly sun locations for each of these sites were taken from 10:00 (10 a.m.) to 16:00 (4 p.m.) for each solstice (21st June and 21st December), which is when the sun would be at extreme angles. This information as well as the input geometries were input into the *SunlightHoursAnalysis* component which ran the calculation and output the combined hours of sunlight for both periods and dates.

The optimisation methodology involved the Galapagos evolutionary solver running for 100 steps, with 50 iterations per step, with an additional 50 iterations in the first step. Therefore 5,050 total iterations. The objective function is the minimum value for: one hundredth the value for the roof area plus the hours of direct sunlight on the bamboo poles. The set of variables which define the gablet roof geometry, and the objective function are each defined by a range, a start and an end value. The variable sliders which were input as part of the *genome* to find this objective function differed in each of the three trials. These are referenced individually for each of the three trials in this study:

- **Baseline - Roof geometry with 45° angle overhang:** As a baseline roof geometry to compare the studies to, a gablet roof is modelled which maintains a uniform overhang on all sides of the building of 45°.

- **Trial 1 - Optimised roof using straight poles:** For Trial 1, all members in the truss and roof rafters are straight. In this trial, input parameter 6 and 7B (Figure 99) are not used.

- **Trial 2 - Optimised roof with percentage straightness (bow) as an input:** The goal of Trial 2 and Trial 3 is to compare a roof design with curved rafters to the roof design with straight poles in Trial 1. In Trial 2 the user can input the percentage out of straightness (bow) value that is required. This can be determined from the available material. In this case 5% has been used. Input 7A is not used.

- **Trial 3 - Optimised roof with percentage straightness (bow) as an output:** It could be the case that the optimal roof area is sought prior to selecting the bamboo poles to be used in construction. Therefore, in Trial 3, the inputs which define the bow of the bamboo poles used as rafters were input into the evolutionary solver to find the most optimal curvature of pole to use.

The outputs of this study are shown in Figure 102 and Table 15. It is interesting to note that in Kunming where the uniform 45° angle overhang was tested, there were still parts of the columns that received hours of direct solar exposure. In order to provide full shade in Kunming, the roof was required to be larger than the uniform baseline roof geometry. In Bengaluru the algorithm validated the required 45° angle overhang as providing enough solar protection. In La Libertad, where the dry climate meant the 45° angle guideline roof overhang was overlooked, the roof was found to be significantly less area yet provide full solar protection to the columns. By implementing curved poles into the algorithm this showed in some cases there could be marginal reduction in the roof surface area whilst still ensuring full solar protection. In all cases an asymmetric truss was found to be optimal with the height at the minimum value of 1m. In Trial 3 which looked to find the most optimal curvature of bamboo pole, the optimal curvature was between 1 and 4 out of 100 (1% and 4%). Given the many inputs, the evolutionary solver may need more than 100 steps for an improved fitness to be found.

Table 15: Baseline roof information and results of all trials. For clarity, the values of input parameters 2, 3, 4, 5 and 7, as referenced in Figure 99, are not shown. (* denotes that the 45° angle guideline roof overhang was not applied and there is no minimum value set for input 7).

Roof type	*Location (EPW file used)*	*% out of straightness of rafters (%) (Input 6)*		*Truss height (m) (Input 1)*	*Roof surface area (sqm)*	*Change in roof area compared to baseline roof area (sqm)*	*Max. daily hours of solar exposure to full-culm bamboo columns (hours)*
		West	*East*				
Baseline – Uniform 45 degree roof overhang	Kunming	N/A		1m	114.14	N/A	< 6
	Bengaluru	N/A		1m	114.14	N/A	0
	La Libertad*	N/A		1m	114.14	N/A	0
Trial 1 - Straight rafters	Kunming	N/A		1m	141.25	+24%	0
	Bengaluru	N/A		1m	112.80	-1%	0
	La Libertad*	N/A		1m	88.03	-23%	0
Trial 2 - Rafter curvature as an input	Kunming	5		1m	141.91	+24%	0
	Bengaluru	5		1m	112.88	-1%	0
	La Libertad*	5		1m	89.12	-22%	0
Trial 3 - Optimal rafter curvature as an output	Kunming	1	4	1m	141.60	+24%	0
	Bengaluru	1	2	1m	111.69	-2%	0
	La Libertad*	2	1	1m	87.49	-23%	0

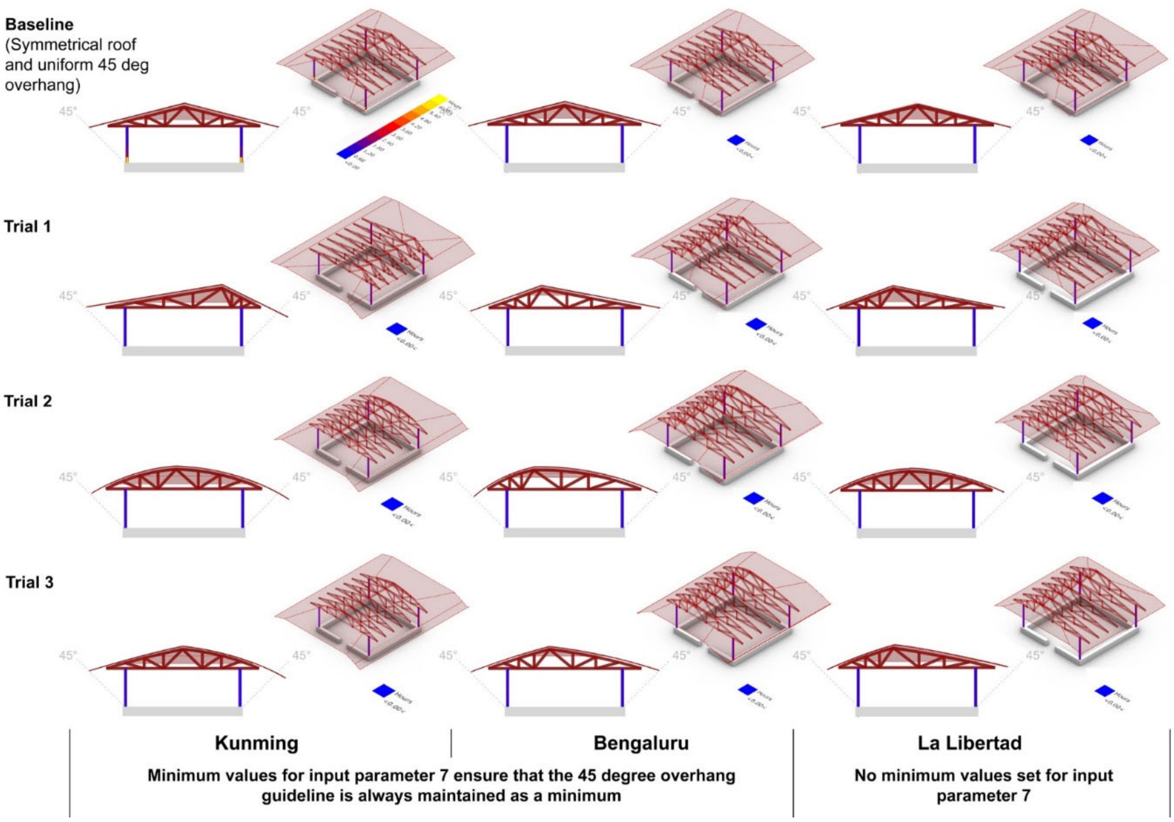


Figure 102: Screenshot front elevations and axonometric views of output geometry from Rhinoceros interface, following the *Sunlight Hours Analysis* in Grasshopper and Ladybug.

A next step could be to run the solver by fixing certain values such as the 1m truss height and the bow of the bamboo poles at 1%-4% to reduce the possible combinations of inputs in future tests. Here, a centre line model was used as the basis of the truss, however this can be taken further to ensure the node, bolt and cut locations are all taken into account when placing secondary members. These can be easily added to the algorithm. The negation of the 45° angle overhang for the steppe climate of La Libertad should be avoided in the design approach. This is a unique context, and the design of a bamboo structure should always still afford protection from even limited rainfall.

This example shows how AD tools can support the design professional in the design for full-culm bamboo durability and addresses the identified research gap from Section 4.4.3. This also shows the application of an evolutionary solver in this process to optimise the design output based on durability performance requirements established at the outset of the process.

4.5.3 Example 3: Situating AD within a design process for full-culm bamboo

As a third applied example, AD tools were integrated into a curriculum of a workshop coordinated by the author in collaboration with Diego Perez Espitia, Cesar Cheng, and Jörg Stamm who provided the professional bamboo construction expertise to the curriculum[24]. This workshop was organised through the Architectural Association School of Architecture in the spring of 2022. This took place at the Mamoní Valley Preserve and Isthmus University, Panama (an example of a country with great potential for bamboo use) with 25 participants who were students or practitioners of architecture from the region with two participants joining from outside Central and South America[25]. The curriculum, workshop phases and iterative design approach fostered by the curriculum are diagrammed in Figure 103. This workshop experience and discussion on the design tools used were presented as a peer reviewed conference paper co-authored with construction professional for the workshop Jörg

[24] As noted in the research acknowledgements, the views expressed in this research do not necessarily reflect the views of those acknowledged and all interpretations, conclusions and any errors in this thesis are the author's own.

[25] A full list of co-organisers, collaborators and sponsors for this workshop are documented in the peer-reviewed paper included as Appendix C.

Stamm and workshop participant Munir Vahanvati. This was published as Naylor et al. (2022) (and documented as Appendix C).

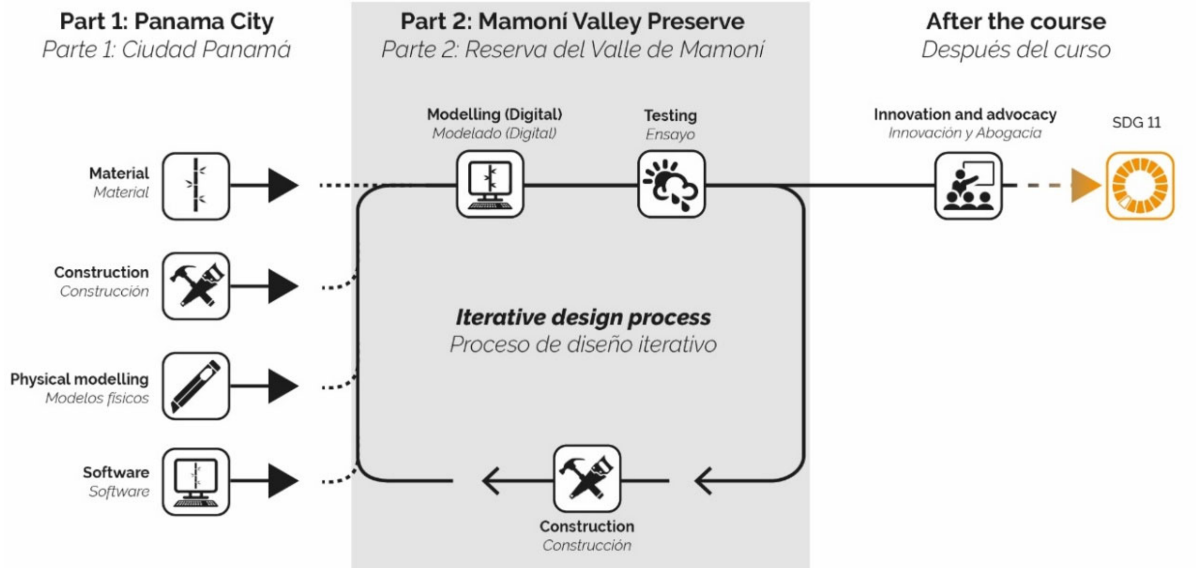
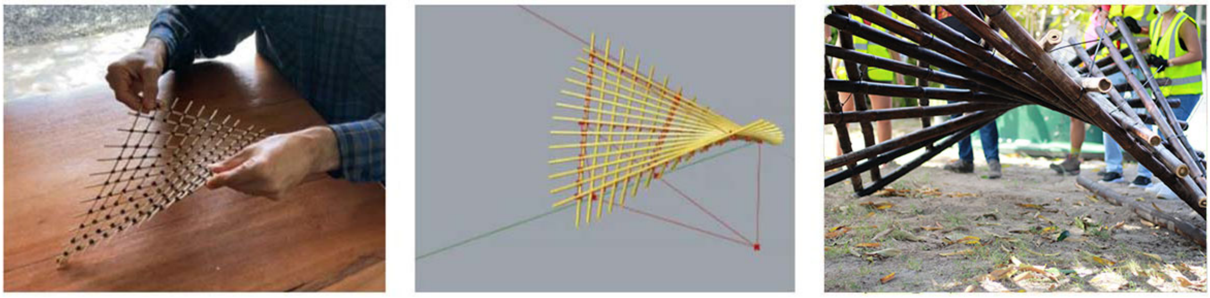


Figure 103: Curriculum and design process used during the ten-day long Panama workshop.

This workshop was designed as an introduction to the material and the software, therefore most participants had not used the software or worked with an AD approach to design for full-culm bamboo. The workshop took place online and in person. The online workshop afforded the ability to deliver all aspects of the curriculum other than physical construction if participants were unable to attend in person due to the COVID-19 pandemic.

Figure 104: Image of hyperbolic paraboloid constructed during the Panama workshop in January 2022 from full-culm bamboo. Photo by author, 2022.

This ten-day workshop in Panama brought together all the design tools discussed in Section 4.3 (other than BIM) and taught a series of exercises and activities including the examples in Section 4.5.1 and 4.5.2. The bamboo construction expertise of Jörg Stamm was crucial to understand the material inputs and outputs required by a construction professional of bamboo structures with global experience. The workshop used three structural systems as the basis of design and material explorations. These were: a hyperbolic paraboloid (Figure 104), a planar truss and columns (Figure 108b), and a space frame. The experience of physical modelling, digital modelling, and one-to-one scale construction of the hyperbolic paraboloid (Figure 105) are discussed in this section.



a) Physical model **b) Algorithmic model** **c) Physical construction**

Figure 105: Mixed media used for design exploration of the hyperbolic paraboloid during the Panama workshop. Images by author, 2022.

Physical modelling was executed with bamboo skewers and rubber bands and is an easy and quick way to build a hyperbolic paraboloid model. Fixed length bamboo skewers are used to create a grid of 10 x 10 skewers tied at each intersection using thin rubber bands (Figure 106b). The rubber bands are an important component as it keeps the grid flexible allowing it to deform. Once the grid is tied and ready, two diagonal ends of the square are pushed together and raised up, this results in the other two corners being pushed together and pushed down. The skewers slide against each other creating a twisted ruled surface. The final shape depends on the amount of pressure applied. Thin string can be tied around the model—from one point to the opposite point along the convex section—to fix the shape, or the skewers can be glued together at the intersections, once a desired shape is achieved.

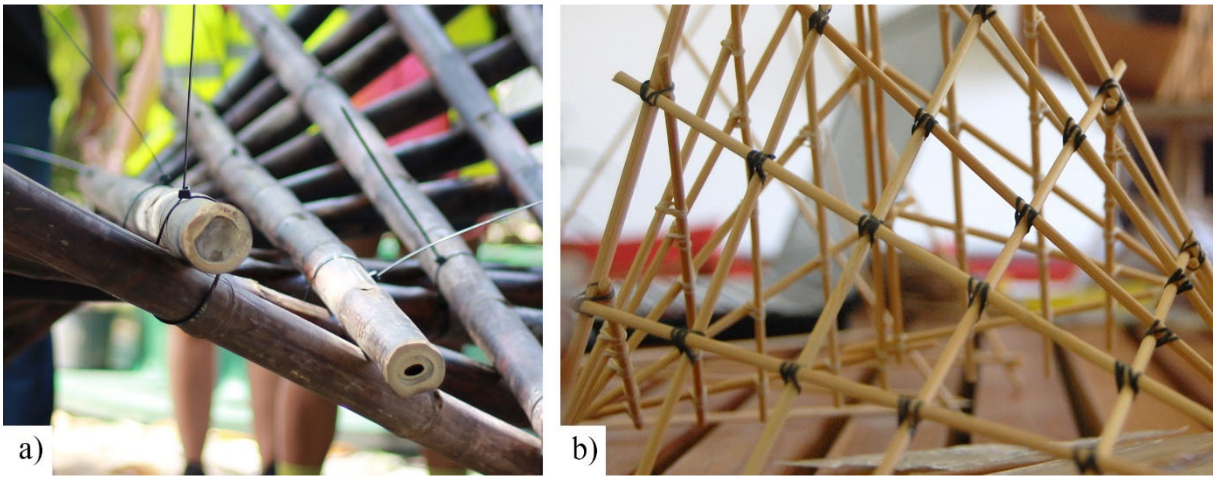


Figure 106: (a) Zip-ties used in the construction of the hyperbolic paraboloid, and (b) physical modelling of a hyperbolic paraboloid with elastic/rubber bands and bamboo skewers.

Various physical models were shared around the group and participants were encouraged to explore various possibilities. Once the hyperbolic paraboloid form has been found through the physical model, by pressing the form flat on a surface, the length and width of each section of grid is reduced in those at the centre of the grid. Once the pressure is removed, the physical model will spring back into the hyperbolic paraboloid form. If more than one hyperbolic paraboloid is placed together it is possible to use this as one element in a larger organisation.

Figure 107: Visual grading applied to determine material availability: The process of sorting bamboo poles onsite for construction used during the Panama workshop, into straight poles (left), and poles with a single curvature (or bow) or more than one direction of curvature (right). Image reproduced from Stamm (2001, p. 34).

The hyperbolic paraboloid was constructed using *Bambusa barbatus* bamboo[26], zip ties, steel bolts, nuts and washers. The *B. barbatus* was sorted to determine which: (1) bamboo poles

[26] The bamboo was provided through sponsorship from IMKM Architecture and Planning.

were straight (or minimal bow), and (2) which poles were poles with a single curvature—or bow—or curves in more than one direction (Figure 107). A grid was constructed flat on the ground with zip ties fastened at each alternate intersection. A number of participants were then tasked with deforming the grid into place raising the two opposite vertices and leaving the other two on the ground but pushing them closer together. Given this was outside this was also an opportunity for wider group work, and peer learning given everyone had the opportunity to stand with the structure and form this into place.

Figure 108: Physical one-to-one scale construction during the Panama workshop of two of the structural systems explored in the workshop: (a) hyperbolic paraboloid, and (b) four pole column to support a planar truss. Photos by author, 2022.

The use of zip ties (Figure 106a) in the one-to-one scale construction allowed for the deformation similar to the physical model. At a larger scale zip ties could be replaced with other materials such as rubber inner tubes, which can enable the same effect. The *stiffness* (not related to the mechanical property of stiffness) when the form was deformed beyond a certain point demonstrated the experience of a constraint alien to the digital realm. The hands-on experience gained from physical and full-scale modelling generated "informed intuition" (a term used by Swann, 2002, p. 51, and discussed in Section 4.6.2) on material performance which could be used when modelling digitally, fostering a dialectic relationship between design and build as advocated by Foote (2013, p. 53). This hands-on work helped define algorithm input limitations to prevent unrealistic digital model deformations. Despite selecting straight poles on-site (Figure 107), minimal bow in the poles could still cause variations in the hyperbolic paraboloid grid intersection points (bolt locations), deviating from the digital model. Zip-ties helped adjust for this variability. Once the desired shape was achieved, holes were drilled for bolts, which were then installed and tightened. Similar to the physical model's use of string, bamboo strips were used to secure the grid shape and triangulate each quadrilateral (Figure 108a). Incorporating experiential learning, the one-to-one scale construction experience continuously informed software exercises.

Software instruction, documented in the textbook provided to participants (an example exercise is presented in Appendix I), centred on exercises to teach designing for bamboo and the software platforms themselves (including those outlined in Section 4.5.1 and 4.5.2). Two additional didactic considerations when teaching software were the use of *Bifocals* (NBBJ Digital Practice, 2017), a Grasshopper software plug-in which aided visual understanding of each component, *Miro*, an online collaborative platform (Miro, 2022), and *Zoom* online video conferencing software facilitated virtual interaction with online participants (Zoom, 2022).

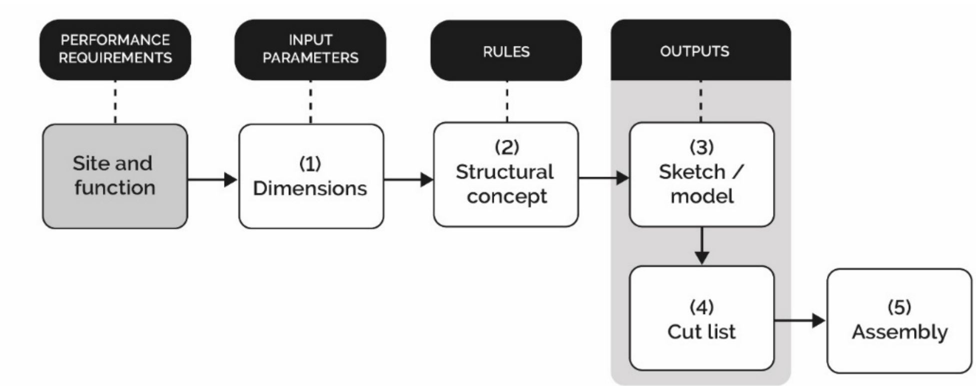


Figure 109: Conceptual representation of the design process followed in Section 4.5.1 to construct the model of the hyperbolic paraboloid following an AD approach.

Figure 109 shows the conceptual representation of the process in Section 4.5.1. However, the physical model and one-to-one scale construction logic differed from this process. This required the reconceptualisation of the design steps.

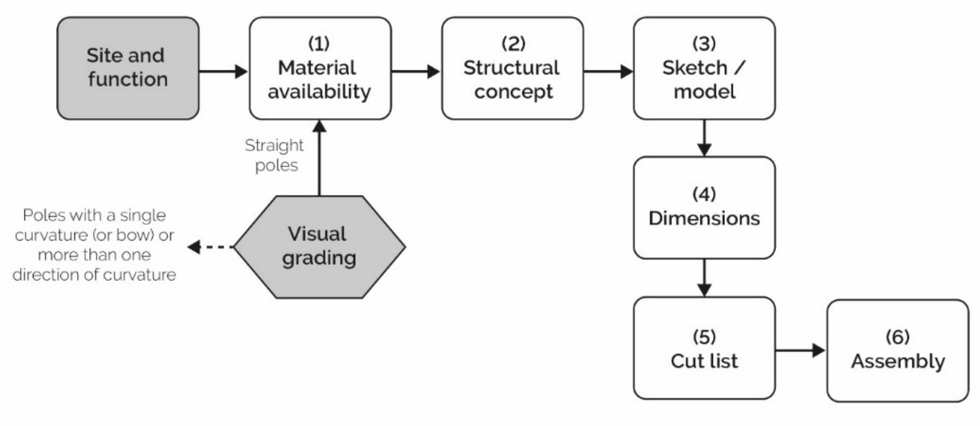


Figure 110: Conceptual representation of the design process established through the activities at the Panama workshop.

Figure 110 shows the reconceptualisation of the design process to consider full-culm bamboo suggested for the curriculum by the construction expertise from Jörg Stamm. This started with the grading of the bamboo poles (Figure 107) to determine what material could be used to construct. This meant the material catalogue was the first step and the logic of the algorithm would be required to follow this.

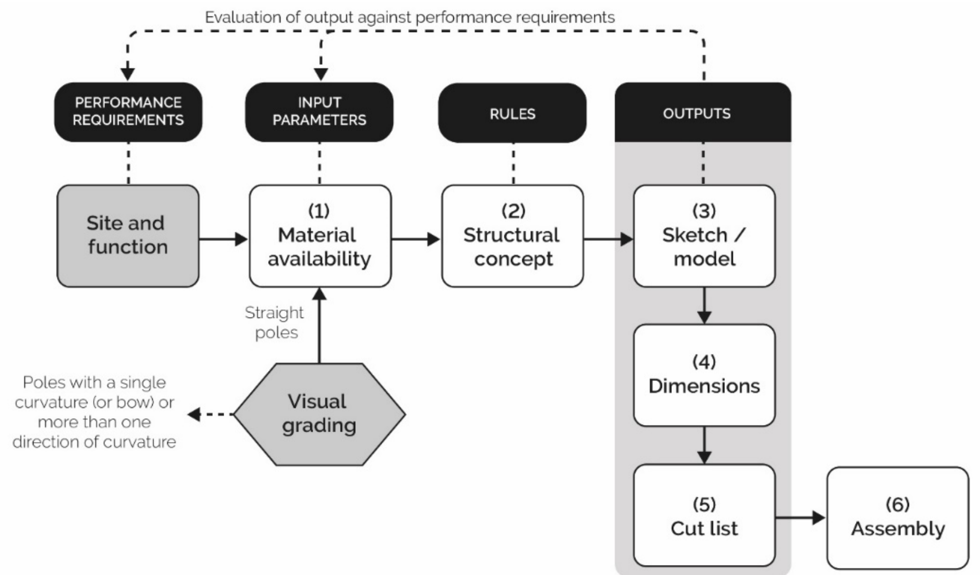


Figure 111: Conceptual representation of the design steps for the hyperbolic paraboloid with each step classified as inputs, rules, and outputs within an AD approach.

Figure 111 captures how AD plugged into this process through the workshop. Clear articulation of performance criteria and desired outputs guides this. It also highlights that for AD tools to be relevant they need to be underpinned by a strong conceptual framework of inputs, rules and outputs. This can be defined by a bamboo construction professional (Figure

110), or codified guidance such as ISO 22156 (2021). Now, as shown in Figure 111, pole lengths were constants informed by grading, while peak point positions served as variables deforming geometry akin to the physical model. The structural concept of the hyperbolic paraboloid remained. Questions which would be difficult to ascertain through manual processes, such as footing, locations for the low points of the hyperbolic paraboloid if peak points change could then be explored in the algorithmic model. This redrawing of the conceptual framework and redefining inputs and rules meant for anyone without knowledge in AD tools, this could be prohibitively difficult with the risk that the efficiency of AD is negated by the time to conceive and redraw. This change however brought materiality and construction logic into the design process. An alternative version of the algorithm to model a hyperbolic paraboloid (compared to that documented in Section 4.5.1) was therefore produced.

In Section 4.5.1 the algorithm extracts the dimensions of the poles from an anticlastic surface (Figure 89 and Figure 90), which is deformed by the low and peak points (Figure 93). This algorithm therefore changes the length of the bamboo poles as the surface changes (Figure 109). The new algorithm for the hyperbolic paraboloid model (Figure 112), also required the use of a live physics engine *Kangaroo* (Piker, 2013) to apply forces to the digital model. As shown in Figure 112, the hyperbolic paraboloid is configured with the distance between the lower corner points: (1) as a variable dimension controlled by the designer. The dimension for the distance between the peak points (2) changes in response to this. This is because the length of the poles (3) is a constant length which can also be defined by the design professional responding to the available bamboo poles.

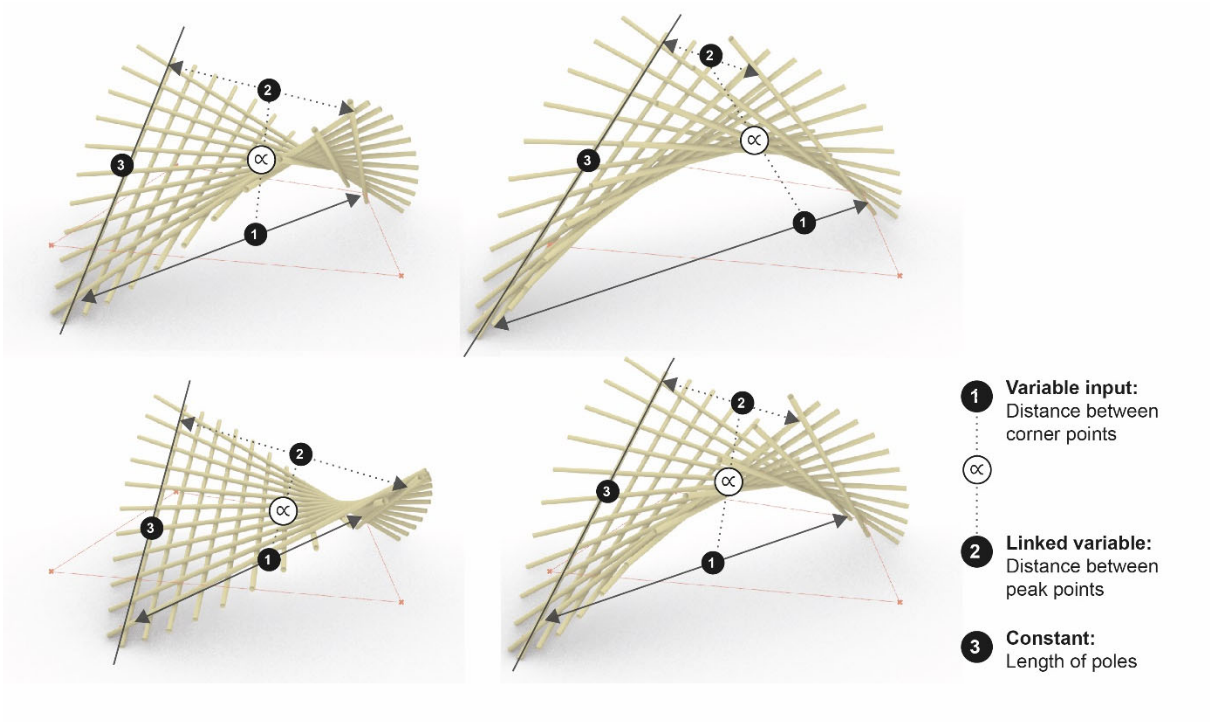


Figure 112: Example of another means of constructing the hyperbolic paraboloid which differs from the process outlined in the example in Section 4.5.1. As the length of (2) changes the structure responds as the length of the poles (3) are a constant length. This is similar to how a physical model of the same structural arrangement would behave.

The intention is the material specification (and logic of construction) which is an input rather than an output, as with the previous example. As the dimension for (1) is adjusted, the digital model will respond in a similar manner to how a physical model of the same structural arrangement would behave. The algorithmic model transitions from Grasshopper to Rhinoceros through “Baking”, enabling NURBS geometry representation for drawings, cross-platform exporting to other software, and visualisations.

The input and comments from the bamboo construction professional stressed the importance of using an AD approach to design for full-culm bamboo. The use of algorithms proves advantageous, especially when designing multi-hyperbolic paraboloid structures (Figure 113b). AD enables the creation of intricate bamboo buildings that were once unattainable using conventional methods. Algorithms establish not only relationships between individual elements but also among paraboloid clusters. This offers insights into manipulating a single element’s impact on the entire building. Without AD, rebuilding and integrating multiple paraboloids manually is arduous and impractical. Using AD, adaptability facilitates complex building design, aiding 3D visualisation, dimension analysis, and footing positioning.

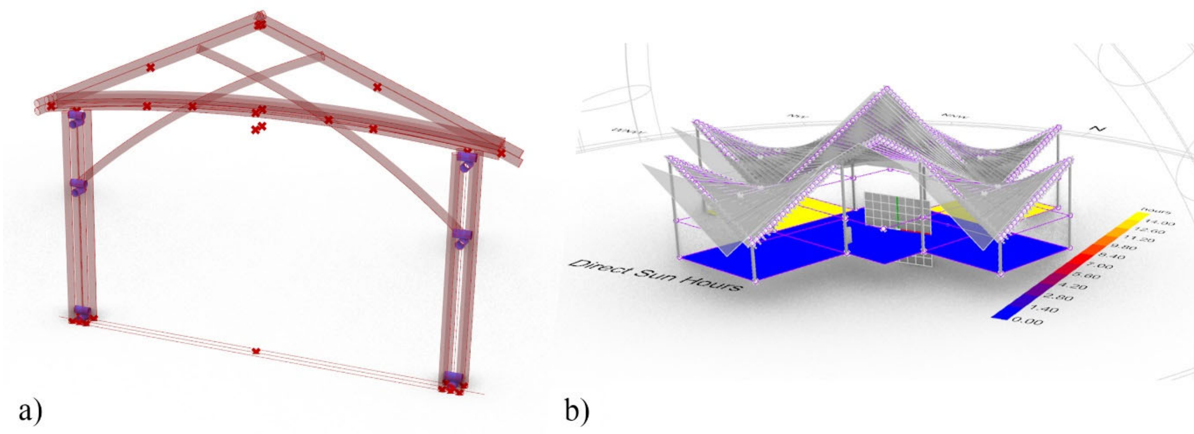


Figure 113: An example of student work from the Architectural Association School of Architecture, Panama workshop: (a) Planar truss representation from a software exercise using Rhinoceros and Grasshopper, and (b) environmental analysis conducted using Ladybug and *Galapagos*, on a multi-hyperbolic paraboloid cluster.

Durability and buildability influence design decisions. In the case of the truss (Figure 113a), the roof overhang was scripted to be extended proportional to the height above ground to protect the columns from driving rain and UV light. The columns which are modelled with the truss (Figure 113a) are based on the construction logic of the one-to-one scale construction of the four pole column type (Figure 108b).

Post-workshop survey results from participants at the Panama workshop show the value of a mixed media approach and illustrates how AD, as a component within this mix, can provide efficiency, calculation and analysis to reduce the challenges faced by design professionals when designing for non-standardised materials such as full-culm bamboo. The experience showed that these tools are more effective when combined with other design tools especially physical modelling or one-to-one scale construction that can inform the AD approach with first hand material experience. The primary advantage in using AD tools was thinking algorithmically, not merely the use of digital tools themselves. Here, AD tools, but more specifically algorithmic thinking, forces participants, and tutors alike, to think and diagram out how the material availability and/or properties influence the overall design. Through the insights gleaned from this participatory research, this study underscores the vital role of AD tools in efficiently and effectively designing full-culm bamboo structures while embracing the inherent properties of the material. This experience presented three important conclusions:

- **Relevance of AD tools:** AD tools are relevant to assist the design and construction professional in the design of structures with full-culm bamboo providing novel means of conceiving and describing complex structures with full-culm bamboo. Input parameter and required outputs needs to be clearly established from the outset, and the re-scripting of algorithms to respond to changes in the requirements can be time consuming and complex. A lack of knowledge of these tools can act as a barrier to this relevance.

- **Importance of a range of design tools:** A range of design tools including one-to-one scale prototyping and physical model making are important to design for full-culm bamboo with an example being how the material parameters and construction logic informed the conceptualisation of the algorithm.

- **Usefulness of algorithmic thinking:** Being forced to consider the design process as a series of sequential ordered steps (algorithmic thinking) through an AD approach informed by the material properties, availability of the material, and construction logic, assists the design professional to inform their design and understand the interrelated impacts these properties have on the overall design.

4.6 Considerations for a design approach to full-culm bamboo

The three lessons from the final applied example (Section 4.5.3) provide important considerations to apply to a design approach for durability in full-culm bamboo structures. Therefore, this section aims to understand two remaining questions to be resolved which have been raised through this Chapter 4. It is important to understand the software trends to understand how an AD approach can work with these (Section 4.6.1), and also comment on and understand how algorithmic thinking can be used to support durability in full-culm bamboo structures (Section 4.6.2).

4.6.1 Software use in early stages and documentation in the architectural design process: Survey results (Q5 and Q6)

Software platforms used in the design process of architectural design and engineering practitioners/professionals and students were Q5 and Q6 in the survey discussed in Section 2.3. Surveys were preferred over literature reviews to obtain current software usage insights and capture nuances and preferences not available in literature. The demographics of the survey are presented in Section 2.3.2. These questions along with the offered format of the response are presented in Table 12.

Table 16: Survey Q5 and Q6 to provide an insight into the software used by architectural design professionals and architecture students.

Number	Question	Response format
Q5	Which software do you use in the initial concept design stages of a project?	Multiple choice allowing multiple responses with a text box allowing an open-ended response to "Other": • Rhinoceros • Grasshopper • AutoCAD • Revit • None • Other
Q6	Which software do you use for producing drawings and final outputs of design or construction information?	Multiple choice allowing multiple responses with a text box allowing an open-ended response to "Other": • Rhinoceros • AutoCAD • Revit • None • Other

Q5 and Q6 were multiple choice questions (Table 16), with results shown in Figure 114. The multiple choices presented are informed by the experience of the author in academia and architecture practice, and the choice of "Other" with an open-ended text response was added to ensure that if none of these softwares were applicable then others would be recorded and avoid forcing responses. Rhinoceros (Robert McNeel & Associates, 2023) can be used for explicit modelling (the process of 3D modelling each geometric object based on explicit coordinates). Grasshopper (Robert McNeel & Associates, 2020) is one such AD platform integrated within the Rhinoceros platform. Though similar software such as *Dynamo* (Autodesk, 2019) exists for the BIM platform Revit (Autodesk, 2022b), it was decided to limit the number of represented options. The open-ended text box for "Other" would be able to pick up this as a response. "Grasshopper" as a response was removed from Q6 as such software platforms are unlikely to be used standalone for the production of drawings or final outputs. However, if the respondent deemed otherwise, then the open-ended text box for "Other" could record this.

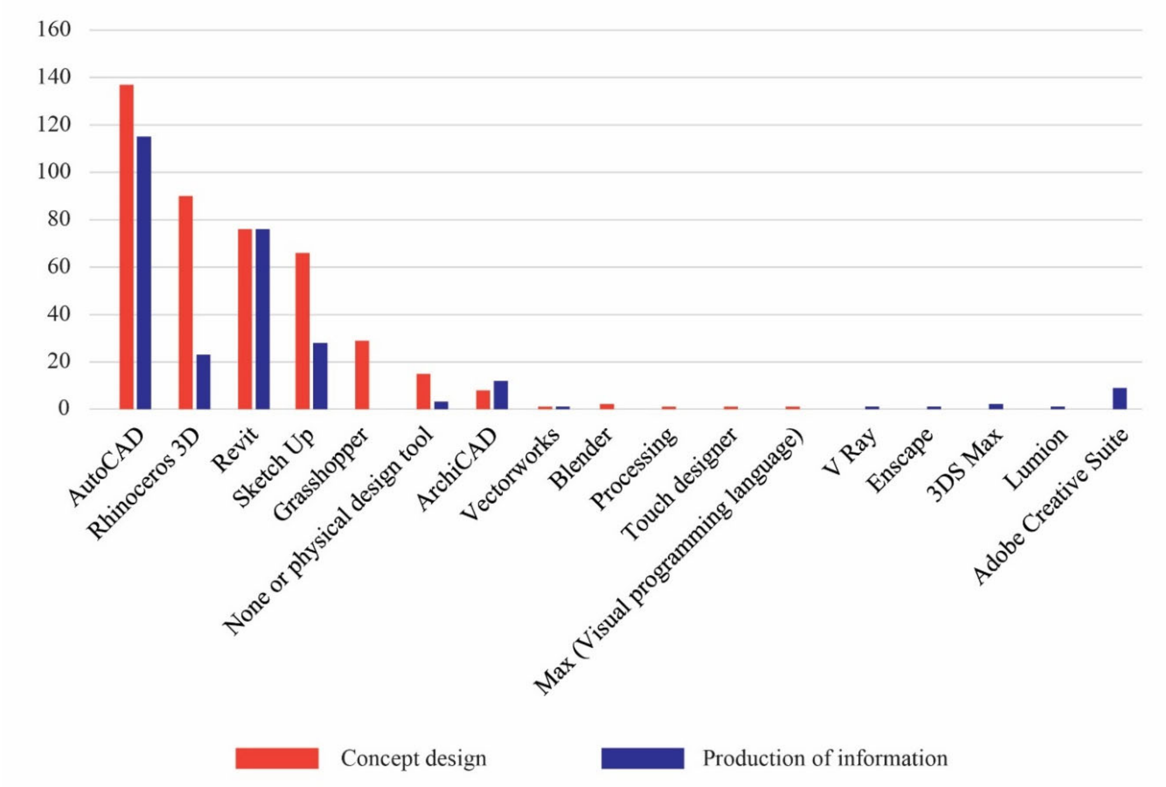


Figure 114: Responses to Q5 and Q6. (There were fewer responses for the production of information question. Therefore bars with each response should not be compared.)

The results for Q5 showed significant use of CAD software in the initial design stages of construction projects with the response "Rhinoceros" highlighted as the main 3D modelling platform for both architecture students and architectural design professionals (Figure 115). The response "Revit" showed use of this software in professionals was higher than for students, and this makes sense as an assumption is made that BIM software plays a more important role in professional practice than in academia. The results for Q6 also show the change in software tools used through the design stages of a construction project. Responses to "Revit" or "AutoCAD" showed these were the softwares most commonly used for the production of information or documentation. Rhinoceros is most applicable to the early design stages. Though software such as *Rhino.Inside.Revit* and the ability to import *DWG* files into AutoCAD, Rhinoceros is well calibrated to provide digital information to the Autodesk platforms. Since some respondents had signed up for workshops which taught AD software and Rhinoceros, this may be a bias against these results since they were signing up to learn these software platforms. However, the survey would pick up their lack of knowledge of these softwares and indicate that they are not used which is still relevant.

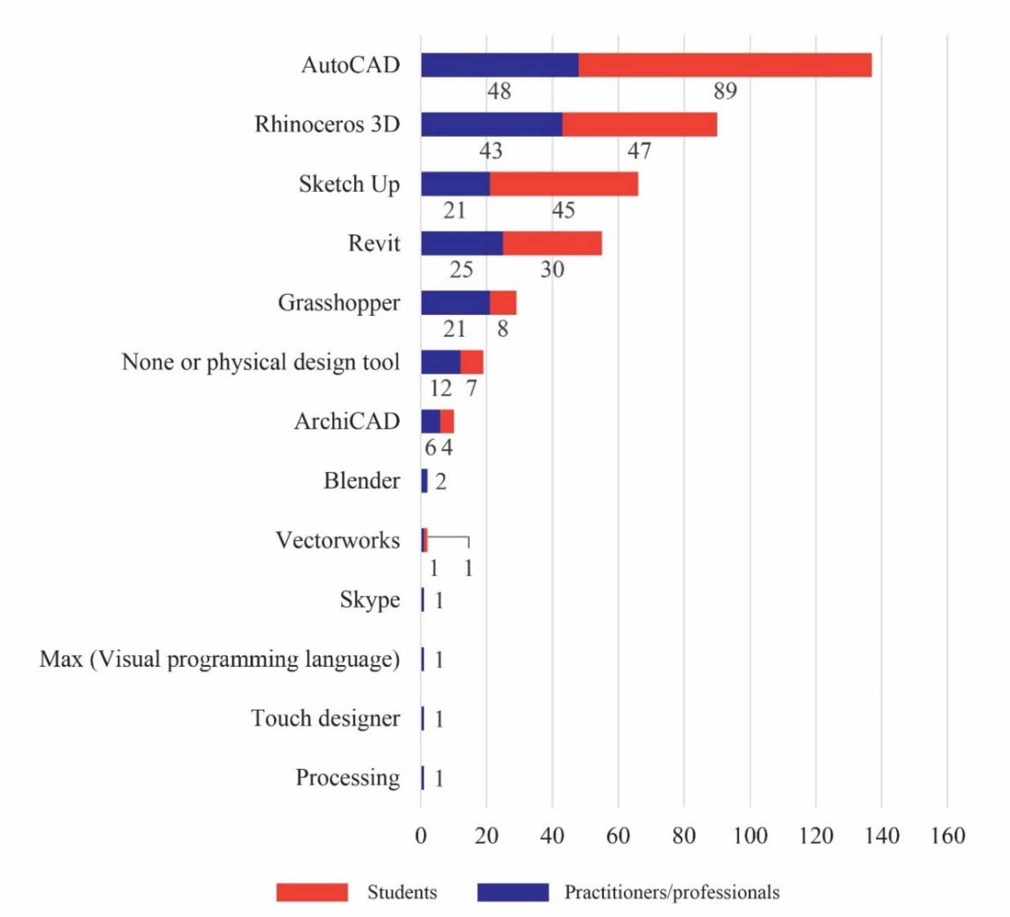


Figure 115: Responses to Q5 which show software used initial concept design stages of a project, broken down by students and practitioners/professionals.

Figure 115 shows which software is used in the initial design stages, broken down by either student or professional. Since it is important that bamboo is considered in the initial design stages of a project, then it is important to understand which software is most applicable in the architectural design process at this same point in the design process. As shown in Figure 115, "AutoCAD" is by far the most used software (137 responses - 59.1%) in the initial design stages. This is predominantly a digital 2D drafting tool. The 3D modelling platforms highest on this list were "Rhinoceros" (90 responses - 38.8%) and "SketchUp" (66 responses - 28.4%). Even though Rhinoceros showed greater usage than *SketchUp* as a 3D modelling platform, student use was similar. Use by professionals was greater with Rhinoceros. This could be a result of the demographics of the respondents. As shown in Figure 27 in Section 2.3.2, most professionals recorded in this survey were based in Europe and this may impact the perceived relevance of Rhinoceros. For AD platforms, Grasshopper was by far the most popular (29 responses) with no other equivalent software recorded. This represents only 12.5% of respondents using an AD platform in their design process. A lack of AD tool use is also recorded in the surveys from the AAVS Haiti surveys which is documented in Appendix D and discussed in Section 1.7.5.

4.6.2 Thinking algorithmically, not only digitally

Looking at the references in Section 4.4, it is apparent that AD tools are underutilised in the design of bamboo structures. This could be the calculation of material to be used, applying the constraints of material availability within the design process, or possibly the application of environmental analysis software. When it comes to applying this within a mixed media of other design tools both analogue and digital (Section 4.5.3), AD tools can enhance other design tools and work together.

When examining the potential application of AD tools in the context of design for full-culm bamboo, it becomes evident that these tools need not be confined to digital processes and can significantly contribute to the design process by supporting systematic problem-solving. In fact contrary to the assertion by Oxman (2017) that, “Algorithmic thinking can be defined as a set of rules written by a source code of explicit instructions that initiate computational procedures that generate digital forms” (p. 10), there is no need for the output to be formal or digital at all. A process which relies on digital applications only, could not be applicable as a way of supporting design professionals given the results from the survey (Section 4.6.1), symposium discussion (Section 1.7.5 and Appendix E), and survey results following the AAVS Haiti (discussed in Section 1.7.5 and Appendix D). Louridas (2020) offers an insightful perspective, framing the executability of the algorithm as a “set of steps that you can follow with pen and paper…close to those used by mathematicians and computer scientists” (p. 5). Algorithmic thinking need not be tethered solely to digital applications, as Louridas (2020) points out, “we had algorithms long before we had computers” (p. 5), only gaining “power on a computer because it can be executed there in a fraction of the time it would take us to perform the same steps, but they are still the same steps” (p. 23). In fact in the 1st Century BC, Vitruvius (as emphasised by Bessa, 2009, and Castelo-Branco, Caetano and Leitão, 2022), asserted that architecture must refer to ideal proportions—or rules—driven by the geometrical interrelationships and mathematical thinking. Thinking algorithmically means, as described in Aish and Bredella (2017), “Instead of just imagining the results and creating a visualisation of the imaginary building, the architect had to decompose the design idea into a sequence of discrete operations” (p. 72). This process forces the design professional to “explicitly reveal and externalise the design process, including the interdependencies, expressions, relationships, and design criteria” (p. 71).

An algorithm is a, “precisely-defined sequence of rules telling how to produce specified output information from given input information in a finite number of steps” (Knuth, 1974, p. 323), and they “define a succession of operations for the solution of a given problem” (Ahlquist & Menges, 2011, p. 11). The design professional is posited as the “author” of the rules, instead of an explicit description of the form (Ahlquist & Menges, 2011, p. 28). This description reflects the universality of algorithms, suggesting that their fundamental nature remains consistent regardless of whether executed digitally or manually. Despite the efficiency of the digital process, human engagement remains indispensable for output evaluation, analytical input, and critical feedback, addressing specific algorithmic challenges. As emphasised by (RIBA/AJ, 1970), the human element provides evaluation and analysis within this process. As discussed in Section 1.2.6 and Section 3.8.1, this is related to—and highlights the importance of—vernacular knowledge in the design process for full-culm bamboo.

Embracing algorithmic thinking entails framing design processes as sequences of finite steps, as emphasised by Knuth (1974) and Louridas (2020), who explains, “The only way to truly understand an algorithm is to perform it by hand. We must be able to execute the algorithm, in the same way the computer would execute a programme that implements it” (p. 25). This involves visualising the relationships between design components rather than creating the final design solution (Woodbury, 2014). The sequential construction focus aligns with the imperative to address design challenges through a finite sequence of steps (Louridas, 2020; Oxman & Oxman, 2014b; Terzidis, 2003).

While not prescribing a design process, algorithmic thinking facilitates segmenting a process into evaluative steps that align with established rules (Swann, 2002) and support a design professional to inform intuitive design decisions and overtime build up knowledge through this design support. Aish and Bredella (2017) attest that “Although design computation requires the externalisation of some underlying design logic, we need to dismiss the idea that somehow design computation is opposed to design intuition” (p. 72), or as Swann (2002) would describe this, “informed intuition” (p. 51). Algorithmic thinking can be a “way in which architects can have a conversation between their logical self and their intuitive self“ (Aish & Bredella, 2017, p. 72) and following the assertion of Zarzycki (2014) that computational tools should align with design goals rather than strictly adhere to procedural logic. This transition involves a shift from intuition driven decisions to incorporate rule-based evaluations though this process. This is particularly relevant for how durability considerations can be inserted into the design process for bamboo structures and over time, these rules can inform the intuition of design professionals.

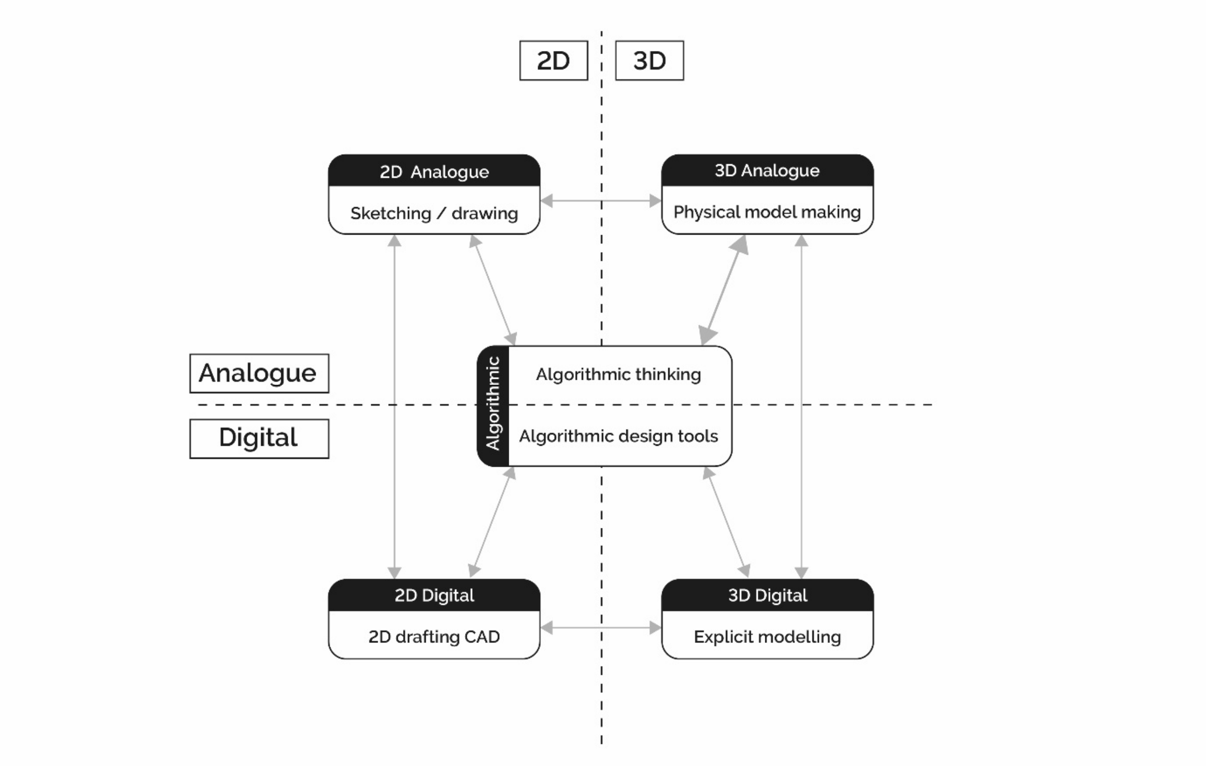


Figure 116: The range of design tools and the position of algorithmic thinking and AD tools and their interfaces both analogue and digital.

The incorporation of algorithmic thinking is not a replacement to a design process, rather, it complements other design methodologies, including physical and intuitive approaches (Figure 116), which can enhance the ability of the design professional to comprehend the impact of design decisions on durability. Terzidis (2008) underscores the need for a synergistic relationship between humans and computers in design, declaring, "Any specific approach to design therefore needs to take into consideration not only systematic, methodical and rational models, but also alternative approaches that address the nature of design as an indefinite, ill-defined and chaotic process" (p. 86). Such an approach enables design professionals to employ algorithmic thinking to inform, guide, and augment their decision-making process both in an analogue format, also with a format procedurally driven, and therefore translatable to digital tools.

4.7 Concluding comments

In conclusion, this chapter has identified the following:

- **Design process definition:** There is a design process that can be considered relevant to how design professionals conceive a design (Section 4.2.1) which loosely forms around: (1) initial design ideas, (2) a more developed concept design, and (3) construction information. Any design guidance for durability through this process should support the design professional through this process at as early a stage as is practicable.

- **Full-culm bamboo has unique design challenges:** Full-culm bamboo has unique challenges which make this a more challenging material than standardised manufactured materials and sawn timber to be cut into standardised section sizes (Section 4.2.6). Therefore, the material properties of bamboo need to be considered by the design professional in the early design stages, and a change in material specification can have an influence over the overall design more so than with standardised materials.

- **Influence of design process on material selection:** The current trends in architecture and design focus heavily on form, often ignoring the material constraints especially in the initial stages of design (Section 4.2.7). This creates complications when using a material such as bamboo that requires consideration of the material properties in the early design stages.

- **Design tool catalogue:** This chapter catalogued a range of design tools which are used by design professionals through a design process. A design approach necessitates integration with many different tools used by design professionals (Section 4.3). 2D CAD and 3D modelling software during conceptual design, along with the incorporation of BIM software for drawing production were identified as the main software platforms used by design professionals (Section 4.6.1).

- **Integration of algorithmic design tools within a design process and within a mixed media of design tools:** There are unique benefits in using AD tools in the design for full-culm bamboo structures. This was supported through the reference projects (Section 4.4), investigations in the applied examples (Section 4.5) and specifically the construction professional feedback (Section 4.5.3). Since the design for bamboo structures requires a greater consideration in the early design stages of the material, AD tools allow for late changes in the design process.

- **Lack of environmental analysis using AD tools:** A gap in the application of environmental analysis tools within digital processes to design for bamboo durability was identified throughout the reference projects (Section 4.4.3). This was explored in Section 4.5.2 and provided the potential for environmental analysis software to support durability considerations in design for full-culm bamboo.

- **Significance of algorithmic thinking:** Section 4.2 showed the unique considerations the design professional needs to give to the material of full-culm bamboo compared to standardised materials and sawn timber. Applying AD tools to the design for full-culm bamboo show how material properties can be embedded as part of a design process, maintained throughout the process and the design output can respond to changes in these properties (e.g., diameter changes as a result of supply chain challenges). As Oxman and Oxman (2014a) explain algorithmic thinking focuses upon, "a logic of associative and dependency relationships between objects and their parts-and-whole relationships" (p. 3). This highlights the benefit to a design professional to conceptualise the interrelationship between different design rules to understand how the material properties and external input parameters (e.g., environmental factors, or supply chain changes) can impact the overall design output.

The systematic procedural approach fostered through algorithmic thinking of evaluative steps is a way design professionals can be supported through a design process. This is developed in Chapter 5.

5 Chapter 5. A design approach for full-culm bamboo durability

5.1 Chapter overview

Through the previous chapters a range of topics have been discussed pertaining to this research. In Chapter 2 the factors which should be considered by a design professional have been proposed. In Chapter 3 the factors which can affect the durability of bamboo elements in the structure have been determined following the guidance of ISO 22156 (2021). In Chapter 4 an overview of design tools and processes—to which a design approach should apply—have been established. In the discussion in Chapter 2 following the qualitative interviews, a series of seven factors were identified that a design professional should be aware of to approach durability considerations of a project with full-culm bamboo (Section 2.5). These were identified as: (1) material knowledge, (2) local knowledge, (3) treatment and supply chain, (4) construction and local workmanship, (5) environmental vulnerabilities, (6) inspection, maintenance and replacement, and (7) joinery and connection detailing.

This chapter will show the development of a *decision tree* for design professionals applied to the environmental factors which can affect bamboo in a structure which are excess moisture (from the ground or rainfall), sunlight, avoiding contact with the ground, and a design which affords good ventilation. All can fall under the umbrella term of *protection by design*. As discussed in Section 3.4, these factors within this term can be quantified using the guidance in ISO 22156 (2021). Environmental exposure of members in a structure determines its *Use class* and anticipated in-service EMC will designate a *Service class*. In addition to designing a structure which follows the principles of protection by design, the design professional also needs to “de-risk” the use of bamboo for clients and end users and inform them of the required maintenance of bamboo. This is a paradigm in which the service life of a material is decoupled from the service life of a building (as highlighted in Section 3.10), a paradigm in which the inspection and replacement of structural members is a normal part of long-term maintenance and designed from the outset of the project. In this decision tree, a series of questions the design professional can ask of the initial design idea, are presented hierarchically which distil the criteria for Use class and Service class designation in ISO 22156 (2021). A decision tree is presented in Section 5.3. In this decision tree, Service class is only used to determine Use class, with more detail on Service class calculation discussed in Section 5.3.6.

The decision tree for protection by design, is then the basis for the process to be scripted digitally using applicable architectural design software which looks to align with software identified in the symposium outcome in Section 1.7.5, and the software use of survey respondents identified in Section 4.6.1. This digital process can take the decision tree and provide a graphical output which can visualise an evaluation of an initial design idea. This digital process also uses environmental analysis software which was discussed in Section 4.5.2 with their use identified as lacking for full-culm bamboo. This parallel digital process is documented in Section 5.4.

5.2 Design approach steps

The seven themes identified in Section 2.5 to ensure durability in a bamboo project should be considered sequentially and as steps of a design process (Figure 117). This is a similar format to Janssen (2000) who recalls a series of questions which a design professional could ask throughout the project. Examples from Janssen (2000) are highlighted in Table 17 with reference to a one of seven factors from Section 2.5.

Table 17: Factors from Janssen (2000, p. 167) that need to be taken into account when technologies are imported to a project site from outside (Column 1). These are relevant questions a design professional should ask on any project which involves bamboo where bamboo may not have been used before. Themes are added to relate to the factors identified from Section 2.5 (Column 2).

Question from Janssen (2000, p. 167)	**Relevant one of seven factors identified in Section 2.5**
Will the differences in culture and climate hinder technology assimilation?	Local knowledge and construction knowledge
Does the recipient have a labour pool with the required skill levels?	Construction knowledge
Does the recipient have facilities for testing, quality control, instrumentation, etc. that are related to the technology process?	Supply chain
Does the recipient have guaranteed channels for unhindered raw material supply?	Supply chain
What is the market forecast for the product in the short, medium and long term?	Supply chain

Is bamboo house a feasible option, according to the local climate and social and cultural preferences?	Local knowledge
Is unhindered supply of bamboo guaranteed, or can it be grown in the region in sufficient quantities and of an appropriate quality?	Supply chain
If bamboo is grown in the region, is this bamboo-growing area located at a convenient distance from the area where the houses are needed?	Local knowledge and supply chain
Is the price of the locally grown bamboo competitive when compared with the prices of traditional building materials?	Supply chain

Reviewing this for both content and format, a similar series of questions have been developed as the basis of the design approach for each of the seven factors. Each of these are questions the design professional can ask throughout the design process. These are laid out in Table 18, as is how they are situated sequentially in a design process is shown in Figure 117.

Table 18: Steps that a design professional should follow, with questions to be asked throughout the process.

Seven factors to consider for durability in full-culm bamboo structures / Design approach steps	**Question for design professional to ask during the design process**	**Description**
Local knowledge	What are the local attitudes to bamboo?	Introducing a new, non-standardised material into a context may come up against entrenched localised bias that the design professional should make themselves aware of.
	What is the local history of bamboo construction?	As identified in Chapter 2, there can be examples of situations where there have been historic good practices of construction with

		bamboo. The corollary may also be true and bamboo may have a local negative impression.
	What are the local socioeconomic and ecological issues that the use of bamboo could engage with?	An example of this can be as seen in Haiti where those who have migrated to the city from rural areas do still own land in rural areas where bamboo could be grown. The user of the building could also economically benefit from growing bamboo.
	Is the specific site adjacent to any vegetation?	As observed in Section 3.4.4, proximity to moisture from adjacent vegetation can cause mould on the bamboo surface.
	Where is the site and are there any transportation constraints?	Given the lengths that full-culm bamboo may be required for the project, are there any issues with transportation to arrive to the construction site such as road turning radii and locations nearby to store bamboo poles.
	Is the site subject to a unique micro-climate or adjacent to water bodies? (e.g., costal location, etc.)	Local knowledge is also knowing unique site conditions such as prevailing winds, proximity to water bodies, and micro-climates so that site climatic data may be irrelevant and require localised information. (e.g., winds may bring in humid air, etc.)
Material knowledge	What species are available?	The available species of bamboo may have an implication on the design, and biodiversity of where bamboo is grown.
	What are the physical characteristics of the available species?	Different species will suggest physical properties such as available diameter and material lengths which should be considered.
	What are the growing conditions of the available bamboo?	The growing conditions of bamboo can affect both physical and mechanical properties. It is important to know where the bamboo is grown and the condition of growth.

Treatment and supply chain knowledge	What treatment is available?	It is important to understand the type of treatment which is being used to know that the bamboo will have increased resistance to insect attack, but that this treatment will also be sustainable and does not contain any toxic chemicals, particularly if the bamboo pole is removed from the structure and discarded at the end of life.
	What are the transportation options from the supplier to the site?	The transportation options can determine the length of available bamboo poles that can be used onsite. Transportation also has a significant impact on the sustainability of using bamboo.
	What is the quality of the material supplied by the suppliers?	It is important to ensure that the bamboo is of good quality, and through inspection, does not contain any indentations or splitting.
	How many bamboo suppliers are available to the site?	Limited supply can increase the risk of delays or problems when sourcing the bamboo onsite.
	What design changes may be required as a result of changing material supply?	It is important to assess the emerging design to understand what would change if the bamboo supply was to change.
Construction knowledge	What construction examples are available as reference?	If the design is in a context with other bamboo structures, these should be inspected to see the local available workmanship and the durability of these structures. This can inform design decisions for an emerging design.
	What are the available contractors to build the project?	An understanding of the available companies or individuals who have a proven track record of building with bamboo.
	What opportunities are there for DfMA?	There could be opportunities to improve quality and enforce safer working practices by considering Design for Manufacture and Assembly (DfMA). Breaking the design into a

		series of repeatable modules is a way to do this. This may come up against local construction practices where labour costs are such that onsite working is a lower cost, transportations of large pre-fabricated modules are a challenge, and there are ingrained practices where material tolerances are addressed by construction professionals onsite.
	What opportunities are there for knowledge transfers?	A project which uses a bamboo structure is an opportunity for knowledge transfer to the local construction industry.
Protection by design	What is the climate (RH and T) of the site?	These are the basis of the decision tree, and a series of questions are identified in Section 5.3.
	Are bamboo structural elements exposed to sunlight?	
	Are bamboo structural elements exposed to direct/indirect rain?	
	Is bamboo in contact with the ground?	
	Are the bamboo structural elements well-ventilated in the structure?[27]	

[27] This evaluation criteria of the emerging concept design is an example where local knowledge—*vernacular knowledge*—of unique micro-climates or site conditions could warrant avoiding ventilation if there is the likelihood this may increase the EMC of the bamboo in-situ.

Inspection, maintenance and replacement	Can poles be removed and replaced if required?	Non-redundant structural members should be avoided. For example, columns should contain at least four bamboo poles and be designed so that the removal and replacement of one pole will not affect the load path (ISO 2256, 2021, Clause 5.4.2). The project should be designed in such a way that the joinery can be inspected, and poles can be replaced if required. These are discussed and addressed in Section 5.3.
	Are joints accessible for inspection?	
Joinery and connections	Is the site in a seismic zone?	If the project is in a seismic zone, there will need to be additional consideration given to connection aspects of the design.
	Can joinery be assessed based on the information in ISO 22156 (2021)?	ISO 22156 (2021, Annex D) contains a series of joint types which can be the basis for the design professional to suggest joinery in the concept design. The design professional can reference other joints in precedent projects and then classify and compare these to those in Annex D. Joinery information of ISO 22156 (2021, Clause 10).
	What are the skill levels available in order to create the joinery?	This is related back to the available workmanship knowledge onsite but suggests a construction professional should be involved to suggest joinery once a concept design has been developed.

In Section 4.2, a design process was defined as having three stages: (1) initial design ideas, (2) a more developed concept design, and (3) construction information. The seven factors (Table 18, Column 1) are grouped into the first two stages. The first stage (Steps 1-4) can be considered as base knowledge which can inform initial design ideas, project feasibility, and the establishment of design principles. Understanding both the available material and workmanship is important within this first stage. Applying ISO 19624 (2018) within Steps 2 and 3 can provide guidance on the quality of the bamboo material.

The second stage (Steps 5-7) occur once an initial design idea—or primary generator—has been established. These are evaluator steps in which the design guidance in ISO 22156 (2021) can be used to support the design professional as a design is refined from this initial design to a concept design which considers protection by design (Step 5), inspection, maintenance and replacement (Step 6), and practical joinery and connections (Step 7). This last step requires input from a construction professional. At this point a concept design has been developed and informed with this information. It is in a position to be taken forward but the detailing of the joinery and structural analysis.

There should be circularity or feedback loops in the process as the design is iterated and refined to become the concept design. There is also the need to interface with other members of a design team as the joinery should be informed both by the design guidance of ISO 22156 (2021) as well as the available workmanship from a construction specialist. Maintenance considerations (Step 6) will also output information which is of importance to the clients and end users of the project. These steps and interfaces are diagrammed out in Figure 117.

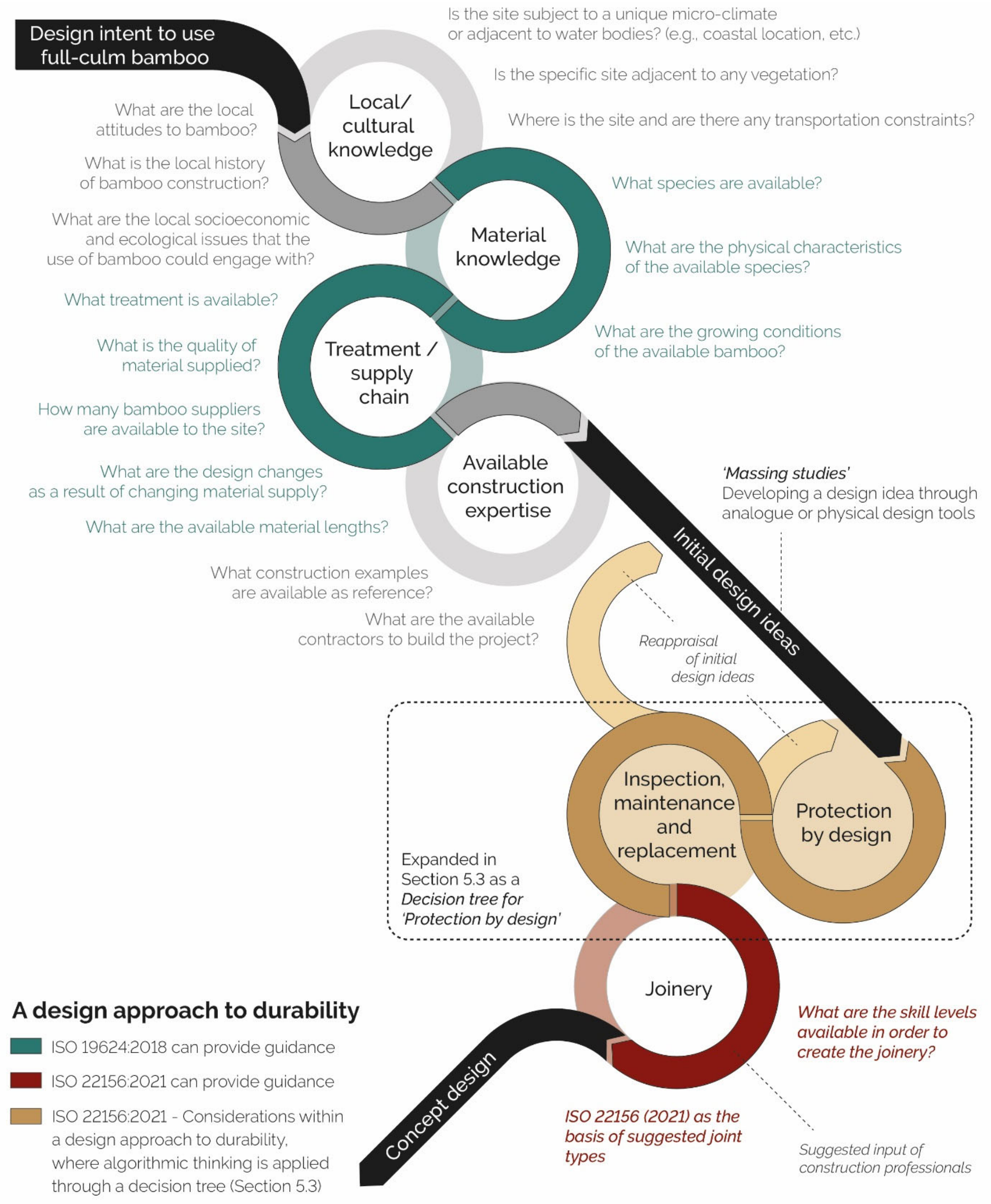


Figure 117: The design approach to full-culm bamboo durability: The seven steps to consider with Steps 5 and 6 (highlighted) to be developed as a decision tree for protection by design.

5.3 A decision tree for protection by design in bamboo structures (Design approach Steps 5 and 6)

5.3.1 Decision tree and criteria

Decision trees are a method to represent a series of rules (Clark & Deurloo, 2005). Decision trees are used as decision support tools where *leaves* represent classifications and *branches* represent *conjunctions of features* that lead to those classifications (Podgorelec & Zorman, 2009). They can be used for classification tasks such as those presented in Quinlan (1986) and are constructed beginning with the *root* of the tree and proceeding down (termed *top-down*) to its leaves. This top-down format is an algorithm known as *Top-Down Induction of Decision Trees* (TDIDT), recursive partitioning, or divide and-conquer learning (Fürnkranz, 2010). The algorithm selects the best attribute for the root of the tree, splits the set of examples into disjoint sets, and adds corresponding nodes and branches to the tree (Figure 118). This can also be described as an expert system similar to that described in Fischer and Tatum (1997), who suggest providing constructability information in the early design stages would assist design professionals on construction projects to avoid costly situations during construction (referenced in Section 1.2.2).

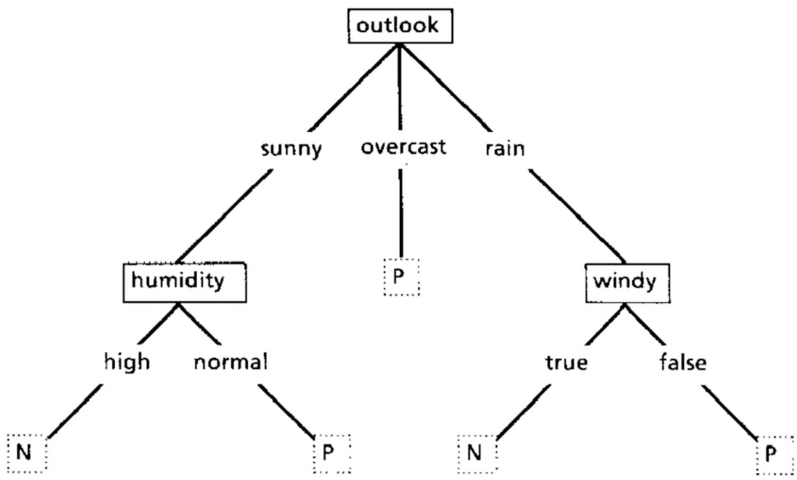


Figure 118: An example decision tree reproduced from Quinlan (1986).

As shown in Figure 118, objects of class *P* and *N* are sometimes referred to as positive instances and negative instances, respectively, referred to as *two-class induction tasks* (Quinlan, 1986). Differentiating between positive and negative instances should be taken into account for clarity to the user, as “Yes” or “No”, or “True” or “False”, may be positive or negative for the durability of the bamboo member being assessed. Therefore, colour coding is used: green to denote if the class applied is positive, red if negative, and black if neither positive or negative. Once a Use class has been determined through the decision tree, colour coding can be applied to the relevant leaf in the tree. Use class designations from ISO 22156 (2021) are colour coded as shown in Table 19. The basis of the decision tree comes from Steps 5 and 6 (shown in Figure 117). Guidance to ensure durability in a design, and the design guidance for inspection and maintenance, is stipulated in ISO 22156 (2021). These are the steps in which there is a qualitative evaluation which can be applied, based on the criteria established by Use class and Service class designation in ISO 22156 (2021). Use class from ISO 22156 (2021) are reproduced with colour coding in Table 19.

Table 19: Use class designations prescribed by Table 2 in ISO 22156 (2021) with columns referring to protection against biological agents removed. Reproduced from ISO 22156 (2021), colour coding introduced by author.

Use class	Service conditions	Typical uses
1	Interior, dry	Framing, pitched roof members
2	Interior, occasional damp (possibility of condensation)	Framing, roof members, ground floor joists, framing built into exterior walls
3.1	Exterior, above ground protected from driving rain and UV radiation	Protected exterior joinery and framing
3.2[a]	Exterior, above ground not protected from weathering	Unprotected exterior framing and joinery including cladding, vertical load bearing members, exposed unprotected culm ends
4.1[b]	In contact with ground or in-ground	Sole plates or columns at ground, columns built into ground, piles
4.2[b]	In-ground severe, fresh water	Piles
5[b]	Marine or brackish water	Marine piles including splash zone
a	Bamboo should not be used in Use class 3.2 except for structures having a design life of less than 5 years.	
b	Bamboo shall not be used in this use class.	

Table 19 also indicates a hierarchy of steps which will assist the rules within the decision tree.

To apply algorithmic thinking to this process it would be as presented in Figure 119. The input of the algorithm would be the initial design to be evaluated, the rules would be design guidance established by ISO 22156 (2021), and the output would be the structural elements evaluated as per Use class and Service class.

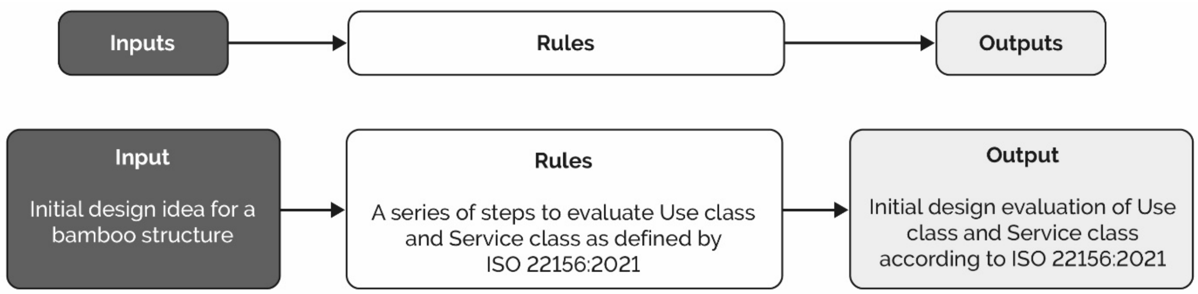


Figure 119: Conceptual representation of the application of algorithmic thinking to durability with proposed inputs, rules, and desired outputs.

The most critical issues for bamboo are those for which Use class should be identified first. Otherwise if an element was identified to be in contact with the ground—whether or not it is exposed to direct sunlight or in an environment with increased (RH)—is irrelevant in this scenario as the fact it is in contact with the ground will designate this element as Use class 4.1 or 4.2 and it should not be used. The specific factors that can affect bamboo in a structure (documented in Chapter 3) are considered as the rules to evaluate the initial design. This can determine Use class and Service class. Elements can then be output each with a Use class or Service class designation as shown in a more detailed conceptual diagram in Figure 120. The use of colours is suggested for clarity in describing these outputs. The following sections (Section 5.3.2-5.3.7) describe the construction of the steps of the decision tree for protection by design.

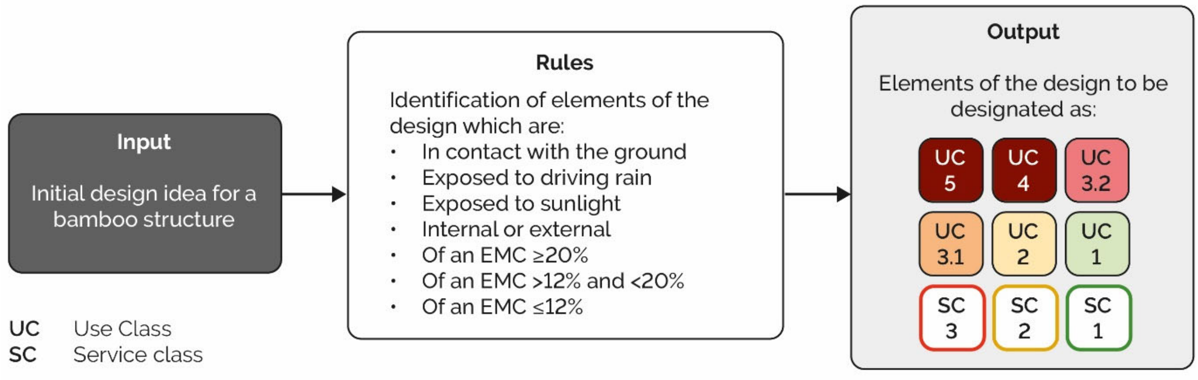


Figure 120: Conceptual representation with specific questions relating to protection by design from Chapter 3 as rules for the basis of an algorithm. An initial design is the input, and an evaluation of the design with Use class and Service class classifications as per ISO 22156:2021 is the output information.

Similar to the function of ISO 22156 (2021) to embrace vernacular knowledge, the decision tree also needs the facility to evaluate the evaluation criteria while considering vernacular knowledge. This has been highlighted in the evaluation step which looks at the ventilation of the bamboo structural members which was highlighted in Section 3.4.4. Proximity to sources of ambient moisture may mean ventilation of the structural member can expose the bamboo to increased moisture, therefore the relevance of the steps should be evaluated by the design professional.

5.3.2 Stage 1: Determination of structural elements to not be used

The first step is to determine if the initial design concept has any bamboo structural members which are designated Use class 4.1, 4.2 or 5. In effect, looking to see if bamboo structural elements are placed where they cannot be used in a permanent structure and conform with ISO 22156 (2021). The first question is to determine if any of the foundations are within a zone above the ground which would be deemed to be at risk from excess moisture from rain events (direct or indirect), flood events, a splash zone, or vulnerable to insects, particularly termites. "In contact with ground or in-ground", is the terminology used in Table 2 of ISO 22156 (2021, Clause 5.7.1), reproduced in Table 19. This is interpreted in this research as bamboo being within a distance from the ground, which can be established by the design professional given local conditions, such as flood events. Figure 121 shows the first in a series of questions that can assess the design. Since no bamboo elements in Use class 4.1, 4.2, or 5 should be used, they have been conflated into Use class 4 for the purpose of the decision tree. If the answer is "No" and they are within a vulnerable zone above the ground, then those structural bamboo members are designated Use class 4, and they should not be used in the structure and still conform with ISO 22156 (2021).

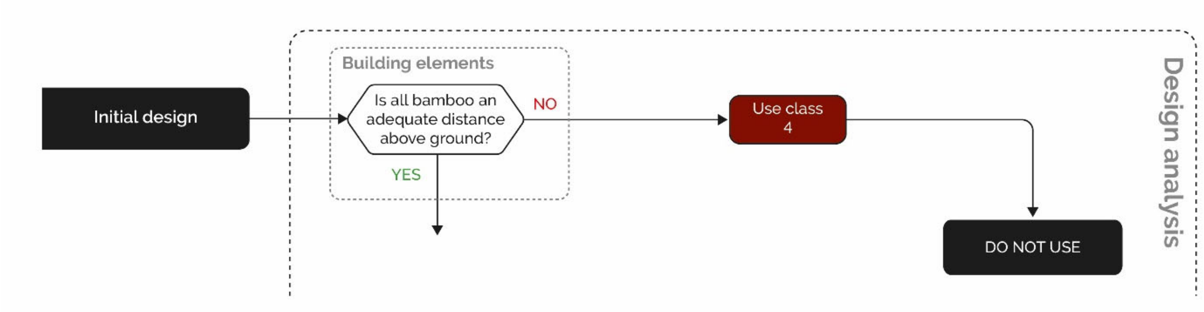


Figure 121: The first decision to be made is the evaluation of the location above the ground of bamboo structural elements in the design.

5.3.3 Stage 2: Use class 3.2 and temporary structures

The second evaluation step of the design is related to protection from driving rain. In order to determine this, it is important that the design either conceals the bamboo in areas it could be exposed to driving rain, or exposed bamboo is covered by a roof overhang of a 45° angle or greater (Hidalgo-López, 2003; Janssen, 2000; Kaminski, Lawrence, Trujillo, & King, 2016), as shown in Figure 122. This protected zone from rain has been termed as a *rain shadow.*

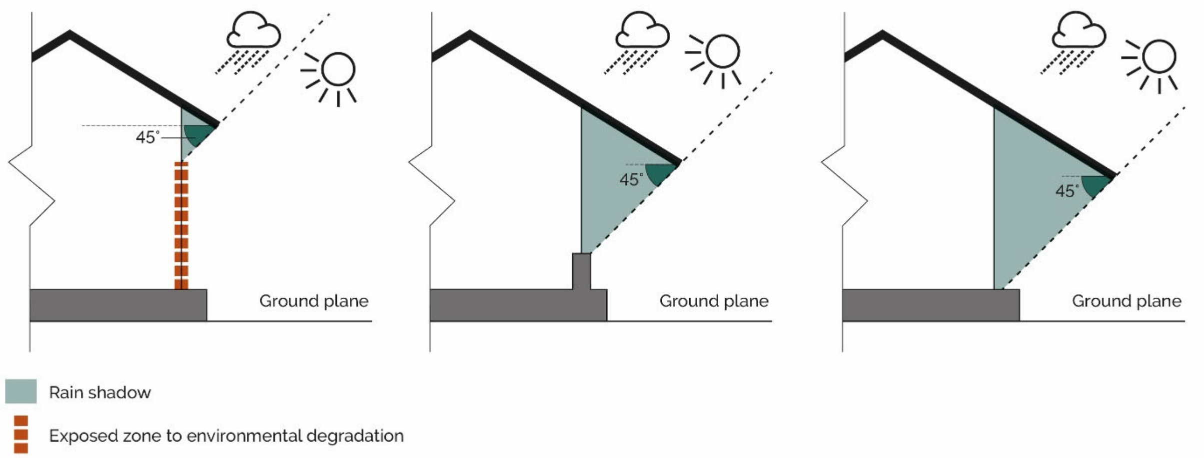


Figure 122: Diagrams highlighting the rain shadow which is a zone defined by a 45° angle from the edge of the roof overhang.

ISO 22156 (2021) assigns Use class 3.2 to bamboo structural elements which are external, above ground, but not protected from weathering (Table 19). As discussed in Section 3.4.1 and 3.4.5, excess moisture in the bamboo can cause fungus to grow if the EMC exceeds 20% (Liese, 1998) and an increased EMC may also cause unacceptable swelling of the bamboo pole and excessive shrinkage from subsequent drying. UV radiation from direct sunlight can cause a temperature differential on one side of the bamboo, which can cause uneven drying and longitudinal splitting. In isolation, UV radiation is not as great a threat to the bamboo integrity than the synergistic effect of the heat from sunlight along with moisture which is the major concern. This means these factors can be applied in a hierarchical manner, with excess moisture and rain, being the first evaluation step (Figure 123) and exposure to UV light following in the sequence. If all of the bamboo structural members are within the rain shadow, then these can be taken forward for further assessment in the decision tree. If not, then the service life[28] can be severely affected and the bamboo will degrade. Understanding the desired design life[29] to make sure this aligns with the service life can then determine the Use class. This decision tree considers a static use over the design life of the building. Any amendments to the structure or locations of openings will require re-evaluation of the durability of bamboo structural members.

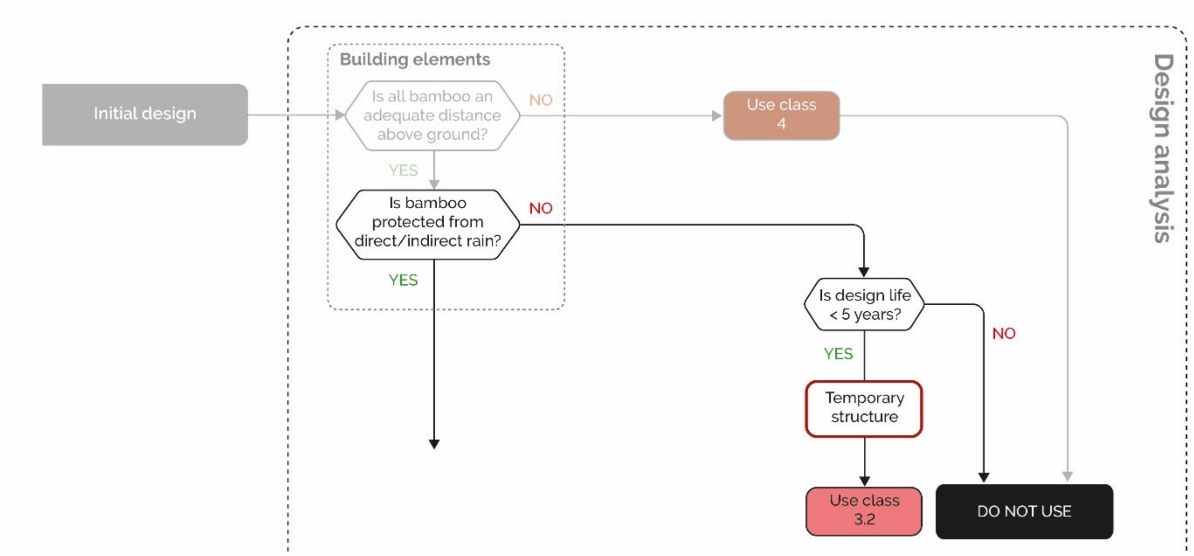


Figure 123: The second set of questions relates to the exposure to rain and the design life of the bamboo structural elements.

[28] The *service life* (*working life* in European documents) is the period of time after installation during which a building or its parts meets or exceeds the performance requirements (WIS 4-28, 2019).

[29] The *design life* of a building or component is the period of use intended by the designer as stated to the client (WIS 4-28, 2019), or required by a client and end user.

As shown in Figure 123, if the bamboo structural element is within the rain shadow this can be taken forward for further assessment. If not, as shown in Table 19, the design life needs to be known since ISO 22156 (2021) states, "Bamboo should not be used in in Use class 3.2 except for structures having a design life of less than 5 years" (Clause 5.7.1, Table 2). If the design life of the structural elements which are not protected from direct or indirect rain is to be less than five years, then these can be designated as a temporary structure and conform with Use class 3.2.

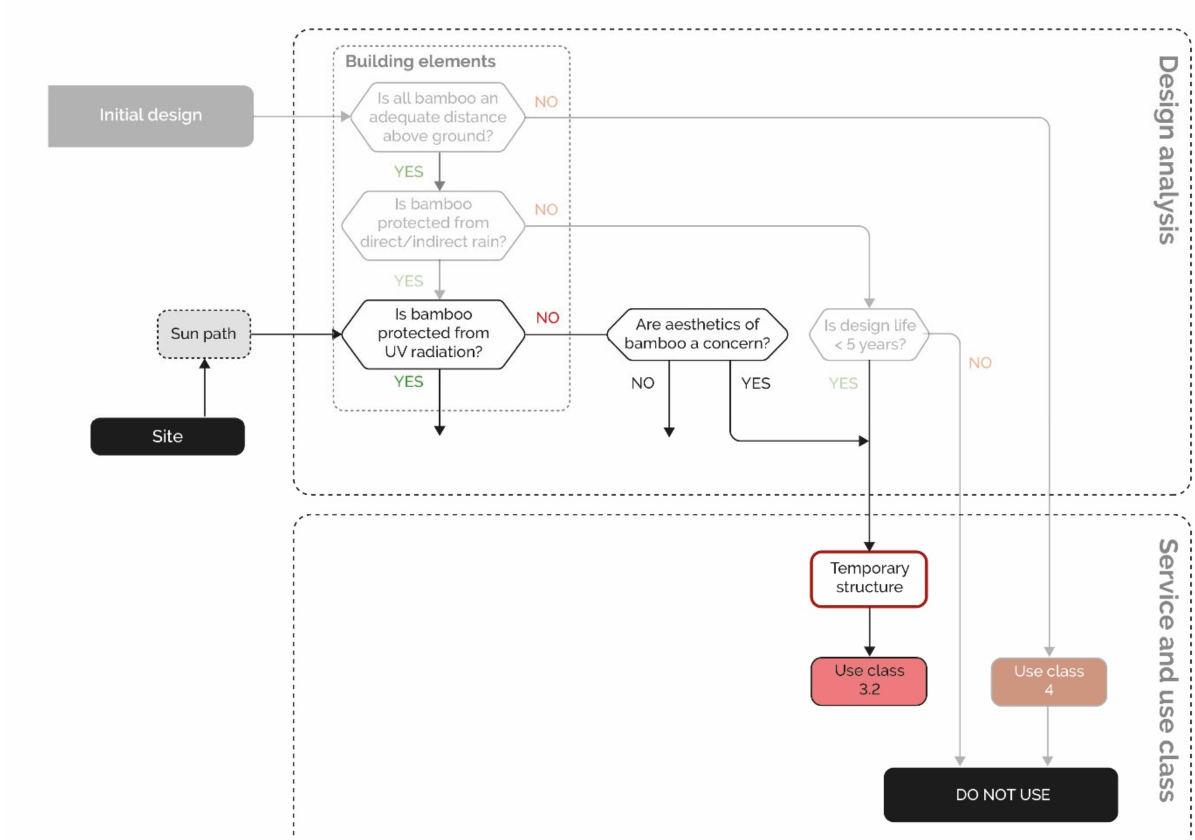


Figure 124: The series of questions to determine if the bamboo is to be a temporary structure and be designated as Use class 3.2.

An additional question needs to be asked to determine the bamboo structural members which fall within Use class 3.2 and this relates to the aesthetics of the bamboo (Figure 124). Since UV radiation alone is not a threat to the structural performance of the bamboo, and bamboo is exposed to UV only, this suggests the bamboo surface will turn grey and coarse (Liese & Tang, 2015a). If for any reason these poles are required to maintain their aesthetic properties, then exposure to sunlight will negate their use, unless as with the previous step, it is for a design life of less than five years. If poles exposed to UV light are to be used in a permanent structure, and aesthetics are important, then these are also classed as Use class 3.2 and therefore a temporary structure (Figure 126). In order to do this assessment, the site of the structure needs to be known to determine the sun path and sun angles which will shine on the bamboo structure. In many cases the 45° angle overhang will provide adequate protection, however the further north or south from the equatorial sunlight, low sun angles may expose the bamboo to UV light radiation beyond the protection provided by the rain shadow. This was demonstrated in Section 4.5.2 and Appendix B. However, if this only occurs at sunrise and sunset this is not a major concern, given the lower level of UV radiation at these times of the day. There are procedures for this analysis to be undertaken manually (Figure 125).

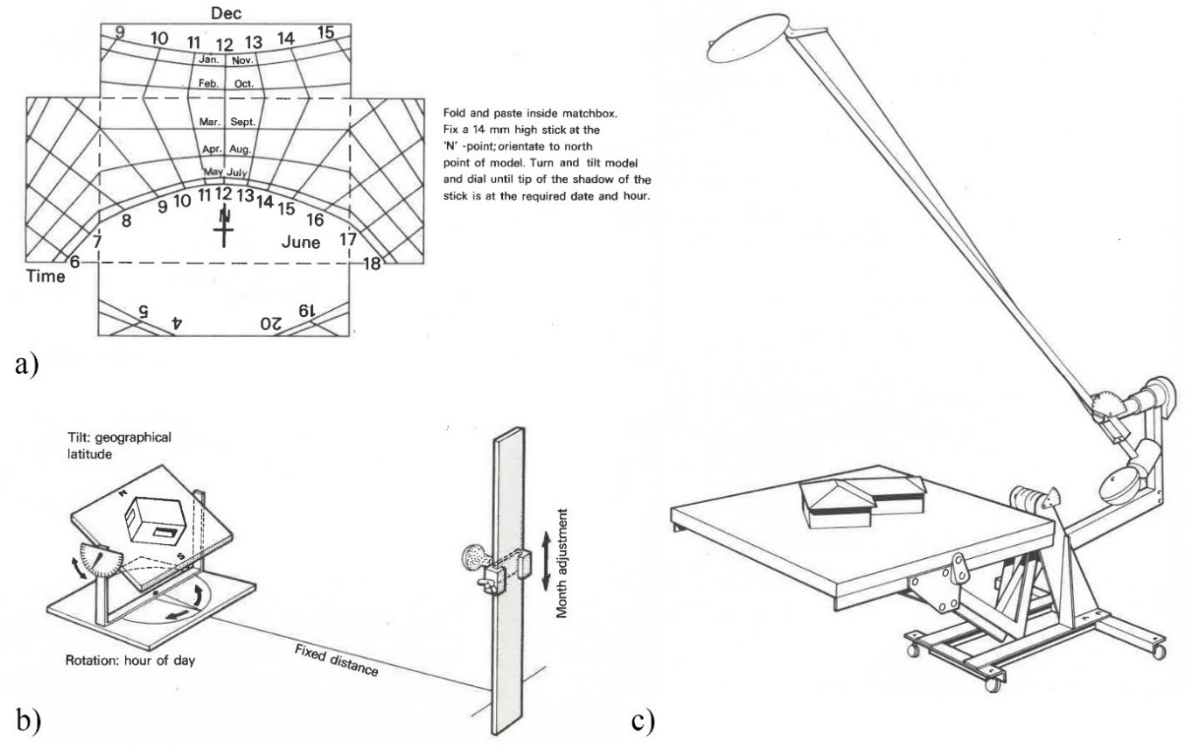


Figure 125: Examples of manual sunlight analysis: (a) *sun-dial*, (b) *heliodon*, a tilting and rotating model-table with a lamp sliding up and down on a vertical rail, and (c) *solarscope*, a horizontal table and a lamp (or mirror) mounted at the end of a long arm, which has a three-way movement. Images and descriptions reproduced from Koenigsberger (1974, pp. 267-270).

Calculating UV values within the decision tree has been omitted due to complex nature of undertaking in an analogue process. However more significantly, there is also a gap in data that prevents precise analysis (as discussed in Section 3.4.6). Though there are existing studies on timber (e.g., Teacă et al., 2013), the unique characteristics of bamboo warrant greater understanding, especially tests on the bamboo in situ, and not in laboratory conditions. A simplified approach was therefore adopted, focusing on binary assessments of sunlight exposure during peak UV hours (10 a.m. to 4 p.m.).

5.3.4 Stage 3: Use class 3.1

In ISO 22156 (2021), Use class 3.1 denotes bamboo elements which are external but protected from environmental factors. Since UV radiation alone is not deemed a threat to the structural performance of the bamboo, if bamboo is exposed to UV only, and aesthetics are not a concern, then these structural elements will be classified as Use class 3.1 (Figure 126).

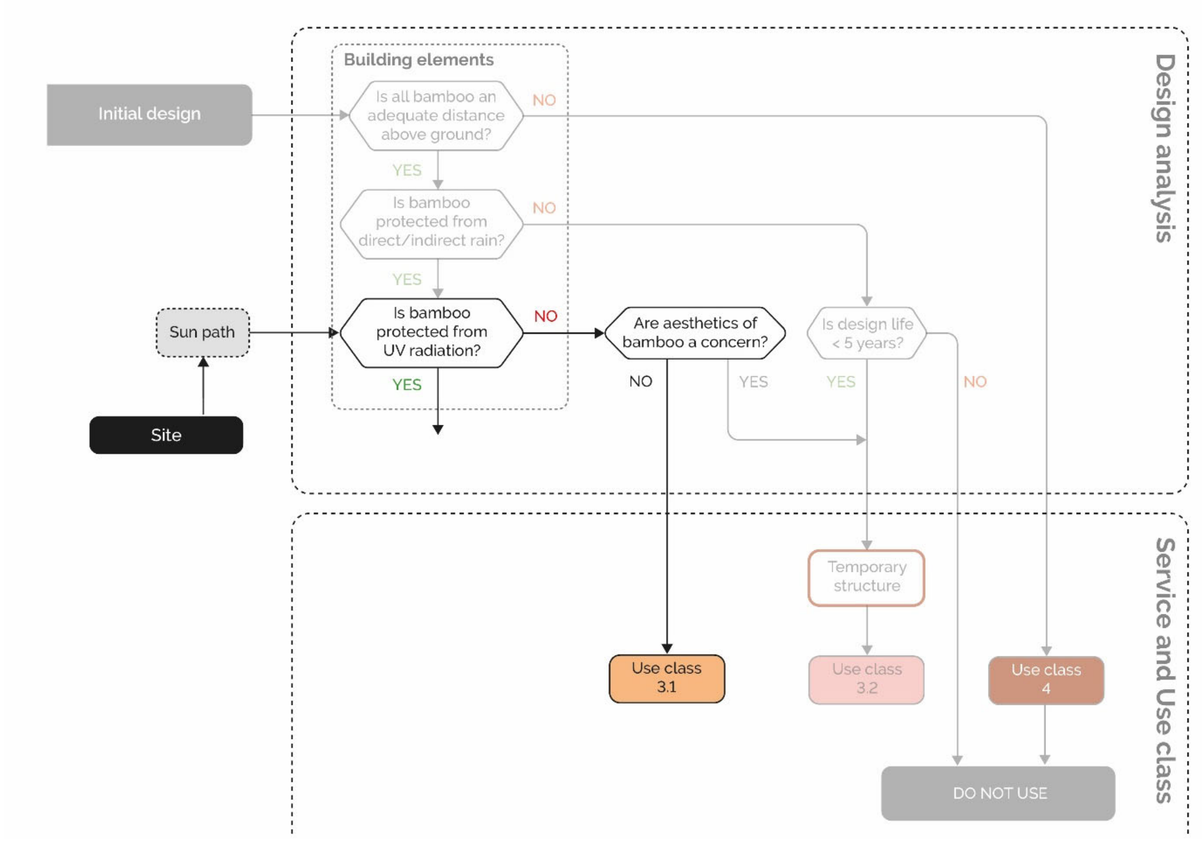


Figure 126: If the aesthetics of bamboo are not a concern, then bamboo exposed to UV light can be designated as Use class 3.1.

A further assessment determines if poles which are protected from UV light are externally placed. The external/internal line, can be the weather wrap (Figure 127a), or the midpoint of the outer most structural element in the event of no weather wrap. These are considered external (Figure 127, b-c), and designated as Use class 3.1, provided these are within the rain shadow (Figure 122). If the bamboo is only internally exposed, then these can be taken forward for further assessment (Figure 128).

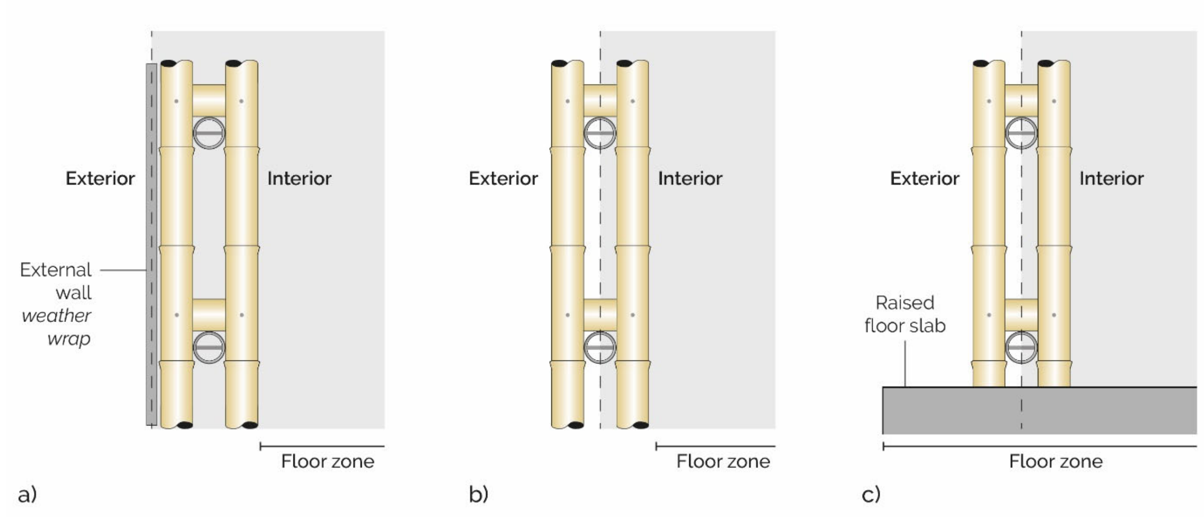


Figure 127: Definitions of exterior and interior which can be applied to the decision tree steps to determine additional bamboo structural elements to be Use class 3.1.

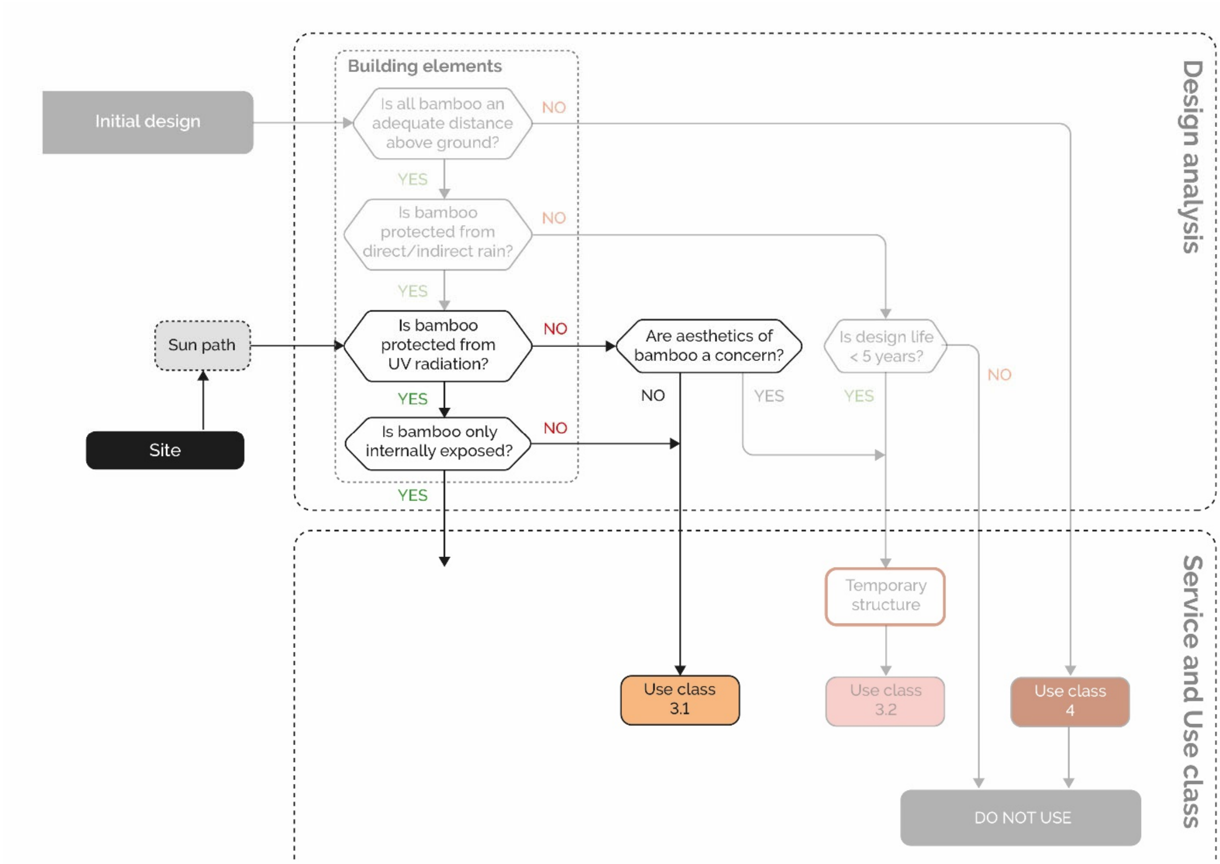


Figure 128: If the bamboo is externally exposed, but within the rain shadow, and protected from UV light, this can be designated as Use class 3.1.

5.3.5 *Stage 4: EMC to determine Service class and Use class 1 and 2*

It is irrelevant to determine the Service class of members which are classified as Use class 3.2, 4, and 5. This is because these members are already in the position in which they are vulnerable to increased moisture content without any mitigations from environmental factors. Therefore, the bamboo structural elements which are classified as Use class 3.1 and bamboo elements which are only internally exposed can then be assessed for their likely EMC based on expected temperature (T) and relative humidity (RH) of a given site.

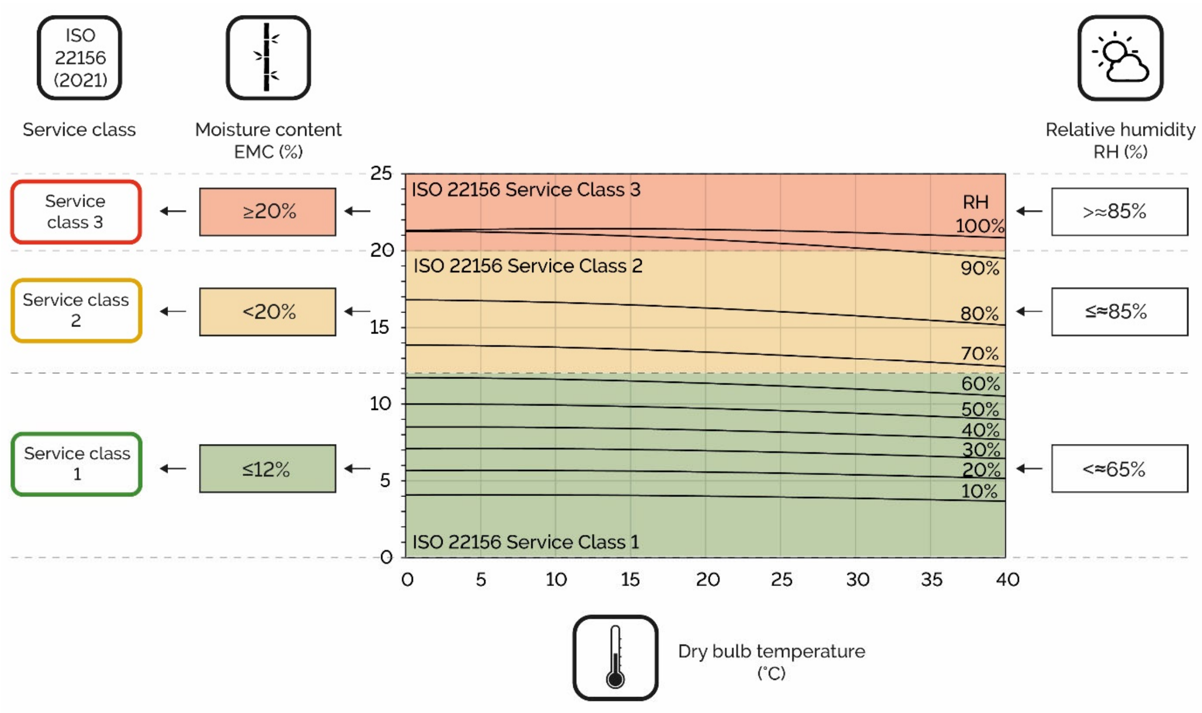


Figure 129: Hailwood-Horrobin (H-H) model showing the synergistic effects of relative humidity (RH) and ambient temperature on the expected equilibrium moisture content of bamboo (EMC) with resultant Service class designation in ISO 22156 (2021).

As shown in Section 3.4.1 (and summarised in Figure 129) there is a relationship between RH and EMC, with a change in T showing minimal effect on EMC. In general, if the RH is 65% or lower, then bamboo members will be designated Service class 1. If RH exceeds 85%, these structural elements will be assigned to Service class 3. Those exposed to RH greater than 65% (but less than 85%) are designated Service class 2. In this case, the Service class 2 elements can go through further assessment (Figure 130). In order to determine the T and RH, this can be done using local meteorological data or there may be guidance that can be used such as that from NSR-10 (2010), *Table G-D-1*, shown in Table 20.

Table 20: Table showing T, RH and EMC (*Equilibrio de Contenido de Humedad,* or *ECH*) for regions of Colombia, reproduced from NSR-10 (2010) – Table G.D.1.

Ciudad	HR%	T ºC	ECH%
Armenia	77	22	15
Barranquilla	76	28	14
Bogotá	80	11	16
Bucaramanga	75	22	14
Buenaventura	87	28	18.5
Cali	75	24	12
Cartagena	79	28	15
Cúcuta	66	27	16
Ibagué	80	21	16
Manizales	78	18	13
Medellín	69	21	12
Montería	82	27	16
Neiva	67	26	16
Pasto	79	17	16
Pereira	75	22	14
Popayán	79	18	16
Quibdó	87	28	18.5
Sincelejo	77	28	15
Tunja	80	13	16
Turbo	85	27	17.5
Valledupar	70	28	13
Villavicencio	75	25	14

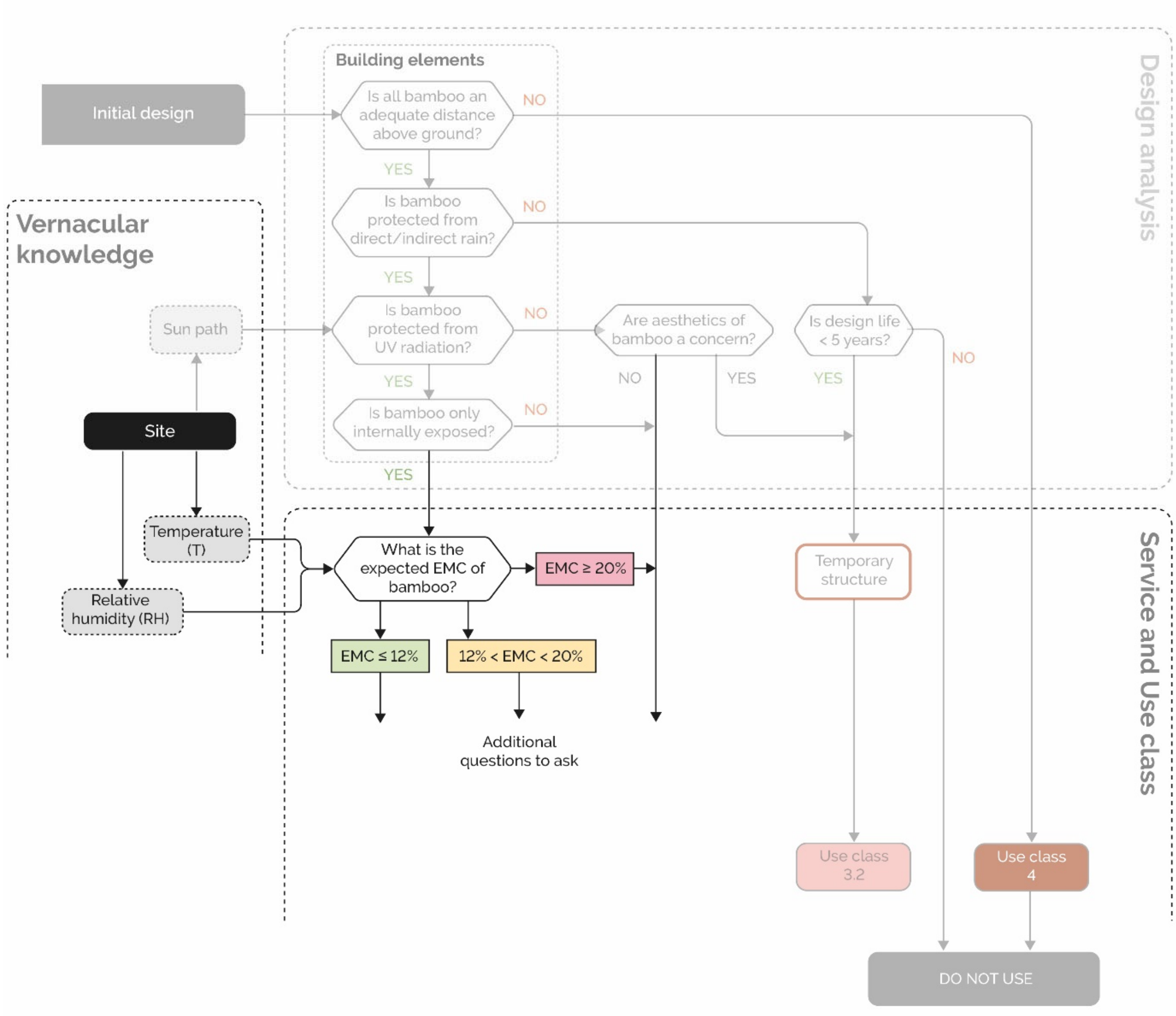


Figure 130: Determination of the expected EMC of internal bamboo structural members.

Use class, while clearly related to Service class, is qualitative and does not specifically consider expected EMC and does not affect the strength or stiffness values of bamboo used in structural design other than the effects of these through the degradation of the bamboo. Typically however (as discussed in 3.4.8), Service class 1 is expected to correlate to Use class 1 whereas Service class 2 may be Use class 2 or 1. Those with an EMC between 12% and 20% (Service class 2) could potentially be considered as structural elements in Service class 1 if they are subject to adequate ventilation which can ensure than any excess moisture will be easily dried. Though it must be proven that this can reduce the EMC to that of Service Class 1. If the structure is designed for a location where proximity to water body, a coastal location, or vegetation could increase the moisture, ventilation will have negligible effect. This is where the vernacular knowledge is important to be input as shown in Figure 131.

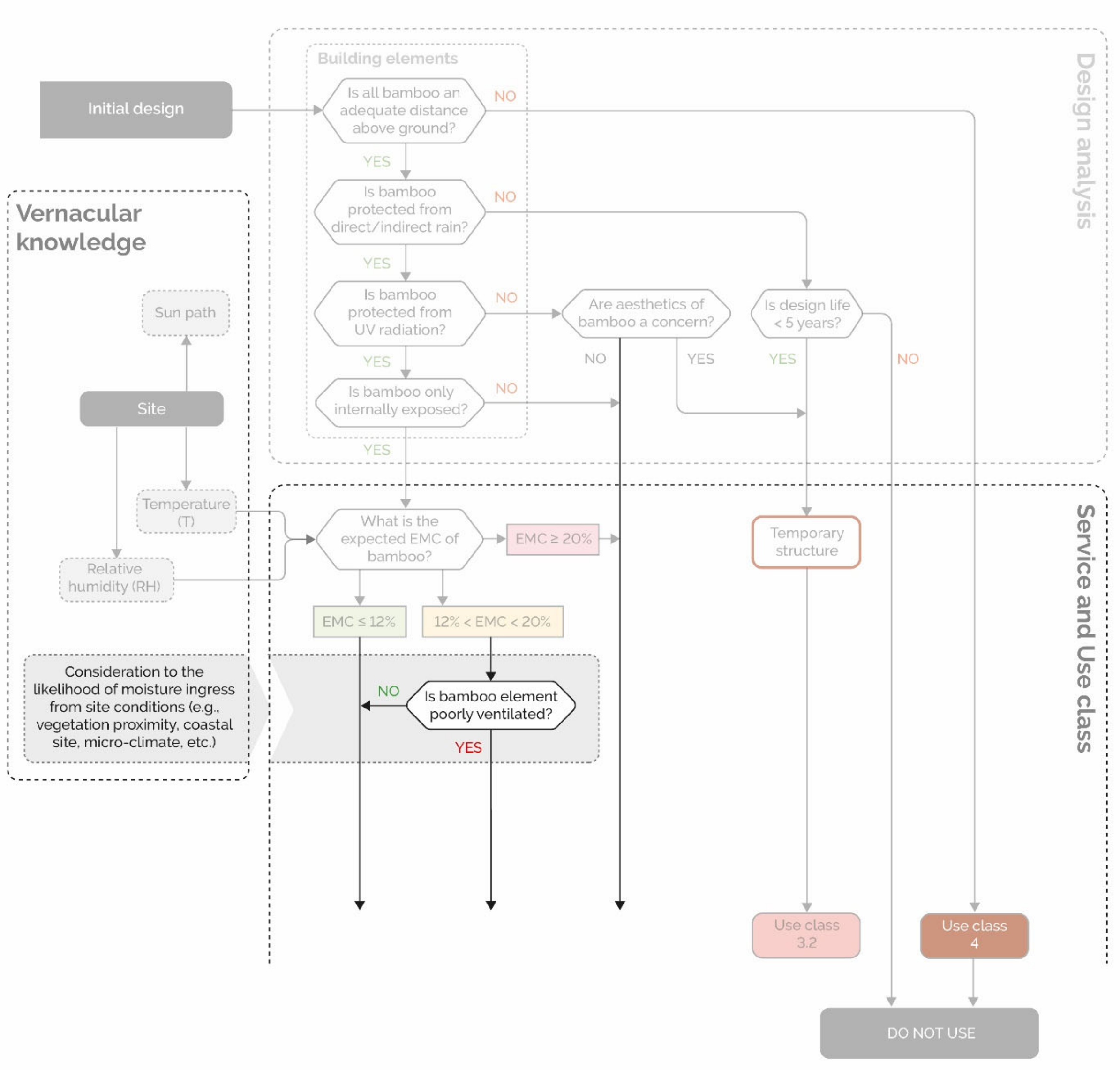


Figure 131: The step to assess whether the bamboo ins the structure is likely to receive adequate ventilation. This step should be informed by local site information (vernacular knowledge).

No known study has determined the effect of air velocity on drying rates for bamboo, however drying rates of green lumber have been shown to increase with increased air circulation (Rosen, 1978; Simpson, 1997). Air circulation will ventilate and reduce the EMC of the bamboo members. Therefore, assessment can be done for those structural members to determine if they will be in locations of potentially poorly ventilated areas. This could be seasonal, in rainy seasons compared to dry seasons. Seasonal analysis of wind is required when assessing ventilation. Any weather wrap should still allow ventilation to structural members being covered.

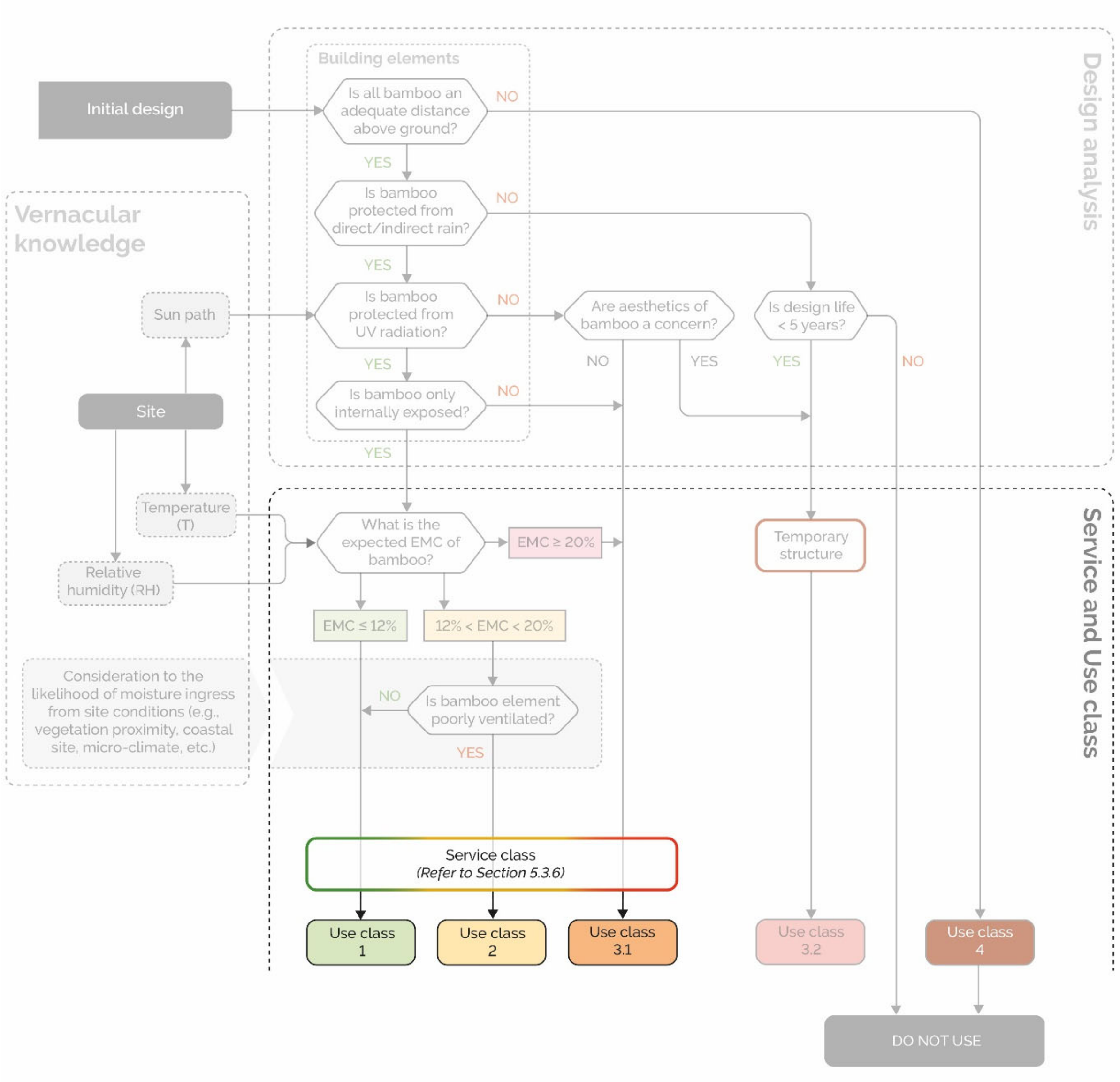


Figure 132: The decision tree showing how each internal structural elements can be correlated to Use class 1, 2, and 3.1 based on their expected EMC, based on the criteria established to this point.

At this point—as shown in Figure 132—internal structural elements can be correlated to Use class 1, 2, and 3.1 based on their expected EMC.

5.3.6 *Stage 5: Information for structural calculation (modification factors)*

At this point in the decision tree, there is an interface with structural engineers. Service class can impact the capacity and strength of bamboo structural members, and factors of safety are discussed in Section 3.4.9. In the decision tree so far, Service class is only used to determine the Use class of internal elements (Figure 130), therefore now, a calculation of expected EMC for all elements is required following the same procedure as Section 5.3.5, including external elements. As shown in Figure 133, in the decision tree it is possible to present the modification factors (C_{DE} and C_{DF}) for Service class to a professional who can calculate the structural analysis following the information in ISO 22156 (2021), Table 3 and Clause 6. Where ventilation rates have been used as a differentiator (Figure 131), modification factors based on expected EMC prior a ventilation analysis should be considered.

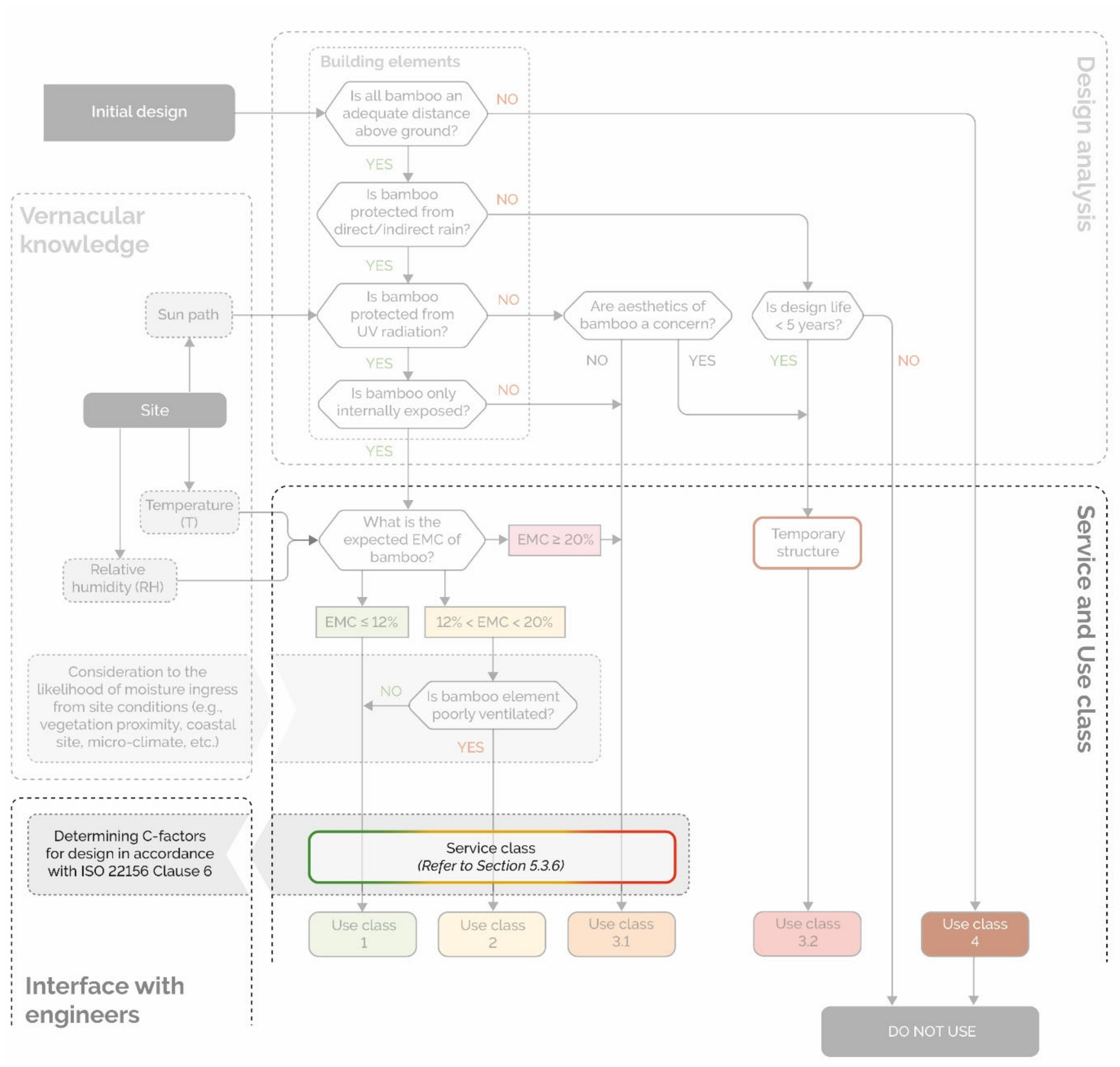


Figure 133: Service class determines the load bearing capacity and stiffness modification factors for the design in accordance with ISO 22156 (2021, Clause 6).

5.3.7 Stage 6: Inspection, adaptability, and maintenance

The last stage of this decision-making process is to ensure that the structure is able to be inspected and maintained. The design professional can assess the emerging concept design to ensure the design allows inspection of bamboo members, joints, and connections in the building system. As shown in Figure 134, any structural elements which are designated as Use class 2, 3.1 or 3.2 are assessed, since these are the bamboo structural members which are susceptible, at varying degrees, to excess moisture. Those in Use class 1 are not assessed as they are internal in an environment in which EMC is not anticipated to exceed 12% and is therefore not deemed to exploit any of the vulnerabilities of the bamboo. For Use class 1 and above, a maintenance document should be prepared which explains how the structure can be disassembled and replaced if and when members are damaged due to exceptional incidents or degradation. If the bamboo structural elements in Use class 2, 3.1 or 3.2 cannot be inspected then these should not be used. Even if the structure is temporary, the integrity of the bamboo could be compromised within the five years (Janssen, 2000), and therefore it is important that even in temporary structures, the bamboo member, the joinery, and connections can be inspected.

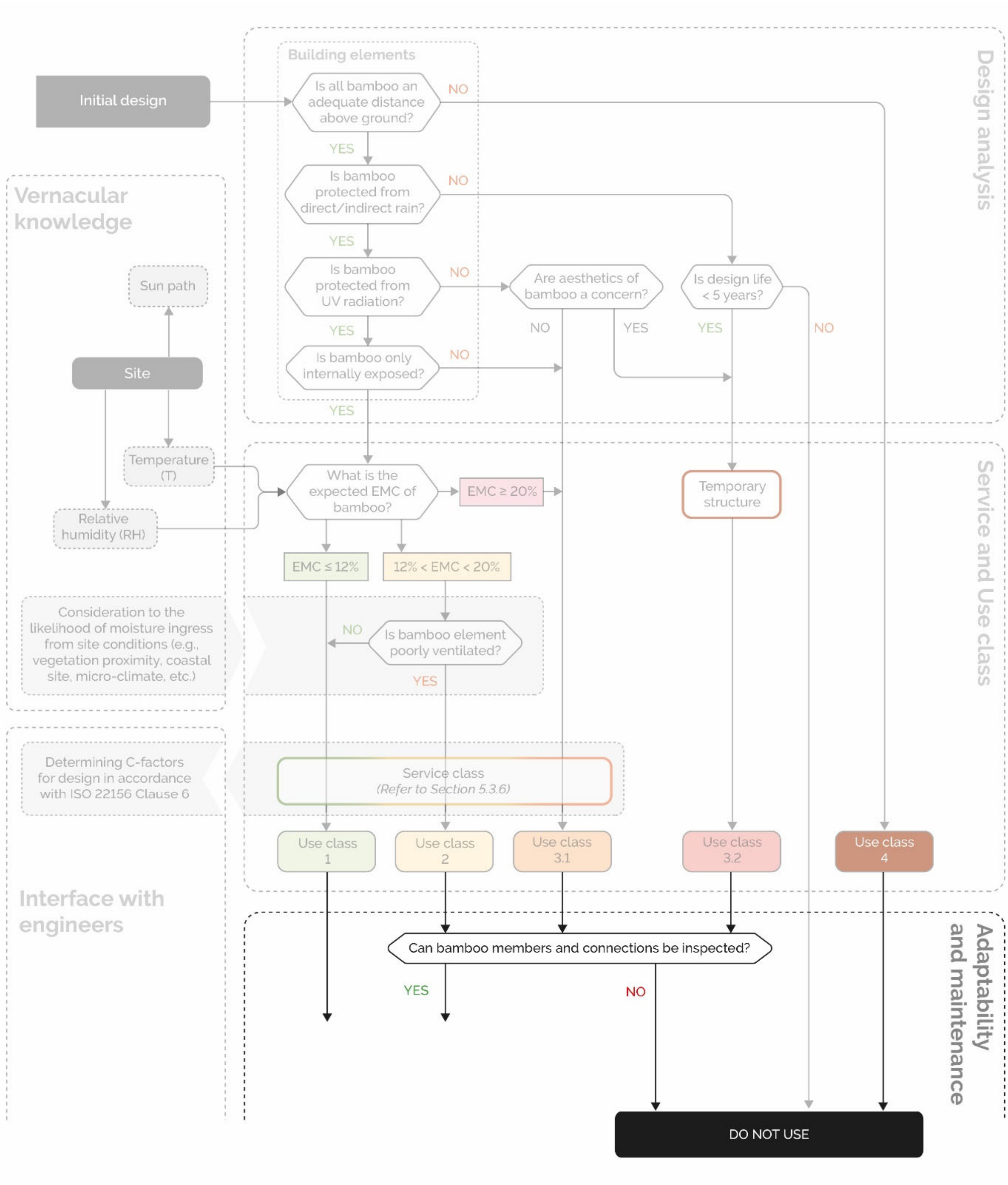


Figure 134: The design is to be assessed to ensure that each of the bamboo structural elements can be inspected.

Those bamboo structural members which are in Use class 2, 3.1 and 3.2 and can be inspected, can now be taken forward to evaluate the maintenance.

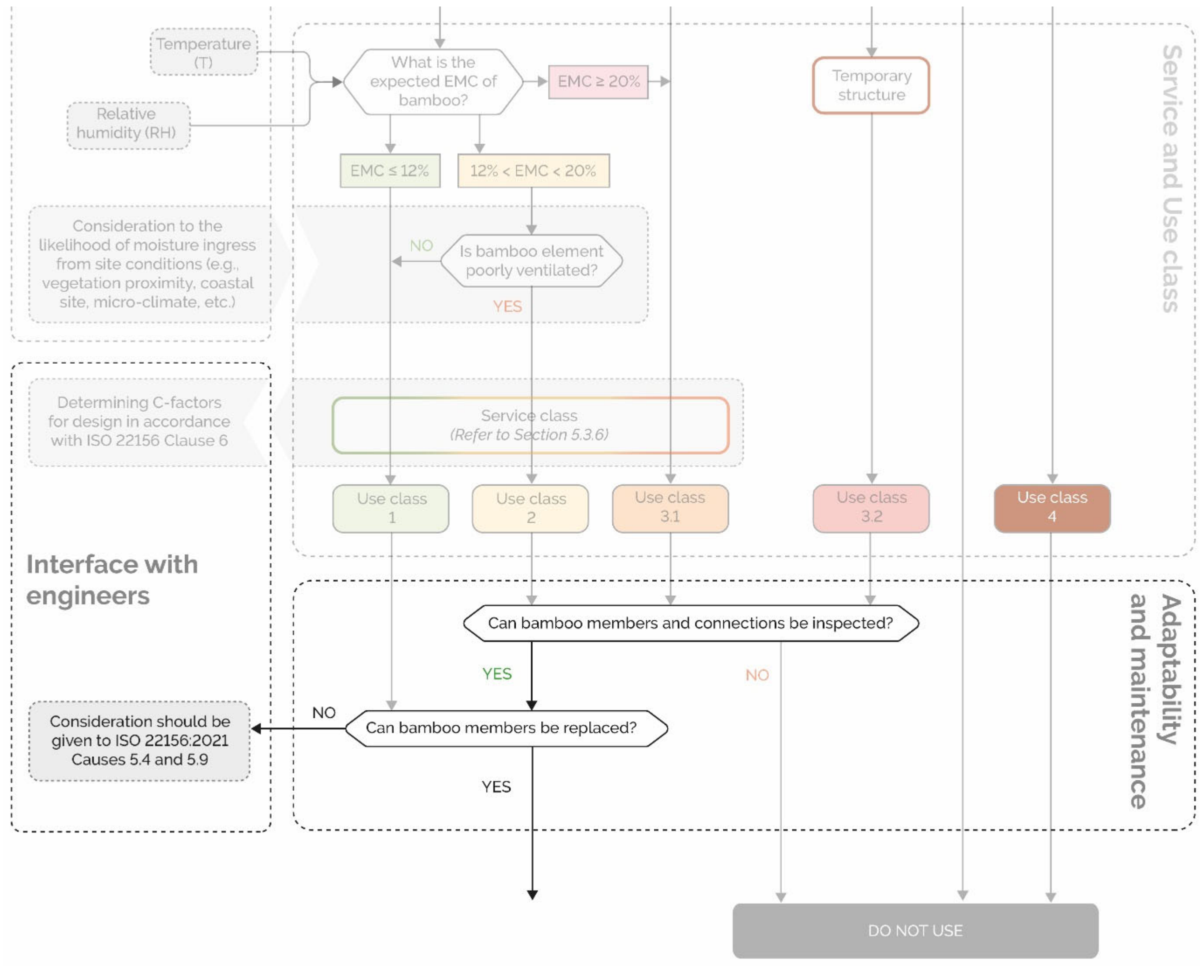


Figure 135: Bamboo structural members which are classified as Use class 1, or Use class 2 and 3.1 and can be inspected, are assessed to determine if they can be replaced.

As shown in Figure 135, it is to be determined if members which are classified as Use class 1 or Use class 2 and 3.1 and can be inspected, are assessed to determine if they can be replaced. Bamboo structural elements which can be replaced are those which conform with Clause 5.4.2 of ISO 22156 (2021). A structural element that can facilitate this is the four-pole column (Figure 61). If it is possible to replace poles, then a maintenance regime can be developed, documented, given to the client and/or end user, to make sure they are consulted (Figure 136). If any of the structural members cannot be replaced then these will be grouped with the other structural members and their inclusion in the structure should be determined in consultation with ISO 22156 (2021), Clause 5.4 - *Redundancy,* and Clause 5.9 - *Maintenance, inspectability and replacement considerations*.

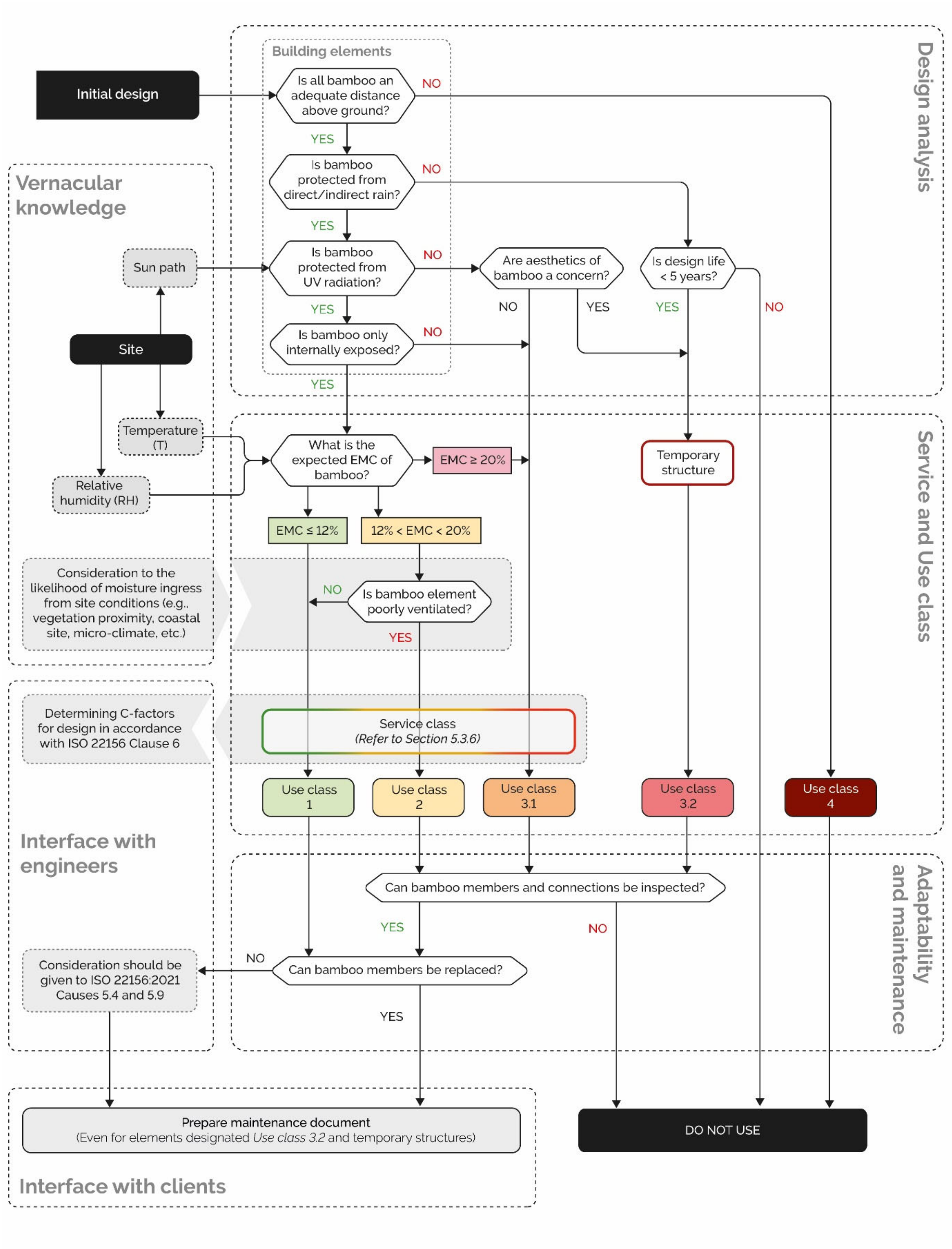


Figure 136: A maintenance document should be prepared for all structural members for the client, or end user. This is the final step in the decision tree for protection by design.

5.3.8 Application of the process

This process can be used in the evaluation of an emerging concept design. When considering the project in section or elevation, these questions posed in the decision tree can be used to evaluate a design constructed through a range of design methods whether 2D or 3D. For example, in 3D, a physical model can be evaluated using this decision tree with coloured stickers applied to the model to determine a range of colours aligning with Use class.

5.4 Digital application: Scripting the decision tree using algorithmic design tools

With algorithmic design (AD), a series of implicit relationships are scripted and by inputting values (which can also include environmental data or CFD analysis), a design emerges. By applying AD tools, the decision tree (Figure 137) is scripted as an algorithm using software[30] such as Rhinoceros and Grasshopper, integrating a range of software including those for environmental analysis (Ladybug Tools LLC, 2020; Open CFD, 2022; Sadeghipour Roudsari & Pak, 2013). This script takes a centre line model or explicitly modelled geometry representing full-culm bamboo structural members in the emerging concept design and provides real-time analysis to annotate each bamboo pole representation with a colour denoting Use class. This allows the design professional using the model, to immediately see the effects of design decisions on the durability and therefore service life of the structure. This workflow can also be extended to a BIM platform so that updated design documentation is simultaneously produced. This can be used to better communicate the expected performance of the bamboo to a client or discuss maintenance requirements of the bamboo structure over its service life due to the more versatile nature of BIM platforms producing documentation of architecture projects (as presented in the survey results in Section 4.6.1 and Figure 114). This visual information can go a long way to develop a positive experience of bamboo for the client and design professional. BIM is a platform which is documented as used in the Haitian construction sector, and the need to communicate with clients is all the more important here (as discussed in Section 1.7.5). The process of implementing the decision tree in a digital process is referred to as an expert system, which will include software to build and incorporate the appropriate knowledge base (Vishnubhotla et al., 1989). In this case the

[30] Inclusion of software in this work should not be construed as commercial endorsement.

software tools are discussed in Section 4.4.4, and the knowledge base is the decision tree for protection by design in Section 5.3.

The software which has been used to perform environmental analysis is Ladybug (Ladybug Tools LLC, 2020). This is an open-source environmental plugin for Grasshopper which allows the incorporation of site-specific environmental data into the algorithm. This can be used to bring sunlight analysis, temperature and RH into the digital model. This information can be extracted from widely-used *EnergyPlus Weather* (EPW) data (Sadeghipour Roudsari & Pak, 2013). Finally, *Butterfly* is part of the Ladybug suite of environmental tools. This plug-in applies CFD simulations using *OpenFOAM* (Open CFD, 2022), facilitated by the *blueCFD* software (blueCFD, 2022). Such CFD analysis can be used to calculate wind velocity and internal air flow to identify where limited ventilation can cause moisture (condensation) to accumulate. This is a key means of deciding which bamboo structural elements designated as Service class 2 can then be assigned to Use class 1 or 2. The BIM platform Autodesk Revit is used (Autodesk, 2022b) and is integrated to the algorithmic model through Rhino.Inside.Revit (Robert McNeel & Associates, 2022). As outputs, geometry and metadata—including material textures to colour Use class designations on members—can be visualised, scheduled in real-time in the BIM platform, and adapted through the functionality of Rhinoceros and Grasshopper. Each evaluation question within the decision tree is overlaid with the corresponding software for each step in Figure 137. As shown in Figure 137, vernacular knowledge is still important even in a digital process. This covers an understanding of the correct inputs, and a qualitative evaluation by the user, not just an acceptance of the outputs.

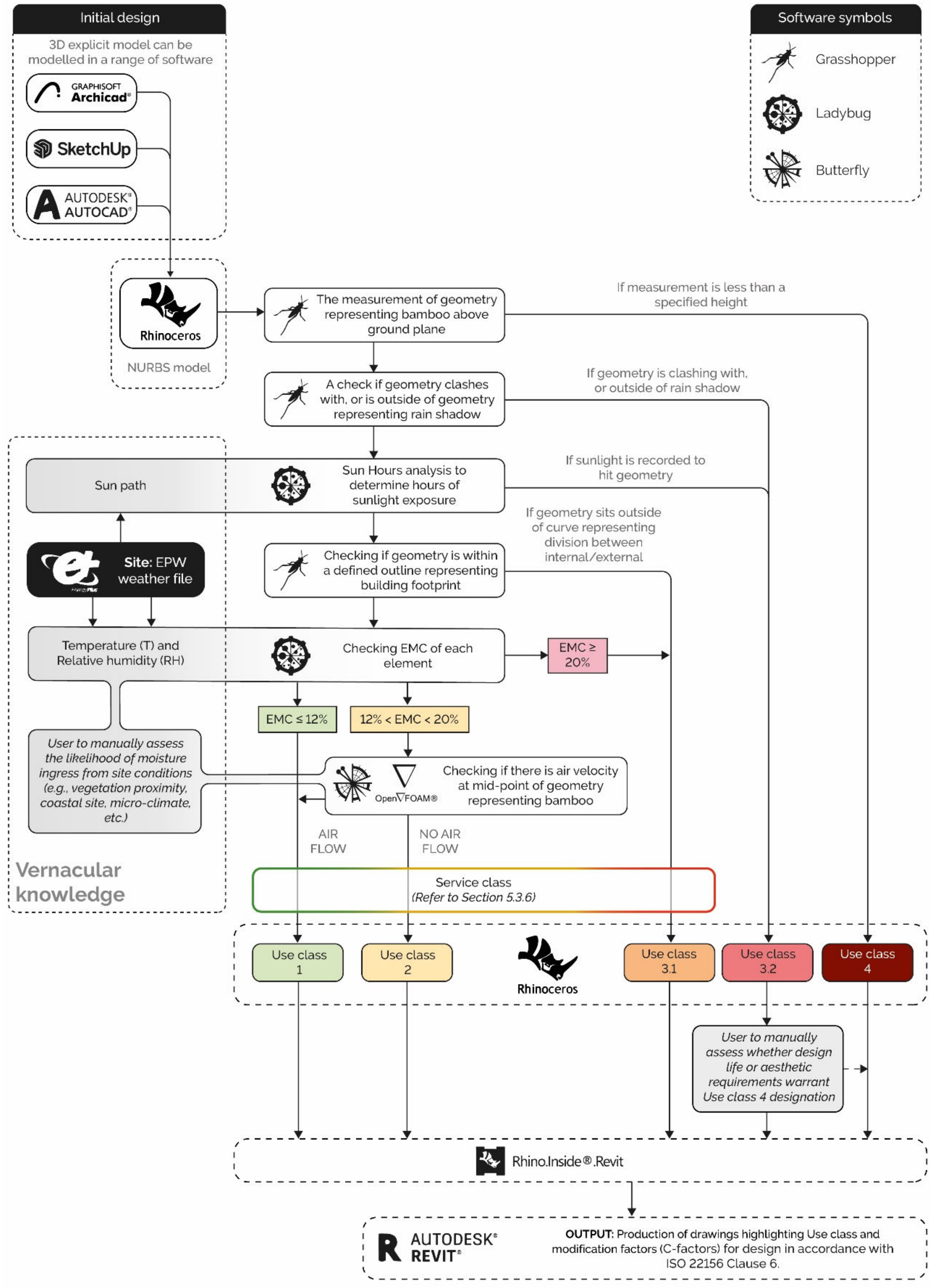


Figure 137: The decision tree for protection by design redrawn to show the software platforms used for each step of the determination of Use class.

5.4.1 Setting up the model to be tested with the algorithm

The 3D model input geometry in Rhinoceros is split into three categories: (1) full-culm bamboo members which are modelled as centre lines, (2) a NURBS (non-uniform rational B-splines) surface or polysurface, or polygon mesh which will represent the roof surface or any other protecting surface such as weather wraps (Figure 127) which will act as shading, and (3) other geometry to be represented in the model but are not associated with the present analysis (e.g., footings for the bamboo columns, etc.). The centre line geometry representing bamboo poles are defined as curves, permitting the modelling of bamboo which has a bow, as permitted within ISO 19624 (2018). Using NURBS geometries, or polygon meshes as the inputs, permit existing digital models, which have been modelled prior to this process, to be produced using other software. A polygon mesh opens up the possibility that the model will be imported from another platform such as *SketchUp*, which was identified with similar usage to Rhinoceros in survey results in Section 4.6.1.

5.4.2 Step 1: Use class 4 and 5

The first step is to determine if any of the geometry in the model representing a bamboo structural element is in contact with the ground, or within a zone above the ground which would be deemed to be at risk from excess moisture or flooding. The end points of each of the curves representing bamboo elements is extracted and its cartesian coordinates (x, y, z) obtained. The z value, corresponding to the elevation above the model plane, is assessed and compared to a number input by the design professional using a variable *Number slider* component. In order to develop this example script, this limit is set at +0.5 m. If the z value falls below the prescribed limit (+0.5 m), the associated curve is deemed to be in Use class 4 and 5 and will be annotated accordingly. All geometry not identified as Use class 4 and 5 is taken forward for further assessment. The *Dispatch* component in Grasshopper is used to determine which geometry is, and is not taken forward for further analysis, based on the input values. This is a key component used at each step of this process.

5.4.3 Step 2: Use class 3.2

Given that increased EMC is a more important consideration than UV radiation alone (as discussed in Section 3.4.6), the first step in this determination is to assess if the bamboo structural member is protected from rain and falls within a rain shadow (Figure 122). The geometry of surfaces in the model to represent those providing environmental protection to the bamboo structure—roofs and walls—can be either a NURBS surface or a polygon mesh.

The component *Mesh shadow* in Grasshopper is used to project the shadow of the surfaces affording protection as an outline from eight directions which are at 45° angle intervals around the perimeter of the plan (Figure 138).

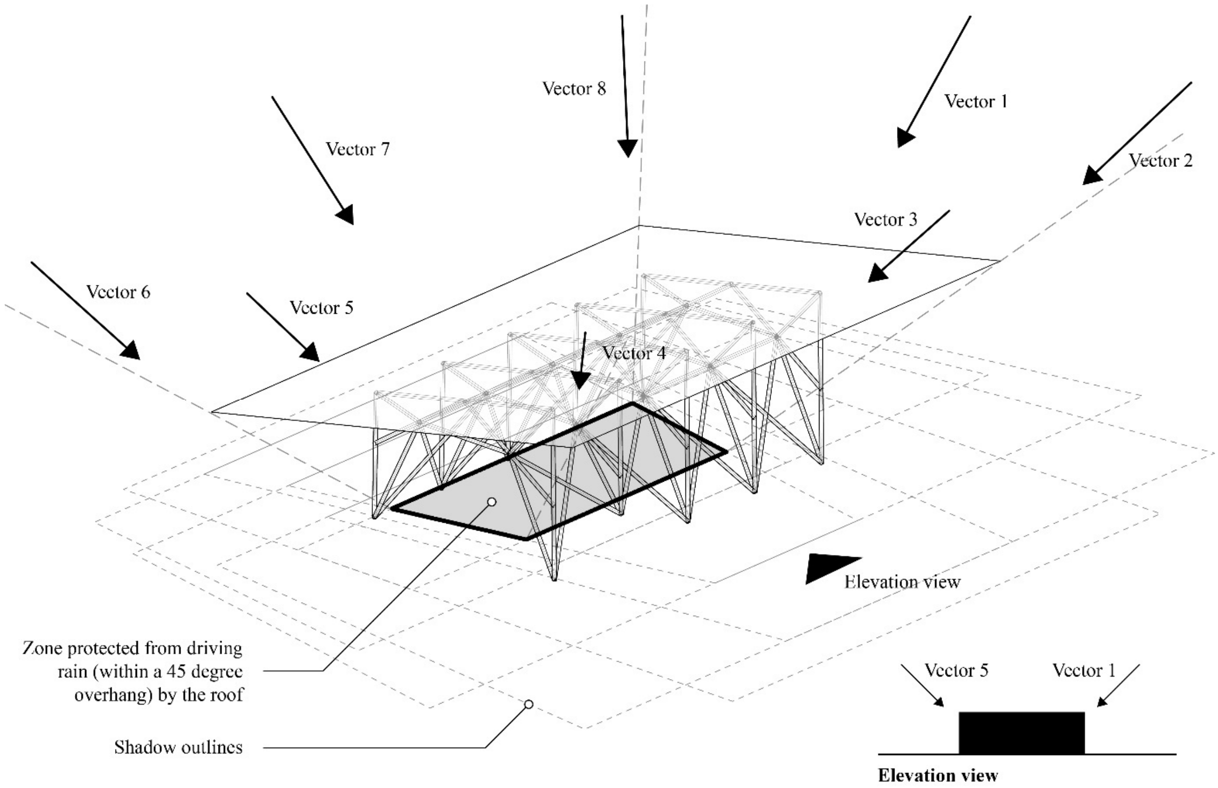


Figure 138: Determining the rain shadow with these eight vectors around the design in 45° angles as inputs to the MeshShadow component in Grasshopper.

Each of these vectors project at 45° to the ground plane and a 3D polysurface geometry is extruded from the shadow outline representing the rain shadow. If any pole is in contact with or outside this rain shadow it is considered to be exposed to driving rain. The next question at this step is to determine if the application of the bamboo structure is permanent or temporary. If the design life is to be less than 5 years, then this will designate those bamboo as temporary structural elements, and therefore Use class 3.2. If the structure is to be permanent, then these elements would instead be considered inadequate structural elements. All structural members within the rain shadow are taken forward for further assessment.

5.4.4 Step 3: Use class 3.1

The next step is to determine if any of the structural members not classed as Use class 3.2 or 4 and 5 are exposed to sunlight. All poles within the rain shadow in the previous step, have sunlight analysis applied to them based on the geographic location of the site. This is achieved using the *Sun Hours* component of the Ladybug plug-in for Grasshopper (Figure 139). This methodology using Ladybug for sunlight analysis was tested prior to the development of this script in Section 4.5.2 and Appendix B.

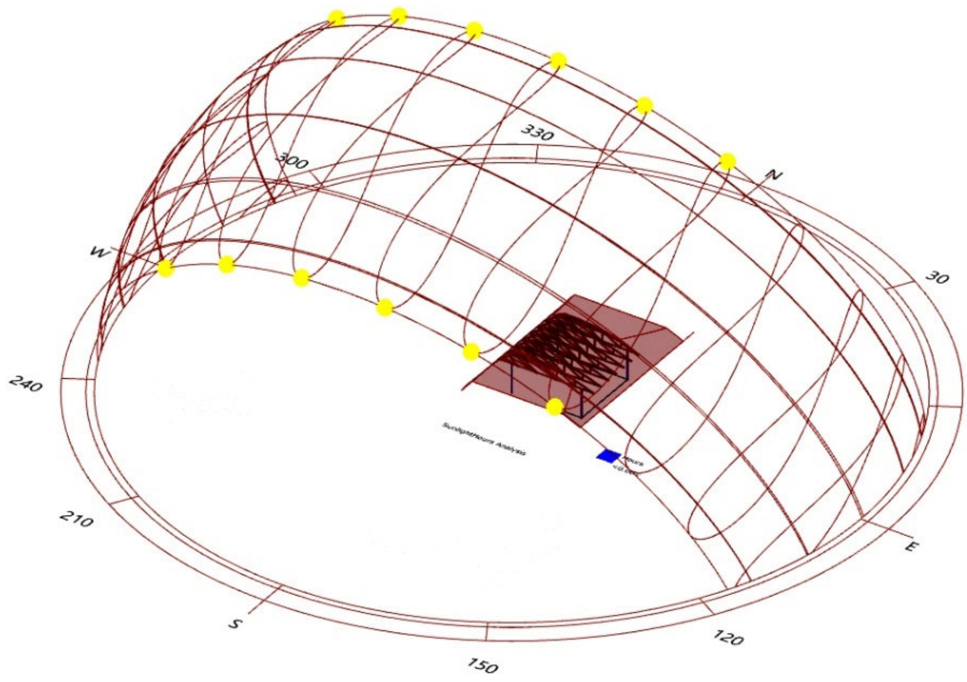


Figure 139: Screenshot of the sun-path from the Ladybug analysis.

Times of day are required to run this analysis, therefore if any of the geometry receives sunlight exposure between 10 am and 4 pm (indicative times when UV radiation will be highest), this will be classed as exposed to UV radiation which suggests the bamboo surface will turn grey. This is a simplified test, as within the software there is the ability to test UV radiation which is received by the geometry of the model being tested. However, as noted in Section 3.4.6 and following to the procedure in Section 5.3.4, the levels of radiation are not assessed. Instead, a simple “yes” or ”no” query assesses if there is any sunlight at all.

If for any reason these poles are required to maintain their aesthetic properties, then exposure to sunlight will negate their use, unless as with the previous step, it is for a design life of less than five years. If poles exposed to UV light are to be used in a permanent structure and aesthetics are important, then these would also be inappropriate for use. In the example presented here, aesthetics are to be maintained for all poles. All geometry not assigned Use class 3.1 or lower is taken forward for further assessment. A further assessment determines if poles which are protected from UV light are externally placed. If so, these will also be classified as Use class 3.1. In the algorithm this is achieved by identifying a curve representing the building footprint. Structural members along this curve (or external to it) are assessed as being external and therefore Use class 3.1. The curve which defines internal/external should follow the location as defined in Figure 127. If cladding or a covering is used on the façade then this geometry can be included with the roof surface when the sunlight analysis is performed.

5.4.5 Step 4: Service class and Use class 1 and 2

Remaining interior structural elements are then assessed for their likely EMC based on dry bulb and dew point temperatures, to generate a relative humidity (RH). This can be extracted from EPW files in the Ladybug software, however EPW files for a site can be too general for this purpose and local knowledge is key here. From this data, if expected EMC is 12% or lower, then the bamboo members will be designated Service class 1 and Use class 1. If EMC is equal to, or exceeds 20%, the interior elements will be assigned Use class 3.1. Those between these limits are designated Service class 2 and Use class 2. The Use class 2 elements can go through further assessment to determine if they are in a location of limited ventilation. An assessment can be achieved using Butterfly *Wind Tunnel Grading*. This will identify if there is ventilation around the geometry representing the bamboo element. In this example, the EPW file provides typical wind direction (degrees) and wind speed (meters per second) information for times of the year. This can be generalised, however, the information from the EPW file will be too general for the specific site for this information. Incorporating local vernacular knowledge is imperative for understanding any site-specific conditions such as prevailing winds and humidity, particularly in coastal areas or near vegetation which can increase ambient moisture (as discussed in Section 3.4.4). The EPW file is limited in scope unless it has been created specifically for all aspects of the specific site. Using files from online libraries which are near to the site risk omitting crucial environmental data. Therefore, in this application, the EPW file is only used to generate location information for sun angles. The EPW file lacks specificity regarding microclimates and vegetation, which are crucial for this step to work. For example, the climatic variances between a weather file for Port au Prince and nearby Kenscoff in Haiti, due to the vegetation and altitude differences, illustrate the significant differences which will not be captured in the weather file. Therefore, real-world expertise and vernacular knowledge must be integrated into this digital process at this point and this step highlights the importance of the professional (whether design, engineering, or construction), to inform the digital process.

and this step highlights the importance of the professional (whether design, engineering, or construction), to inform the digital process.

Prevailing wind direction and wind speed can be manually input into the script. Any building geometry which may block the ventilation (such as outer walls or a roof) can be used as part of the geometry to be tested along with the geometry representing the bamboo structural elements. This can allow the velocity around the poles to respond to any elements which will block the ventilation. The midpoint of each pole is the point at which wind velocity is measured (Figure 140) using Butterfly, OpenFOAM and blueCFD softwares. In this example bamboo members with air passing with a speed of less than 0.05m/s remain Use class 2. Those subject to air velocity exceeding this are designated Use class 1. The choice of wind speed is arbitrary and is chosen as a means of identifying which locations have moving air and which do not. With greater study into the drying rates of bamboo, this value for velocity could be refined further by the designer.

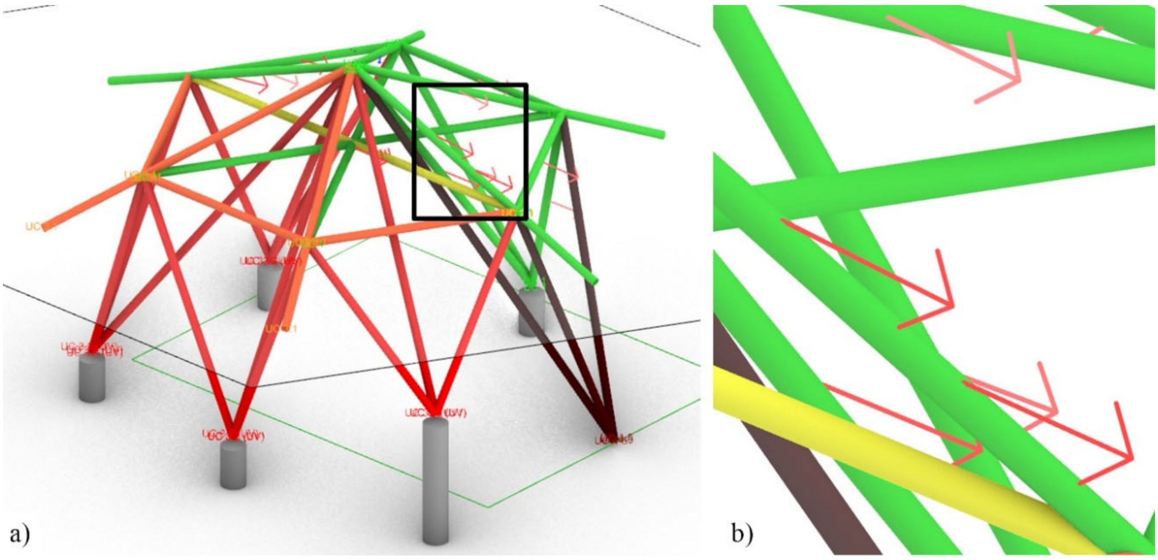


Figure 140: (a) Screenshot from Rhinoceros showing the visual results of the Butterfly CFD analysis, which (b) displays an arrow at the midpoint of each pole, indicating the resultant air flow vector and the length represents relative air velocity. The green footprint outline in (a) represents the line between internal/external used in the assessment.

5.4.6 The output of the digital model

Two initial design ideas are assessed following this script. The first is a structure which is hexagonal in plan and the second is rectilinear composed of three identical truss frames (Figure 141). Both designs are evaluated using the EPW file for Kunming, China (25° N; 1900 m elevation). This reflects a location in which bamboo is endemic which has greater variation in sun angle through the year. Each structure is also assessed in two orthogonal orientations: having their primary plan axes-oriented N-S and E-W. In total, four cases were assessed. This algorithm connects to the BIM Autodesk Revit with the each individual element (i.e., bamboo pole) within the BIM model uniquely identified. Use class can clearly be labelled as a colour texture and as metadata for each building element, which can then be listed out in a schedule.

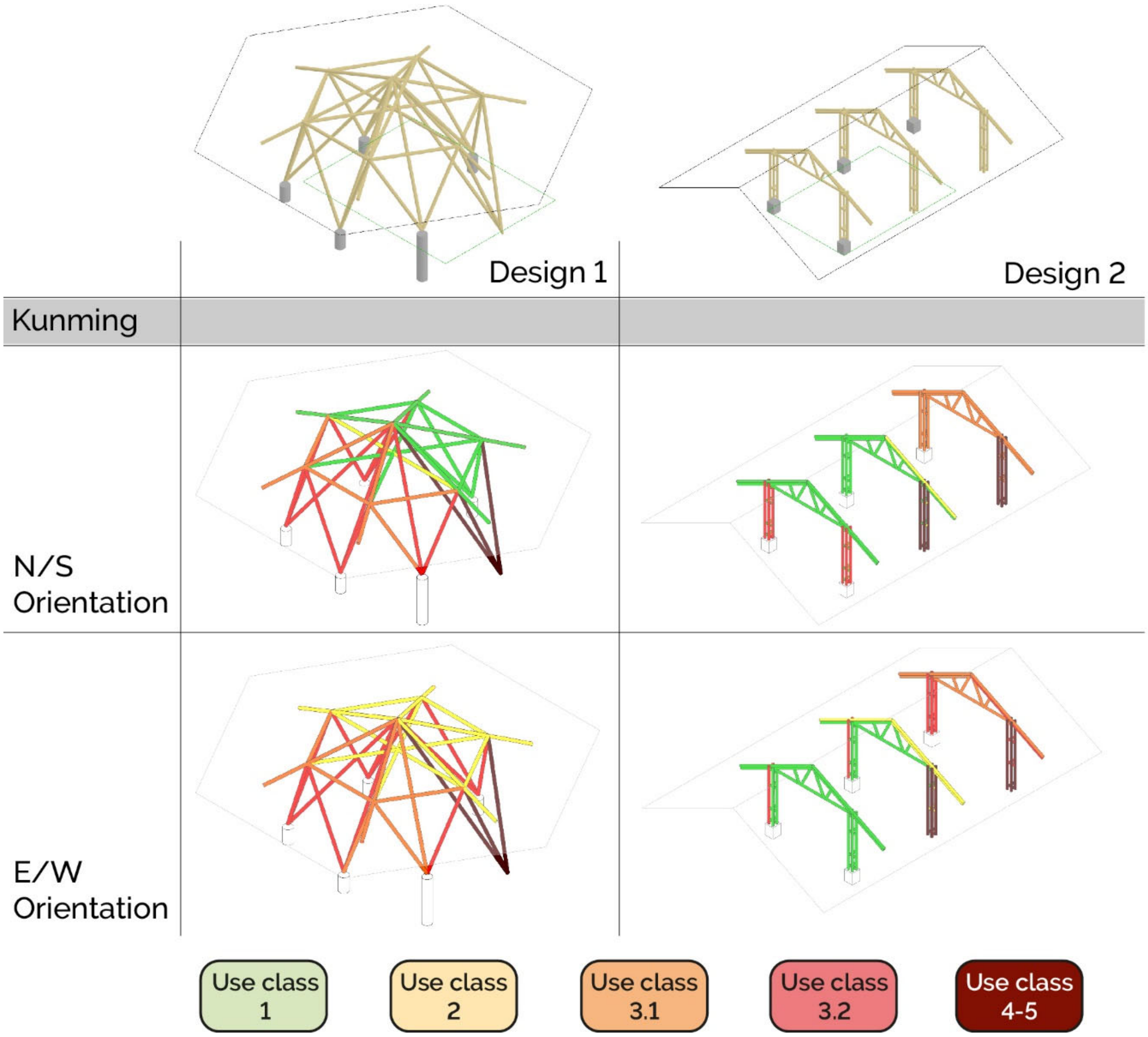


Figure 141. Results showing two digital models evaluated in two different orientations on a site (Kunming, China), with the geometry representing the bamboo structural members colour coded to represent Use class as determined by ISO 22156 (2021).

5.4.7 Future directions and optimisation of the digital application

Once the analysis has been completed by the script, any changes to the model to respond to this information are required to be done manually. This will involve the model being edited in Rhinoceros at which point the script will instantly re-run the steps of the analysis and update the output image of the Use class designation on the model in Rhinoceros or Revit through the *Rhino.Inside.Revit* software. If the model was originally imported into Rhinoceros, the model will have to be amended in the original software platform, (e.g., SketchUp) and then re-imported back into Rhinoceros for the analysis to be run again. These steps require manual modelling changes to respond to the information from the analysis. The analysis output informs the manual modelling decisions of the user (design professional).

With a knowledge of AD and scripting in Grasshopper, the design could be scripted and therefore variable inputs could be amended at which point the analysis will re-run automatically once there is a change in the design. With the use of optimisation plug-ins such as *Galapagos* or *Opossum* (as discussed in Section 4.4.4), it will also be possible to test different input values into the script to change the design and use the analysis and an evaluation criteria or fitness. Therefore, using this information on durability, it would be possible to optimise the design itself and provide the design professional the design output. This can suggest window opening locations, building orientation on a site, or optimal roof dimensions to balance the needs of environmental protection and material use.

The sunlight analysis could be extended to record the UV light radiation, rather than a “yes” or “no” of sunlight hitting the bamboo. With this information it would be possible to determine at what radiation level the bamboo is affected, and therefore not base this assessment on a question of “if” sunlight hits the bamboo during the peak hours of UV radiation during the day but understand the specific amount of radiation which would hit the bamboo. However, as discussed in Sections 3.4.6, and 5.3.4, there is lacking information in this field. With UV radiation data, it may be possible to calculate indicative temperature information of the bamboo poles, which could be used to input the modification factors (as discussed in Section 3.4.9) for load bearing capacity and stiffness as established in ISO 22156 (2021) into structural analysis software.

This process and use of these tools, fills a gap identified in Section 4.4.3 and Figure 85 in AD tool use, to integrate environmental analysis into the design process for full-culm bamboo. The algorithm could be taken further to conduct FEA analysis on the bamboo with these modification factors included. Though, the same challenges identified in Section 4.4—in which it is difficult to input the physical and mechanical properties of bamboo into FEA software—would still exist. The algorithm presented in this chapter as the digital application of the decision tree is a base demonstration of how this can be scripted digitally, however this is also a starting point for further development and innovation using a range of open source and widely available software tools, informed at all steps by vernacular knowledge.

5.5 Concluding comments

This chapter developed a design approach (Section 5.2) with a particular focus on design to afford environmental protection to a full-culm bamboo structure (Section 5.3 and 5.4):

- **Section 5.2:** The design approach for durability (Figure 117) which organises the considerations for durability from Chapter 2 into sequential considerations of a design processes, established through Chapter 4.

- **Section 5.3:** Steps 5 and 6 of the design approach for durability are diagrammed out as a decision tree for protection by design (Figure 136) based on the Use class and Service class classifications in ISO 22156 (2021).

- **Section 5.4:** The decision tree for protection by design for Steps 5 and 6 of the design approach are scripted digitally (Figure 137).

The design approach (Section 5.2), offers a structured methodology for design professionals by presenting research from prior chapters into questions aligned with specific design steps. These steps are categorised into two phases (Figure 117): (1) Steps 1-4 focus on initial idea development, and (2) Steps 5-7 expand that initial idea into a concept design. This approach is adaptable and can integrate with various design processes and tools (investigated in Chapter 4).

Steps 5-6 are expanded as a decision tree based on the information in ISO 22156 (2021), aimed at supporting design evaluations for durability. An algorithmic tool, built upon these engineering codes, provides a streamlined, consistent, and efficient evaluation process that is applicable for an analogue design process, and can be scripted digitally. The digital format and integration with a wider software palette and open-source software further aids implementation.

A challenge for algorithmic thinking can be in the oversimplification brought to a problem through systematising the steps. There are an array of intricate environmental factors, yet the decision tree using the guidance in ISO 22156 (2021) focusses solely on quantifiable metrics like temperature and moisture levels within the algorithmic framework which risks neglecting complex interactions and vernacular knowledge, among other factors and their cumulative impact on bamboo durability. An example of this is the location of adjacent vegetation which is not taken into account in the decision tree, but as shown in Section 3.4.4, proximity to vegetation can create increased moisture levels in the bamboo which can grow mould quite easily. Instead this is identified as a place in which the design professional needs to input specific local information and vernacular knowledge.

The digital model presents only an example, and this could be developed to be a much more comprehensive use of digital tools for this process, as discussed in Section 5.4.7. Another challenge of the digital model is the potential over-reliance on digital outputs may prompt the design professional to neglect expert advice, or vernacular knowledge. As discussed in Section 4.3.7, there would still be many challenges in incorporating bamboo physical and mechanical information into the digital model and translating this into practical construction information. This translation requires the input and expert advice of a construction professional. Further data or updates to ISO 22156 (2021) would require the decision tree to be reconceptualised.

The digital model does not take into account joinery or suggest the placement of bamboo poles based on how they would be positioned or cut to be connected in a structure. The model which is analysed in the script requires the user (design professional) to model the poles in the correct location prior to assessment. Future research could develop a software programme that models joinery similar to those for timber discussed in Section 4.4.2. The angle at which two poles of bamboo intersect can suggest a joint type from the list presented in Widyowijatnoko and Harries (2020) and ISO 22156 (2021), Annex D. Analysing the angles at which geometry in a digital model intersects could suggest, or model, the relevant joint type in a software platform. If such a software programme could be developed as a plug-in for Grasshopper, it could be included in the algorithm shown in this research and add Step 7 of the design approach (Joinery and connections) to the decision tree. Though again, this will also require the input of a construction professional. This also does not bring in construction realities (discussed in interviews in Section 2.4.6 and 2.4.9) into the design process to inform it.

As explained in Section 5.4.5, data accuracy is another challenge. The weather data in the digital model is used as design inputs in the algorithm and provides precise analysis based on the weather information. However, the information from an EPW file will not be adequate for the local nuances or the effects that neighbouring structures or vegetation may have on wind speeds on site. Therefore, local climatic knowledge is required which can be built up through site visits and local meteorological data. Many of these limitations recorded here can be addressed by human input of local, material and construction expertise, also termed vernacular knowledge.

Overall, the design approach provides the design professional with a series of key considerations at key points of the design process. This design approach is done in a way which will not prescribe a design, but assist the knowledge of the design professional as they develop initial ideas. The decision tree and digital application provide structured and procedural evaluation to initial design ideas by design professionals throughout the transition to a concept design. Again, these do not prescribe a design but evaluate a design based on the information in ISO 22156 (2021), within a design professional's process and toolset.

6 Chapter 6. Conclusion and future research

6.1 Conclusion

The research aims were set out in Section 1.2.7 and Figure 7. The following sections of this chapter discuss how this research has addressed these aims:

- **6.1.1 –** Develop a design approach to address the primary reason behind negative perceptions of bamboo, which is identified as durability in Chapter 2.
- **6.1.2 -** Follow the design guidance for ISO 22156 (2021) to provide a bridge between the design and engineering disciplines, with a standard approach to classifying durability risk, and communicating this to clients or end users.
- **6.1.3 -** The design approach should present itself so that a design professional can evaluate their emerging design ideas though the early design stages.
- **6.1.4 -** The design approach should take advantage of AD tools but be applicable with or without the use of digital tools.
- **6.1.5** - The design approach should be applicable in a LMIC context (Haiti).

6.1.1 Address key factor which causes negative perception - Durability

This research identified the widely purported but little researched non-technical barriers to the use of bamboo in construction and discover the key factor behind the perception of bamboo as a *poor man's timber* (Chapter 2). Quantitative surveys did not provide deeper insights other than trends (Section 2.3). Following qualitative interviews with those working in the field of bamboo construction (Section 2.4), this key factor was identified as durability. This is a term which encompasses many aspects within a building project such as material quality, supply chains, joinery and the design decisions which expose bamboo to environmental degradation. Efforts were made to gather global perspectives from regions where bamboo grows using interpretative phenomenological analysis (IPA). This proved useful given the corroborating experiences of the challenges to address the poor natural durability of bamboo and the impact this has on user and client perceptions of the material. Further research could engage clients and end users to triangulate the results. A range of factors within the design and construction of bamboo structures were identified that can affect the service life of a structure (Section 2.5 and Figure 117): (1) material knowledge, (2) local knowledge, (3) treatment and supply chain, (4) construction and local workmanship, (5) environmental vulnerabilities, (6) inspection, maintenance and replacement, and (7) joinery and connection detailing. To understand the extent at which the design professional can address these factors, these aspects of durability were explored in Chapter 3.

6.1.2 Addressing durability and ISO 22156 (2021) alignment

From the seven identified factors (Section 2.5), designing for protection from environmental factors and designing for adaptability and replacement are factors the design professional can address by design, also known as protection by design. Case study research in Colombia was fruitful in seeing real world good practice examples of bamboo in structures and those which had suffered the effects detailed in the interviews (Section 2.4), and the literature review (Section 2.2 and Chapter 3). Previous experiences were used to reference other case studies from other bamboo growing regions and Haiti. As a design professional in order to address durability, ISO 22156 (2021, Clause 5.7.1) provides clear guidance and categorisations of the risks of degradation based on the location of bamboo structural elements in a structure. This provides an opportunity to classify aspects of durability and present this to design professionals. This part of the research also observed the opportunity to bring design standards used by engineers to the attention of design professionals (e.g., architect or appropriately qualified and experienced person to design a building) and foster closer working between architecture and engineering professions. Service class designation in ISO 22156 (2021) was also investigated following the use of an H-H model (Section 3.4.1), typically used for softwood but demonstrates the relationship between RH and T in the environment and EMC in bamboo.

6.1.3 Alignment with contemporary design processes

Reviewing contemporary design methods, there is evidently an abstraction in contemporary design processes (Section 4.2), a focus on form (Section 4.2.3), and these trends emerged in conjunction with manufactured materials (Section 4.2.4). This trend was supported by the results of quantitative surveys (Section 4.2.7). Such form-based design processes present a challenge for minimally processed bio-based materials such as bamboo compared to standardised manufactured materials.

The design methods and tools were investigated in Chapter 4 which highlighted that algorithmic thinking for full-culm bamboo durability can be used as a support framework but also presents a format which can be easily scripted digitally. It was evident that physical design tools, particularly physical modelling, are very important when designing for bamboo, even in a process in which digital tools are used. Reviewing the range of tools, AD provides many opportunities to support design for bamboo through a range of digital environmental analysis tools, and through the scripting of a design for bamboo, it would be easier to embrace design changes late into a project. With minimally processed materials such as full-culm bamboo, such changes are more probable and significant to respond to the specificities of the material whether physical and/or mechanical. Following three applied examples it was apparent that there is scope to apply material constraints within the design process (Section 4.5.1 and Appendix A), apply environmental analysis tools to streamline design for bamboo durability (Section 4.5.2 and Appendix B), and that using an AD approach, was validated by construction professionals as providing unique opportunities for design and construction with full-culm bamboo, and the design process also benefits from other design methods and tools (Section 4.5.3 and Appendix C). Thinking algorithmically about the design of a bamboo structure is a process which can be used to classify in a procedural and standardised manner and this aligns well with the categorisations of durability in ISO 22156 (2021, Clause 5.7.1), reproduced in Table 8.

6.1.4 A decision tree for protection by design and integration with AD tools

Algorithmic thinking to design with full-culm bamboo has benefits that it could be applied both with and without computers, however it presented some challenges. The absence of AD tool usage in the software use surveys in Section 4.6.1 and the software use identified in the AAVS Haiti surveys (discussed in Section 1.7 and Appendix D), highlight the need for a process applicable in an analogue format. A decision tree is proposed to offer design support for full-culm bamboo structures that adhere to ISO 22156 (2021), engage engineers, clarify durability to clients, and evaluate durability impacts of design decisions. This process can be digitally scripted using prevalent AD modelling platforms, connecting with 3D explicit modelling software and BIM platforms.

In creating a decision tree, there was the need to address different categorisations which relate to durability in ISO 22156 (2021). The first being Use class which refers to the physical location of elements in a structure and their environmental exposure, and the second being Service class which relates to the environmental conditions of RH and temperature (T). This challenge to combine Use class and Service class within one decision tree and to simplify this process was addressed in Section 5.3.5.

6.1.5 Applicability to a LMIC context (Haiti)

Another evaluation criteria of the design approach is the applicability to a LMIC context, that of the Haitian built environment. The design approach and decision tree for protection by design are evaluated against each evaluation criteria established through the symposium in Section 1.7 and listed in Section 1.8. This are shown in Table 21.

Table 21: Table of criteria established through the symposium in Section 1.7.

<table>
<tr><th>Evaluation criteria established in Section 1.8</th><th>Assessment comment</th></tr>
<tr><td>Ubiquitous informal construction sector and even projects which seek regulatory authority will not be subject to code compliance or structural verification. Supporting public discourse on architecture and design can impact the informal construction sector in Haiti.</td><td>The decision tree (Section 5.3) for protection by design provides output which can support durability and promote design professionals to produce durable structures which can be presented within the public discourse, or built in visible and accessible locations.</td></tr>
<tr><td>Communication is crucially important for the design professional with clients, end users, and other AEC professionals and organisations.</td><td rowspan="2">The output of the decision tree (Section 5.3) provides qualitative information which aligns with an international design standard, ISO 22156 (2021), which can be conveyed to clients and end users to raise awareness of maintenance expected service life, and interface with other AEC disciplines.</td></tr>
<tr><td>There is a lack of expertise in the construction sector and a challenge for clients and/or end users to envisage a liveable and desirable space with bamboo.</td></tr>
<tr><td>Predominant use of 2D drawing and BIM software but there are challenges for compatibility between other professionals and disciplines, and infrastructural challenges to software use which includes cost, inconsistent electricity provision, or internet access.</td><td>The digital application of the decision tree (Section 5.4) uses Rhinoceros and Grasshopper as the base platforms. These pieces of software are not in wide use in Haiti. However, the choice of these softwares provides an open-source range of plug-ins to perform the environmental analysis and can use a range of different model formats as inputs, and output directly into a BIM platform.</td></tr>
</table>

<table>
<tr><td>Lack of control for the design professional over material quality for both cementitious materials (such as CMU blocks) and steel rebar due to no consumer protections for imported materials. Material quality is susceptible to price volatility and blurred material purchasing roles by clients themselves.</td><td rowspan="2">Though outside the scope of the design professional on a project, the overarching aims of this research endeavour to address this through developing wider use of bamboo. These factors support the argument for the relevance of this research.

The design approach (Section 5.2) and decision tree (Section 5.3) output can inform the client of bamboo's performance to support client decision making and attitudes to bamboo.</td></tr>
<tr><td>Locally sourced bamboo becomes an opportunity to decouple material costs from currency fluctuations and the opportunity to inspect the material before purchase.</td></tr>
<tr><td>Bamboo structures would need to demonstrate security for occupants and structural adequacy, not only aesthetics. If the structure fails, this will immediately revert attitudes.</td><td>Security and aesthetics need to be considered by the design professional through the feasibility and design process of a bamboo structure. Security would fall within local knowledge of the design approach (Section 5.2). However, the design approach and the decision tree endeavours to support design professionals to design long lasting structures with full-culm bamboo which can foster a better reputation in built projects.</td></tr>
<tr><td>Maintenance and associated costs will need to be communicated to clients which may negatively impact attitudes to bamboo.</td><td>The decision tree (Section 5.3) includes outputs which will be able to inform clients and end users of the maintenance requirements for the bamboo structure.</td></tr>
</table>

6.2 Future research

This PhD research was conceived as just one component for design professionals, as part of a wider agenda to develop greater use of full-culm bamboo in construction industries of tropical low- and middle-income countries (LMICs) where bamboo can be a viable addition to the material palette of their construction sectors. The reasons for this were both global and local. Globally, urbanising and increasing populations will require more buildings and this demand will occur mostly in tropical regions. Using materials such as concrete and steel for this will increase CO_2 emissions and cause negative environmental impacts at the time when the reverse is needed. Locally, many countries in the tropical area are LMICs and therefore will have restricted access to quality finite construction materials which will result in reduced quality construction materials being used. Haiti is an example of this context. Enfranchising locally available minimally processed bio-based materials can supplement existing construction materials, support quality construction and reduce the demand for imported materials and finite materials such as sand.

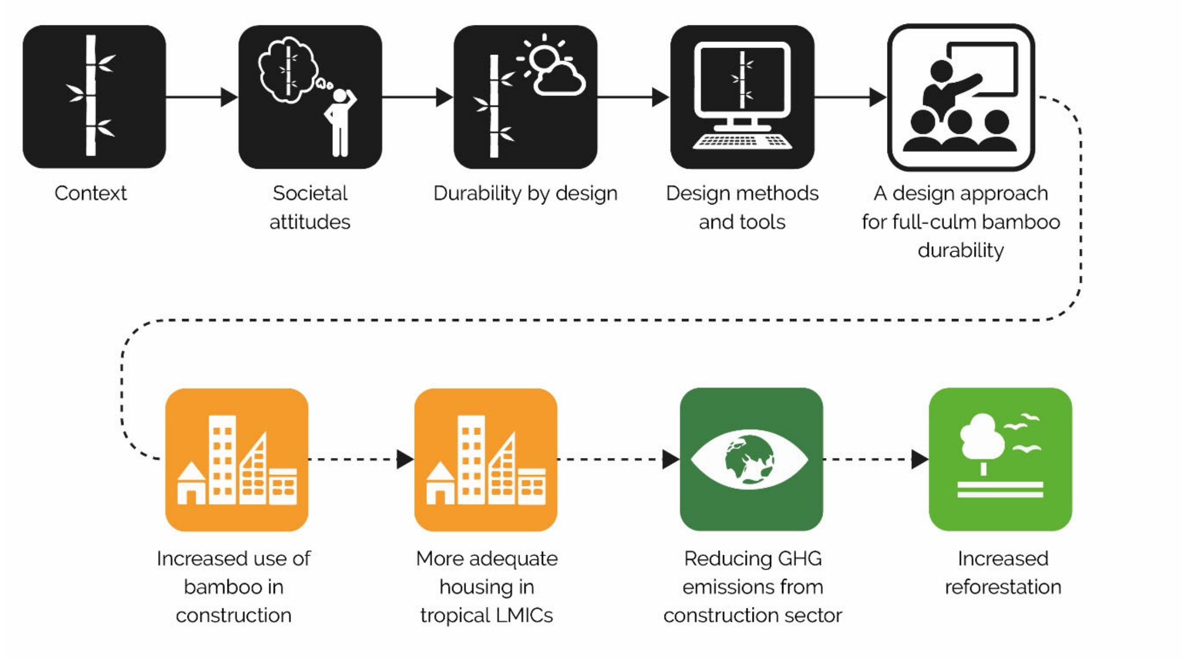


Figure 142: The themes of thesis chapters 1-5 (in black and white), and how this is intended to support the wider agenda of this research (colours of related UN SDGs).

The overarching research goals—and how to support the wider bamboo use in construction in tropical LMICs—is highlighted in Figure 142. The future research is conceived to support this wider goal.

In 2021, during this PhD research, the author was also involved in the *4th Bamboo in the Urban Environment Symposium*[31] held online and hosted between Newcastle University and the University of Pittsburgh. This symposium provided an opportunity to identify research

[31] The 4th Bamboo in the Urban Environment Symposium was held over four weekly sessions in September and October 2021 https://conferences.ncl.ac.uk/4th-bamboo-itue/

needs and knowledge gaps from attendees through post-symposium surveys. The symposium was comprised of four sessions covering the broad areas of: (1) determination of material properties, testing and grading, (2) bamboo connection techniques and technology, (3) bamboo durability and fire performance, and (4) construction using engineered bamboo. Over the four sessions, there were 240 unique participants who were asked to complete a post symposium survey on research gaps, needs and priorities. 42 responses (18%) were received representing a range of stakeholders from at least 12 countries. Of the respondents who identified their interest, 24 were academic researchers, six were involved in the bamboo construction industry, eight had an interest in bamboo, and nine identified as being new to bamboo construction; some respondents identified more than one interest category while some did not respond to this question. The survey results were written up, peer reviewed and presented as a conference paper, of which the author of this thesis is a co-author. This is documented in Appendix F, and published as Harries, Mofidi, et al. (2022). Therefore, the knowledge gaps and research needs identified from this symposium provide commentary to the wider relevance, or lack therefore, as comment to the author's own future research observations from this PhD research. These are: (1) testing the application of the design approach, (2) sustainability, (3) AI and new technologies, (4) fire performance, (5) urban applications of bamboo, and (6) language barriers to knowledge dissemination.

6.2.1 Testing the design approach and the decision tree for protection by design

There is the need to have a practical evaluation through participatory action research of this design approach, and decision tree in the academic and practice context of the Haitian construction industry. The curriculum of a workshop would include the following:

- **Lecture series:** This serves two purposes to both teach the information of bamboo as a plant and construction material, and to expose participants to reference projects for bamboo and how to construct with bamboo. ISO 22156 (2021) would be introduced through lectures as would the design approach and decision tree for protection by design. When presenting ISO 22156 (2021) and the decision tree to participants, it is important that these are choregraphed as informal discussions between tutors and participants and not delivered too formally, in one direction. This is an opportunity for the tutors to learn from participants and encourage a frank debate on what are the real world scenarios in which this knowledge can be applicable—whether it is in their studies or professional practice context. This can be a difficult subject to engage with, especially when participants are within their peer groups. Both the format of a code document, and thinking algorithmically can be alien concepts to design professionals or students and therefore it is imperative to understand and tailor how this information is delivered, share information, and make it relevant to the participants and context.

- **Software tutorials:** The workshop introduces participants to AD tools, algorithmic thinking (anticipating that the majority of participants will be familiar with explicit 2D or 3D modelling but not AD), and highlight the applicability of these tools to design for full-culm bamboo. This would be delivered in tutorial sessions where exercises would be in a textbook format so students can follow along outside of sessions (an example exercise is included in Appendix I).

- **Construction – General techniques, material experience and prototyping designs:** Construction would be taught to participants to generate awareness of the material of bamboo (as presented in Section 4.5.3), and as an opportunity to prototype design ideas that are generated through group work projects. This means the material realities can inform emerging design ideas. Construction exercises would also be an opportunity to engage construction professionals who can transfer skills to bamboo such as those working with timber locally. This offers the opportunity for long-term capacity building in construction professionals who can continue to work with design professionals following the course. This also generates an important feedback loop with local construction professionals who can inform the design professionals with the constraints of tools, and techniques. These constraints will also inform, as defined by Crolla (2018b), how the digital tools that the participants learn can be "reconfigured" to manage the imprecision of non-standard materials (p. 305).

- **Design brief following design approach (groupwork):** The thread through which modelling, software, and construction activities are all linked is through a design brief delivered to groups of participants. This allows the participants to develop their own design challenges which need to be addressed. Design challenges require the participants to innovate and engage with the material and software and apply these to a real world brief, rather than isolated and detached exercises. Groups working together facilitates peer-learning.

- **Physical model making (decision tree analogue application):** Creating physical models using bamboo skewers facilitates a design stage where the material parameters of bamboo skewers inform the design process (as discussed in Section 4.5.3). These dynamic models can be used by participants to develop design concepts, and through the parallel experience of digital modelling and physical construction, these models can be assessed and developed. For example, using elastic bands to create joints in the bamboo model can see many poles joined in one location. The experience of physical construction can then feedback into the physical modelling process to assess where joints should be placed. This approach allows for immediate tactile feedback on the structural principles. Though a limited material supply, the “cannibalisation” of physical models representing design concepts which are unsuccessful can also help refine a single design concept through the modelling process.

- **Evaluation of the decision tree for protection by design (digital application):** Once software skills have been developed, a software exercise will be the scripting of the decision tree. This will facilitate an understanding in the participants of all the steps, and participants will build these steps up themselves before implementing this into their designs. Though it would be possible to bring a model into the existing script and perform a test, the goal of the evaluation, and an objective of the workshop would be to use every opportunity to teach AD software. Scripting the algorithm will also teach the procedural steps which is an important learning outcome of a workshop. This also increases the chances that participants themselves may innovate and look at ways to critique the decision tree developed in Chapter 5, and find efficiencies, augmentations or evolutions of the decision tree and this PhD research.

A workshop length should be no more than one week as professionals will need to engage and taking more than one week off work can be problematic. Such a workshop is informed by the author’s ongoing experiences leading the AA Visiting School bamboo programmes and the AAVS Haiti workshops. Such a workshop would follow similar formats. This can also allow the outcome of this research to be refined through real world testing informing it with current supply chain information, realistic maintenance expectations and encompassing socio-cultural factors. Efforts have been made in this research to create a framework in which the design approach could be developed and evaluated against a tropical LMIC context, for this to be applicable (Section 6.1.5).

The results of the symposium survey (Appendix F) showed that in the third session, which focussed on durability, design guidance and awareness of protection by design in designers was ranked as fourth in Session 3. Four of the top five related to fire (this is discussed in

Section 6.2.4). This shows that there is appetite for more guidance on durability and therefore setting up research which engages students and practitioners.

6.2.2 Sustainability and LCA data for bamboo

The sustainability of bamboo is the key driver for client and professional interest in bamboo. This is due to its rapid growth and renewable nature. To quantify this, comprehensive life cycle assessments are required to account for factors like harvesting, processing, transportation, and end-of-life disposal. These assessments can be intricate and context-dependent, making it challenging to draw generalised conclusions about bamboo's sustainability. Furthermore, the lack of standardised methods for evaluating the environmental performance of bamboo can hinder its accurate comparison with other construction materials (Zea Escamilla, 2015). Variability in bamboo species, growth conditions, treatment methods, and regional contexts further complicates these assessments. Inadequate data and research on bamboo's long-term durability, and performance in various climates also contribute to the challenge of gauging its sustainability. Bamboo is only sustainable if it is used in long term durable applications. This research aims to support this, but more work needs to be done. Interestingly, the incongruity between the purported significance of bamboo's sustainability (identified in Section 2.3.4) and the lack of emphasis on this aspect in research gaps and needs surveys, as evidenced in the *Knowledge Gaps and Research Needs* conference paper (Harries, Mofidi, et al. (2022) and Appendix F), reveals a potential disconnect. The reason for bamboo's adoption often hinges on its sustainable attributes. More research needs to be done to validate these aspects. This will provide design and engineering professionals, and clients, with reliable information to make informed decisions about the environmental benefits of bamboo, enhancing its role as a critical material to develop sustainable construction.

6.2.3 AI and design for bamboo

Thinking algorithmically about bamboo reveals its intricate relationship with various input factors—environmental conditions, species, and growing conditions—which shape its physical and mechanical properties. Deep learning and Artificial Intelligence (AI) could take this information and harness this complexity, potentially reducing bamboo's natural variability in construction and the design process. This process could also start to infer material information on physical and mechanical properties of bamboo on growth conditions of a particular region and apply this information to a building design on a local site. A database of this information globally could start to inform design professionals of local factors which can affect the bamboo they propose to use on their projects. The results of the symposium survey showed that in the Session 1, which covered bamboo testing, grading and material properties, such a database was ranked the joint highest priority. Therefore, there is awareness that such a resource is required. Deep learning and AI provide an opportunity to populate such a database.

The increased use of AI in design, such as the generation of building images through software such as Midjourney (2023); SDXL (2023) or DALL·E (2023) pose challenges identified in the design process and discussed in Section 4.2. Overreliance on AI-generated images might inadvertently lead to diminished material consideration in the design process, simply recreating images of buildings on many scales that look like they have been constructed with poles given a bamboo texture. It is essential that those working with bamboo in a practical manner share information on best practice and continue to advocate. Proactive efforts are needed to question design methodologies, paralleling the approach advocated in this research. In essence, while AI has the power to reshape design practices and incorporate material information into a design, it should be integrated thoughtfully to ensure a consideration of the material requirements and the unique inherent properties, over merely form or image.

6.2.4 Greater understanding of fire performance of bamboo

This research focussed on the environmental aspect of durability for full-culm bamboo and how design to protect bamboo from the environmental factors that can affect the bamboo in a structure. However, the fire performance of bamboo is a major factor to overcome to make clients, end users, insurers and finance providers comfortable with full-culm bamboo not just when bamboo is in the final structure but also when the project is under construction. Full-culm bamboo *(G. angustifolia)* have been shown to take more exposure time to achieve ignition than plywood made of *Pinus radiata*, with a charring rate almost three times lower than the charring rate obtained for plywood (Mena et al., 2012). However, there is still a lot more research to be done, including the testing of full-scale structures. Testing elements in isolation can never provide a true picture of the fire performance and if bamboo is used with other materials, the combined effects on the fire performance also need to be understood. Though bamboo may take longer to ignite and char, bamboo is hollow. When treated through immersion the solid nodes are penetrated inside the culm to allow the solution to circulate. This provides a consistent cavity through the bamboo, which is different from solid timber, and therefore, unwise to make comparisons. In fact the hollow culms explode loudly due to heat expansion, from which the name bamboo may have originated (Liese & Tang, 2015a).

Applications without a proper understanding and fire protection of bamboo members can lead to misleading expectations and safety risks. Currently, the way this is dealt with is by applying a height limit to bamboo structures in NSR-10 (2010) and ISO 22156 (2021). However, for larger scale examples of bamboo structures to be constructed, which can inform future iterations of code documents, more information on the fire performance will be required. The symposium surveys showed that within the research community of bamboo, in Session 3 which focussed on durability, four of the top five priorities related to perceived gaps in knowledge related to the fire performance of bamboo (Harries, Mofidi, et al. (2022) and Appendix F).

6.2.5 Hybrid construction with engineered bamboo in urban contexts

The relative homogenous properties of engineered bamboo products (EBPs) minimise variability, ensuring structural reliability and alignment with regulation. For these reasons this is more likely to be the form of bamboo which is applied in more densely settled and urban areas. While this will be a great use of bamboo, this runs the risks of creating a market for bamboo outside bamboo growing regions and could see bamboo exported. Then, locally available full-culm bamboo becomes worth more as an export product than a locally available minimally processed construction material. As research to develop wider use of EBPs continues, the research on full-culm bamboo should not be left behind. There is also scope even in urban areas to implement full-culm bamboo alongside EBPs. This could be by using full-culm bamboo as the final two stories on top of a structure constructed by EBPs. The environmental benefits of using the minimally processed full-culm bamboo which does not contain the resins which are used in EBPs warrant its use wherever possible. The resins used in EBPs is also something that needs to be considered in future research and this was also identified in the symposium survey (Harries, Mofidi, et al. (2022) and Appendix F). Alternatives to phenol-formaldehyde based resins such as tannin, lignin, polyurethane, and castor oil-based resins appear promising for outdoor use since they are stable.

6.2.6 English language nature of research

A significant personal challenge remains accessing literature from non-English speaking bamboo-growing regions and engagement in these locations. This is despite concerted efforts such as the bilingual course in Panama and bilingual surveys in Spanish and English (Section 2.3 and Section 4.5.3). This challenge is reflective of a broader issue impacting the understanding and dissemination of bamboo construction practices globally. Firstly, limited access to non-English literature impedes a comprehensive understanding of bamboo's construction nuances, as valuable insights and methodologies might be overlooked or inaccessible. Secondly, the scarcity of translated literature hampers the wide-reaching dissemination of effective bamboo construction information and best practices. Vital knowledge remains confined to specific linguistic communities, impeding the transfer of valuable expertise to regions grappling with similar construction challenges. ISO 22156 (2021) aims to address this point, by allowing, "Experience from previous generations (i.e., vernacular construction) that is well preserved in local tradition and dutifully transmitted to people living today can be considered to be an informal, noncodified 'standard'," requiring the knowledge is for the same scale of building, used within the same locality of that tradition, and a series of criteria to be met (ISO 22156, 2021, Clause 5.11.2). Bringing in more vernacular construction knowledge to create a greater pool of data and references, as well as bridging language gaps is imperative to foster a global exchange of insights that could enrich bamboo construction practices universally.

6.3 Reflections

Experience though this PhD has revealed abrasion between the academic and professional worlds of bamboo design and construction. In situ conditions compared to controlled laboratory conditions reveal differences as do other factors such as funding models for research. A large proportion of research in this field have been focussed on developing work which creates visual output, such as small built temporary structures. However, it is apparent that the major barriers to wider bamboo use lay in either the non-technical and social, or technical research into aspects of design for bamboo that do not result in a photogenic structures, (e.g., fire testing, engagement with the insurance sector, or the development of standards and codes, etc.). Bamboo is a remarkable material and through focusing on the perceived challenges of the material, it is stark that these challenges are solvable with research. What is not solvable—without a diversification of the global construction material palette and greater use of materials such as full-culm bamboo—are the global challenges of climate change and reduced material quality in tropical LMICs. Bamboo provides a major opportunity to fix these global challenges and it must be grasped.

Digital algorithmic design tools can help design professionals design in a way in which materiality is embedded in the design, moving us aware from a focus on purely form and abstraction. It is important these tools are used with other design tools. This is an addition, not a replacement to physical modelling, sketching and one-to-one scale prototyping. These tools can save time, and money both in material use, creating durable designs, and efficiencies for designers. Nowhere is this need for greater bio-based material use, value, and efficiency more relevant, that in bamboo growing, tropical LMICs.

The most rewarding aspect of this research has been the people encountered. Engaging with local practitioners, students, and professionals have provided invaluable insights and perspectives, enriching the research process. Meaningful conversations have deepened understanding and fostered connections that extend beyond the research, highlighting the importance of community engagement in advancing bamboo use and knowledge dissemination. Due to security concerns, the author was unable to travel to Haiti during this research, preventing on-site fieldwork for a deeper understanding of bamboo construction's applicability. Consequently, a recommended next step is to organise physical workshops akin to the AAVS Haiti workshops (Section 6.2.1). These workshops would enable hands-on learning and direct engagement with local practitioners, validate the research findings, and support capacity building, ensuring a contextually relevant approach to designing bamboo structures. In response to this lack of opportunity, the symposium developed an evaluation criteria up front for the context of Haiti which have been used throughout this research.

The COVID-19 pandemic had an impact on this research, though did not warrant any mitigating circumstances. This experience emphasised the significance of engagement and human interaction particularly in the knowledge sharing of bamboo construction. It underscored the importance of human storytelling and revealed disparities between many bamboo growing regions and the Global North with fast internet connections, government job support schemes and access to booster vaccines before many countries in the Global South had even one. In the face of all these difficulties it is all the more touching that during this time so many people shared their time for meaningful engagement with this research.

Appendix A: The Opportunities and Challenges of Using Parametric Architectural Design Tools to Design with Full-Culm Bamboo

Conference paper

Published as: Naylor, J. O. (2020). The Opportunities and Challenges of Using Parametric Architectural Design Tools to Design with Full-Culm Bamboo. ICACE 2019. M. Awang and M. R. Meor M Fared. Singapore, Springer Singapore. 59: 9-18.

The Opportunities and Challenges of Using Parametric Architectural Design Tools to Design with Full-Culm Bamboo

Case Study: A Design for a Hyperbolic Paraboloid for Gutter-Less Rainwater Capture Using Full-Culm Bamboo

John Osmond Naylor

Abstract Tropical developing economies are some of the most vulnerable societies to natural disasters, and by 2050, some 50% of the world's population will live in the tropics. Tropical developing economies already have a shortage of housing which lacks structural quality, durability and is considered non-adequate. Tropical developing economies have an opportunity to utilise locally sourced lightweight natural materials such as bamboo. Computational design processes save time, which allows greater scrutiny of design options and the testing of various iterations. A challenge is in the use of computational design tools with their great accuracy, and the natural variability of full-culm bamboo. Architects will need to develop a synthesis between their current computational design processes and materials with natural variability such as bamboo in order to improve affordability, efficiency and ensure durability. This paper presents such a synthesis, and discusses a case study of an algorithm to generate a design for a hyperbolic paraboloid. This studies the capabilities of commonly used architectural design software, and observes the efficiencies and limitations of this process. The process embeds principles in the design which will increase the durability and buildability of full-culm bamboo. If we can develop these syntheses, as designers we can obtain tools which can increase the use of renewable natural materials with variability such as bamboo, and begin to meet the need for durable, functional and adequate housing in tropical developing economies.

Keywords Full-culm bamboo · Parametric design · Adequate housing · Sustainable development

J. O. Naylor (✉)
School of Architecture, Planning and Landscape, Newcastle University, Newcastle upon Tyne, UK
e-mail: j.naylor73@newcastle.ac.uk

M. Awang and M. R. Meor M Fared (eds.), *ICACE 2019*,
Lecture Notes in Civil Engineering 59, https://doi.org/10.1007/978-981-15-1193-6_2

1 Introduction

Tropical developing economies are some of the most vulnerable societies to natural disasters and by 2050, some 50% of the world's population will live in the tropics [1]. Over one-quarter of the urban population of South East Asian tropical developing economies reside in non-adequate housing [2–4]. The UN Sustainable Development Goal 11 (SDG11) targets by 2030 the access for all to adequate, safe and affordable housing, and suggests that the building of sustainable and resilient buildings utilising local materials should be a catalyst for development [5]. Cement production is the third-largest source of anthropogenic emissions of CO_2 and could rise by 23% by 2050 given current trends [6]. Sand for construction is also being unsustainably sourced which in the coming decades will affect the concrete supply chain [7, 8]. We need to look at new sustainable, locally available natural materials for construction, and architects will need to respond to this challenge and develop new processes to work with natural materials which ensure structural integrity and affordability. Tropical developing economies are large producers of bamboo [9], a material with good tensile and compressive properties and a low carbon footprint when sourced locally [10]. Bamboo can be worked with simple tools and can be grown locally on a village scale or even a family scale [11]. Bamboo can also absorb CO_2 and stabilise slopes to tackle the effects of deforestation [12]. If we are to increase the use of renewable materials, then we should look to non- or marginally engineered building materials to ensure that the most affordable form of bamboo, 'full-culm bamboo', (also named 'round bamboo') is used [13, 14] (Fig. 1b). Bamboo will degrade if not designed or built correctly. Exposure to UV light and moisture can bleach, crack and encourage fungal growth causing structural and aesthetic damage which impacts greatly the perception of bamboo in the mind of potential end users, reinforcing a notion of bamboo as temporary, or the 'poor man's timber' [15].

In tropical developing economies, it is a reality that the architect will not design the majority of housing [16]. The minimum construction materials are purchased, and design and engineering input is often unaffordable. Architects can however be

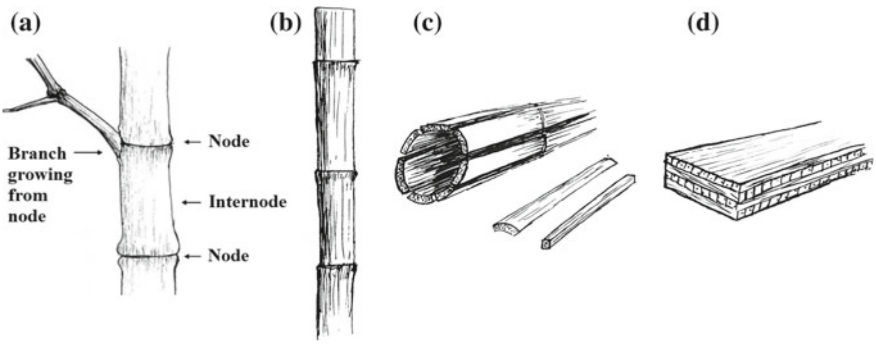


Fig. 1 **a** Culm terminology, **b** full-culm bamboo, **c** bamboo splits, **d** example of engineered bamboo

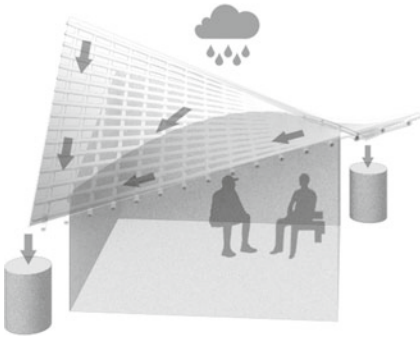


Fig. 2 Render illustrating rain collection strategy of the hyperbolic paraboloid

active in reducing the cost of design and raise awareness of good practices promoting open-source designs of adequate housing which ensure structural and aesthetic integrity [17, 18]. In order to reduce the cost of design, there have been moves by architects to develop a greater synthesis between their current computational design processes and materials with natural variability such as bamboo. The ZCB Pavilion in Hong Kong is one such example which pushes the boundaries of the design solution space of bamboo architecture [19]. Computational design tools allow the architect to visualise ideas and they can be modified and analysed interactively, though this modification can still be time-consuming. Parametric software allows us to build on this process and specify relationships among parameters and instantly output versions or iterations of a design, based on associative rules set by the designer [20]. Willis and Woodward in 2005 suggest it will be impossible to achieve a direct correlation between digital data and a constructed building. Some design parameters like material flaws, grain directions and inconsistent densities will be difficult to anticipate in modelling software. However, this gap between the building and the model will continue to narrow [21]. The following is a case study which demonstrates the use of an algorithm to generate a design for a small dwelling with a hyperbolic paraboloid roof to be built of full-culm bamboo [22]. This is a roof form which follows a convex curve about one axis and a concave curve about the other. It is practical, easily constructed from straight sections, and draws rainwater which falls on this roof, towards the two lowest points, without the additional expense of guttering (Fig. 2). This algorithm embeds certain design principles of building with full-culm bamboo, which will increase the durability, material efficiency and buildability of this roof.

2 The Tools

In this process, two pieces of software well known to the architectural profession have been used, and emblematic of a set of tools which use a visual language environment. Rhinoceros 3D [23] is a three-dimensional computer graphics and computer-aided design software which uses non-uniform rational basis splines (NURBS) to build

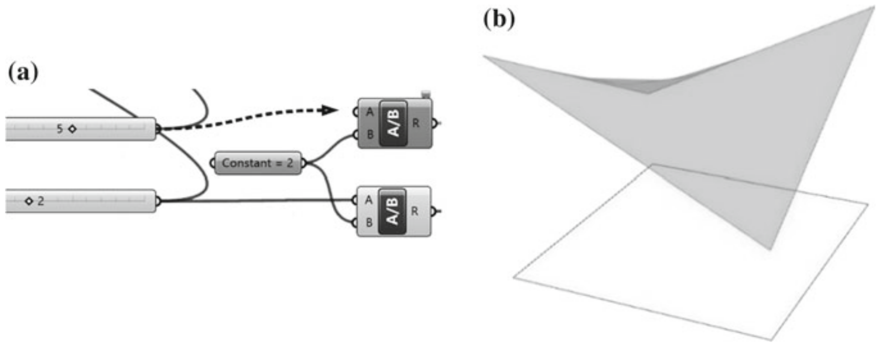


Fig. 3 **a** Example of nodes, inputs and outputs on the Grasshopper graphical algorithm editing canvas; **b** a screenshot of the Rhinoceros 3D interface showing the polygonal outline which defines the area for the surface to cover, and the hyperbolic paraboloid

geometry as opposed to a polygon mesh-based system. The second is Grasshopper [24] which is a visual programming environment which runs within the Rhinoceros 3D platform. The main interface for algorithm design in Grasshopper is the node-based editor. Algorithms are scripted by dragging components with inputs and outputs onto a canvas (Fig. 3a). A collection of components forms an algorithm, and the output of these commands is displayed in the Rhinoceros 3D window. The initial input geometry can either be assigned from Rhinoceros 3D or generated in Grasshopper. For this case study, a planar quadrilateral has been drawn in Rhinoceros 3D and assigned as the starting geometry of the algorithm in Grasshopper, though this does not have to be planar accepting the possibility of a sloping site. This algorithm will then generate a hyperbolic paraboloid above this quadrilateral, to heights defined by the user. The algorithm can respond to any quadrilateral site option to accommodate the variability of sites. Characteristics of bamboo are considered in the algorithm to improve the durability of bamboo and provide a practical means of constructing a hyperbolic paraboloid as a roof using full-culm bamboo.

3 Negating the Natural Variability of Bamboo

Bamboo has natural variability which means that there are certain characteristics of full-culm bamboo which are indeterminate. Two rational assumptions have been made in the algorithm to negate effects of variability:

- **The curvature of a bamboo culm**: The bamboo culm is modelled as a straight line, or a cylinder, as the bamboo culm for use in construction will be selected to have a very negligible curvature. It is advised that any bamboo poles selected for construction purposes will have 1% out-of-straightness limit [25].
- **The tapering diameter of a bamboo culm**: The diameter of the bamboo culm input into the algorithm is a single value across the algorithm and therefore the

design. In reality, a bamboo culm will have a diameter greater at the base than the top. This is not taken into account in this algorithm as depending on the species or specific plant the tapering can vary in extremity. When selecting the bamboo culm to be used, it is for the architect to select the culm which tapers minimally. Additionally, it is the middle section of the bamboo culm which should be used for this application. The use of the middle section will reduce the maximum and minimum diameter of the poles [26] and a decision has been made to discount this in the algorithm.

The quadrilateral building footprint is drawn in Rhinoceros 3D as a '*Closed polyline*'. It is not required to be planar which accounts for the possibility that the site may not be flat. This can reference a physical site or an isolated pre-determined quadrilateral shape defined by the needs of the brief which will consider the necessary occupancy of the building. The algorithm will generate a hyperbolic paraboloid from this initial building footprint. The algorithm for generating the hyperbolic paraboloid will extract the nodes at each corner of the quadrilateral, move the nodes vertically (Z-axis) to a point defined by the user which corresponds to the intended peak and eave heights of the roof and finally the '*Surface from 4 points*' component generates a hyperbolic paraboloid (Fig. 3b).

The roof will be constructed from straight bamboo poles with a series of longitudinal (u) poles and a series of latitudinal (v) poles placed above (Fig. 5). Within the algorithm, a new hyperbolic paraboloid is created from the generated surface by using the '*Offset Surface*' component. The distance of this offset is input into the algorithm by the user and is the diameter of the bamboo poles to be used in construction (d). Now there are two surfaces, a lower and an upper surface. Longitudinal members (u) are extracted from the lower surface and latitudinal members (v) are extracted from the upper surface (Fig. 4a). The offset of the roof is connected to the diameter of the bamboo (d) to be used. This will save a lot of time for the designer as this algorithm will adapt the design if alternative bamboo species, alternative sites or new suppliers of bamboo are required.

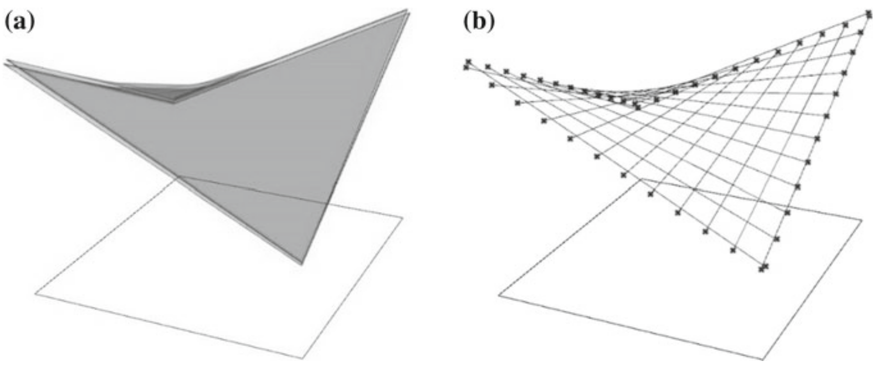


Fig. 4 **a** Two surfaces, with the upper surface offset from the lower surface, with required edge curves highlighted; **b** the 600 mm grid, with chosen node locations represented as points

4 Designing for Durability and Buildability

The distance between each pole (k) in the roof grid is again set by the user which can be determined by factors such as standardised widths of cladding materials or building codes of the region. In this example, (k) is set at 600 mm. The lengths of the opposite outer edges of both the longitudinal (u) and latitudinal (v) directions are measured. The longer of these two lengths is then divided by this user input distance (k). This will give the quantity of poles required to span the roof. The poles can then be arrayed between the first and last poles with the '*Tween Curve*' component (Fig. 4b). This ensures that the distance between the poles in the roof grid will always be less than or equal to this value (k), even if the quadrilateral plan is not orthogonal. The algorithm can instantly update the design if the grid spacing needs to be altered.

The first and last poles of each series must align in plan with an edge of the quadrilateral building footprint, so these poles can be attached to the top of the walls, beams or columns. When attaching the bamboo poles, it is important to use bolts for joints [27]. Each longitudinal (u) pole used in the roof structure will be bolted to the latitudinal (v) poles placed above. The first and last bolts in each pole which connect to a beam, or top of a wall, will need to respect the position of the nodes and be bolted on the internal side of a node (Fig. 5). It is important to place the connection in a bamboo structure in such a way that a connection is made either at a node or as near to a node as possible [11]. The algorithm projects a point on each longitudinal (u) and latitudinal (v) line in the roof grid which represents the pole, aligned with the edge of the quadrilateral footprint. The algorithm then translates this point outwards at either end of the line by a numeric value set by the user (Fig. 4b). This distance represents the desired position of the node relative to the desired bolt location. This should be roughly 2.5–5 cm. Each longitudinal (u) and latitudinal (v) member in the roof now has two points at either end of the line representing the first and last node placements. A measurement can be taken in the algorithm. This will tell the user the required distance between the first and last nodes which will be useful information when selecting the specific poles to use for each roof member.

The hyperbolic paraboloid covers the plan of the initial outline (Fig. 3b). A major issue for durability is that bamboo must be kept out of sunlight, and excess moisture and rain must be avoided [28]. The roof has an important role to play in protecting the bamboo used in the structure from driving rain and a large roof overhang is often

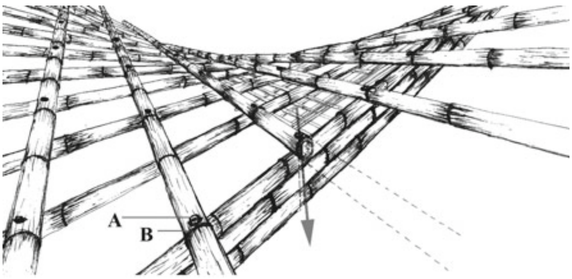


Fig. 5 Locations of bolt connections (**A**) to the beam, adjacent to a node (**B**) on the internal side

required to shelter the walls and structure. The algorithm is designed to extend each line in the roof grid, by a length which is the height above the ground plane of the roof at that location, divided by a constant value (*c*) (Fig. 6). The constant value (*c*) defines this proportion. This is a balance between the maximum angle of the driving rain and the likely exposure the overhang will have to tropical cyclones for that site, following input from a structural engineer.

Once the lines representing the roof members have been extended (Fig. 7a), the lengths of each pole can be measured (Fig. 8). This gives the user the ability to review this information against the material availability and logistical practicalities. Using

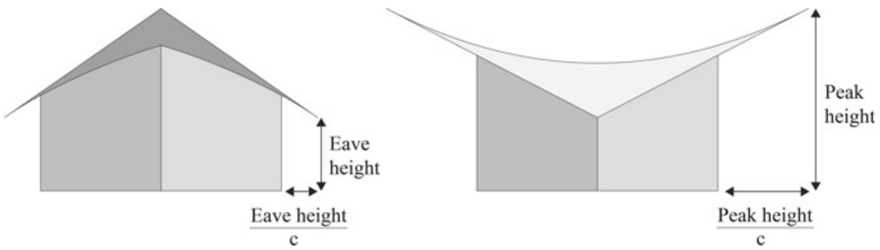


Fig. 6 The relationship between the peak and eave heights, and the roof overhang

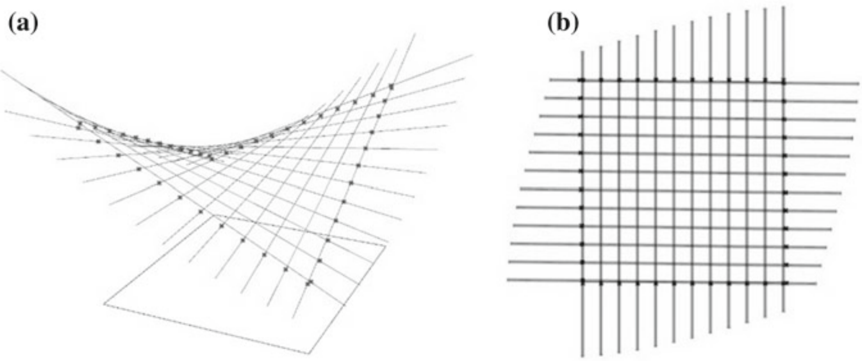
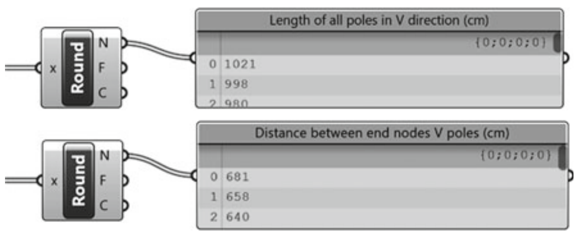


Fig. 7 The model of the roof grid: **a** as lines in perspective view; **b** as 3D volumes to represent the pole diameter in plan

Fig. 8 Grasshopper algorithm screenshot showing: lengths in cm of all the poles and lengths between the first and last nodes to be bolted on each member, in the latitudinal (v) direction



the '*Pipe*' component, the line which has represented the pole to this stage in the algorithm will generate a 3D volume which visually represents how the pole will appear (Fig. 7b). The input value of the diameter (d) is linked to the input which as discussed in Sect. 3 is also the value which was used as the offset of the roof grid. Therefore, when the user alters the value of the diameter of bamboo (d) to be used, the offset of the latitudinal (v) members will also raise simultaneously.

The output from the algorithm includes the following:

- The quantity of poles required to generate the surface.
- The lengths of bamboo poles, rounded to the nearest cm (Fig. 8). This can assist the designer or builder in determining the availability of bamboo culms, the limits of transportation to site and the cut lengths.
- The required distances between first and last nodes for each pole, which will be useful when selecting poles to be used for specific roof members.
- Visual output of the massing in order to view the form in 3D.
- NURBS geometry output which can be used to produce diagrams, drawings and rapid prototyping.
- Locations of connections where bolts may be placed. These measurements can then be used to mark out the poles prior to construction to prevent having to drill in situ which can be more dangerous to construction teams, than a workshop environment.

5 Discussion

The opportunities that processes such as these provide, allow architects to interact more closely between their computational design tools and materials with natural variability such as bamboo. However, there will always be a gap between digital and real-world environments [21]. The challenges of these tools and this process are seen in the negation of properties of bamboo. Characteristics such as the tapering of the diameter and natural curvature of the bamboo culm could have structural and architectural significance which sadly is not taken advantage of through this process. Future developments in this field can find ways to include these as well as the input of the mechanical properties of bamboo within Grasshopper through live physics and parametric structural engineering plug-ins to perform preliminary structural analysis. Overseen by a structural engineer, this can create interactive simulation, form-finding, and can further optimise the design to increase resilience to tropical cyclones. This presents the opportunity to also optimise the quantity of bamboo required for structural performance, and can also enfranchise species of bamboo currently available but unused for construction. This would however require the mechanical testing on these species to gain the input data. Questions then arise into the variability of the structural properties of bamboo even within a species, and how these variabilities are also considered in a computational design process. Given the lack of competence or literacy available in construction industries in developing economies, communicating accuracy on which the aesthetic appeal, long-term durability and structural integrity may depend can be problematic at best. A further challenge of this process is in the translation from design to construction, and therefore such a computational process may need to add robustness or margin of error into the design to compensate.

6 Conclusion

The efficiencies of the process are numerous. The algorithm embraces many quadrilateral plot shapes, and instantly amends the roof design to improve durability, simultaneously updating material lengths and quantities allowing instant evaluation against practical constraints such as material availability and budget. Processes such as these can give architects an ability to improve the durability of bamboo in their designs and save time and money for those who need resilient, sustainable buildings. If we are to succeed in reducing the global population living in non-adequate housing and achieve SDG11 by 2030 to provide access for all to, adequate, safe and affordable housing, then architects will need to more greatly align their current tools, to design with, and be vocal activists for sustainable, locally sourced, natural materials.

Acknowledgements Thank you to Osmond and Christine Naylor, Jane Wynne, Franck Vendryes, Doria Reyes Córdova, Ben Bridgens and Thomas Wortmann who provided insight and expertise, although interpretations, conclusions and any errors in this paper are my own.

References

1. Edelman A, Gedling A, Konovalov E, et al (2014) State of the tropics 2014 report 43:146–149. https://doi.org/10.1177/0011000014564251
2. United Nations (2015) The millennium development goals report 2015
3. UN-Habitat (2015) Issue paper on informal settlements. Habitat III issue Pap 22
4. UN Habitat (2018) Slum Almanac 2015/2016
5. UN-Habitat (2016) Sustainable development goals: goal 11 monitoring framework:56. https://doi.org/10.1016/j.jasms.2004.03.003
6. Harvey C (2018) Cement producers are developing a plan to reduce CO_2 emissions. E&E News, Sci Am:1–13
7. Andrew RM (2017) Global CO_2 emissions from cement production. Earth Syst Sci Data:1–52
8. Torres A, Brandt J, Lear K, Liu J (2017) A looming tragedy of the sand commons. Sci (80-) 357:970–971. https://doi.org/10.1126/science.aao0503
9. Lobovikov M, Paudel S, Piazza M, et al (2007) World bamboo resources: a thematic study prepared in the framework of the global forest resources assessment 2005
10. Van Der Lugt P, Vogtländer JG, Van Der Vegte JH, et al (2014) Environmental assessment of industrial bamboo products—life cycle assessment and carbon sequestration. In: 10th World Bamboo Congress
11. Janssen JJA (1995) Building with Bamboo: a handbook

12. Tardio G, Mickovski SB, Stokes A, Devkota S (2017) Bamboo structures as a resilient erosion control measure. Proc Inst Civ Eng—Forensic Eng 170:72–83. https://doi.org/10.1680/jfoen.16.00033
13. Paraskeva T, Pradhan NPN, Stoura CD, Dimitrakopoulos EG (2019) Monotonic loading testing and characterization of new multi-full-culm bamboo to steel connections. Constr Build Mater 201:473–483. https://doi.org/10.1016/j.conbuildmat.2018.12.198
14. Harries KA, Sharma B, Richard M (2012) Structural use of full culm bamboo: the path to standardization. Int J Archit Eng Constr 1:66–75. https://doi.org/10.7492/ijaec.2012.008
15. INBAR (2003) Proceedings of Bamboo housing workshop. In: International Network for Bamboo and Rattan (INBAR) & Bamboo and Rattan Development Program (BARADEP). WITC, Kumasi Ghana
16. Hardoy JE, Satterthwaite D (1989) Squatter citizen: life in the urban third world. Earthscan Publications, London
17. Seksan N (2017) Seksan design: open source drawings [Internet]. https://www.seksan.com/open-source-drawings
18. Aravena A (2019) Elemental [Internet]. http://www.elementalchile.cl/en/
19. Crolla K (2017) Building indeterminacy modelling—the 'ZCB Bamboo Pavilion' as a case study on nonstandard construction from natural materials. Vis Eng 5. https://doi.org/10.1186/s40327-017-0051-4
20. Jabi W (2012) Parametric design for architecture. Laurence King Publishing, London
21. Willis D, Woodward T (2005) Diminishing difficulty: mass customisation and the digital production of architecture. Harvard Des Mag:71–83
22. Weisstein EW (2019) Doubly ruled surface. In: MathWorld. http://mathworld.wolfram.com/HyperbolicParaboloid.html
23. Robert McNeel & Associates (2019) Rhinoceros 3D
24. Robert McNeel & Associates (2019) Grasshopper
25. Kaminski S, Lawrence A, Trujillo D (2016) Structural use of bamboo Part 1: introduction to bamboo. Struct Eng 94:40–43
26. Minke G (2012) Building with Bamboo. Design and Technology of a Sustainable Architecture. Birkhäuser, Berlin, Basel
27. Hidalgo-López O (1981) Manual de Construccion con Bambu. Estudios Técnicos Colombianos
28. Kaminski S, Lawrence A, Trujillo D, King C (2016) Structural use of bamboo. Part 2: Durability and preservation. Struct Eng 94:38–43

Appendix B: Protection by Generative Design

Conference paper

Published as: Naylor, J. O. (2021). Protection by Generative Design. Towards a New, Configurable Architecture - Proceedings of the 39th International Hybrid Conference on Education and Research in Computer Aided Architectural Design in Europe. V. Stojaković and B. Tepavčević. Novi Sad, Serbia, eCAADe (Education and Research in Computer Aided Architectural Design in Europe). 1: 618.

Protection by Generative Design

Designing for full-culm bamboo durability using sunlight-hours modelling in Ladybug

John Osmond Naylor[1]
[1]University of Newcastle upon Tyne
[1]j.naylor73@newcastle.ac.uk

High yield cultivated construction materials such as bamboo could reduce our overconsumption of concrete and sand. Full-culm bamboo has low natural durability which in construction makes it imperative that the design affords protection from rain and sunlight. This paper presents and advocates a generative design workflow for full-culm bamboo using widely applicable architectural design software. A series of trials were carried out to modify the geometry of a planar truss and gablet roof with input parameters tested to determine the optimal roof surface area which could provide full solar protection at three different sites. This algorithmic process tested both straight and curved poles. Depending on the site, when compared to a symmetrical uniform 45 degree overhang, less or greater roof surface area is required in order to provide full solar protection. The use of curved poles and an asymmetrical truss could maintain full protection yet reduce the roof surface area further.

Keywords: *Full-culm bamboo, Generative design approach, Ladybug, Architectural design, Digital materiality*

INTRODUCTION

By 2050, some 50% of the world's population will live in the tropics (State of the Tropics, 2020). Tropical Low-to Middle-Income Countries (LMIC's) have a shortage of housing which lacks structural quality and durability (UN-Habitat, 2016) yet have a latent opportunity to utilise locally sourced bamboo (Lobovikov, Paudel, Piazza, Ren, & Wu, 2007). Our global construction industry has a decisive role to play in climate-change mitigation with annual cement production accounting for around 8% of anthropogenic carbon dioxide emissions (Lehne & Preston, 2018). Replacing conventional materials with bio-based materials that store carbon can be one solution to help us reduce our overconsumption of concrete and sand (Pomponi, Hart, Arehart, & D'Amico, 2020; UNEP, 2019; van der Lugt, 2017). In many regions of the world, timber will most likely never be able to provide the sustainable alternative we need. Given the speed of growth and quantity required, extraction could have a deleterious effect on ecosystems (Pomponi et al., 2020). Therefore we need to develop the use of high yield cultivated construction materials such as bamboo (van der Lugt, 2017). Bamboo can absorb carbon dioxide and stabilise slopes to tackle the effects of deforestation (Tardio, Mickovski, Stokes, & Devkota, 2017).

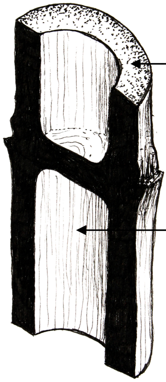


Figure 1
Sketch section and terminology of a bamboo culm through the node. Sketch by author.

It can be a challenge however to incorporate bamboo into contemporary design and construction practices. This is due to the natural variability of bamboo between the over 1200 species of bamboo, individual plants, and individual culms. Within culms there is a non-regular distribution of node locations, a tapered diameter of the bamboo culm, and a reduced width of the culm wall over the length of the culm. Even within the same species, mechanical properties can differ since bamboo grown in drier areas and on slopes may have a higher fibre density and increased strength properties (Liese & Tang, 2015b). One response to this has been to standardise the material through the manufacture of Engineered Bamboo Products (EPBs) (Sharma, Gatoo, Bock, Mulligan, & Ramage, 2015). However, the greater challenge is to use the raw form of bamboo, *full-culm bamboo*. In doing so, we can ensure that the most affordable and sustainable form of bamboo is enfranchised (Harries, Sharma, & Richard, 2012). Another challenge for architects when designing with bamboo, and the focus of this paper, is the low natural durability of bamboo (Kaminski, Lawrence, Trujillo, & King, 2016). Bamboo is more prone to decay than timber. Bamboo does not develop reaction wood, and though there are minor amounts of resins, waxes and tannins, none of these have enough toxicity to provide any natural durability (Kumar, Shukla, Dev, & Dobriyal, 1994). Bamboo is hollow (Figure 1) and with typically thin walls, this means that a small amount of decay can have a significant effect on the bamboo (Janssen, 2000). There are abiotic factors which can affect bamboo in a structure (Liese & Tang, 2015a). If bamboo is exposed to the sun and rain and in contact with soil the lifespan of the bamboo in the structure can be only 1-3 years (Janssen, 2000). Changes in temperature and humidity may produce steep moisture gradients between surface and inner layers, and direct exposure to sun causes unbalanced and repeated swelling and shrinkage (Liese & Tang, 2015a) (Figure 2).

Figure 2
Full-culm bamboo poles cracked and showing signs of mould due to exposure of excess moisture and bleaching due to sunlight exposure. Photograph taken by author in 2020.

UV and visible light radiation also causes photodegradation which breaks down bonds of the lignocellulosic polymer causing the bamboo surface to turn grey and coarse (Liese & Tang, 2015a). Such processes have contributed to a societal attitude of bamboo as a temporary *"poor man's timber"*. When bamboo is exposed or inappropriately applied in a structure and degrades, bamboo will often be blamed for the action of the architect. As Janssen writes, *"No chemical treatment will be good enough to solve the problems caused by incorrect design"*. (Janssen, 2000). This is a rallying call for architects to make sure that fundamental to any design process for bamboo, the bamboo is protected from rain and UV light. This is a concept known as *protection by design*. The title of this paper refers to this phrase. Large roof overhangs provide protection to bamboo members from wind driven rain (Figure 3), with a rule of thumb of 45 degrees (Kaminski, Lawrence, & Trujillo, 2016a). The angle of wind driven rain is largely consistent worldwide, however the sun angle is not.

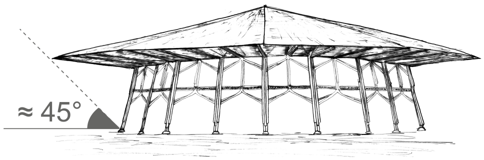


Figure 3
A large roof overhang provides protection to the structural full-culm bamboo members. ZERI Pavilion, Simon Velez, 1999. Sketch by author based on the ZERI Pavilion image from the book, Grow your own house: Simón Vélez and bamboo architecture (Vélez et al., 2000).

In some locations and orientations the overhang of 45 degrees will always be required to protect against wind driven rain but this may not provide enough solar protection particularly if a site is further away from the equator. A design decision can be to cover the bamboo behind adobe or cement mortar such as bahareque construction techniques (Kaminski, Lawrence, et al., 2016a). However for cost, aesthetic or biophilic reasons the designer may decide to make the full-culm bamboo visible. There are impressive examples of buildings with structural full-culm bamboo visible externally such as the Amairis Factory in Puerto Caldas, Colombia, by Ruta 4 [4], or the ZERI Pavilion, by Simon Velez in Manizales, Colombia (Figure 3). Conversely, where rainfall is low and characteristic of a dry steppe climate or subtropical ridges, this overhang can be surplus to needs. Large overhangs can also reduce the occupiable footprint of a building if the necessary extension of the roof requires an encroachment into a neighbouring site. Large overhangs can also be aesthetically cumbersome and also prone to wind uplift. Whenever bamboo is exposed, the design should afford the bamboo protection to maintain its structural and aesthetic properties.

Computational design processes and full-culm bamboo

Generative Design refers to a design approach that uses algorithms to generate designs (Caetano, Santos, & Leitão, 2020). Such processes save time and allow the testing of various iterations in order to find a more optimal design solution (Jabi, 2013). The process of *form-finding* emerges from analysis with the output exclusively determined by function (Laiserin, 2008). In the case of this paper, generative design tools applied to the architectural design process are designed to deliver an optimal design output which provides full protection from sun and rain with minimal material usage and minimal cost on a site by site basis. A wider challenge of computational design tools with their great accuracies and full-culm bamboo is the difficulty in accurately modelling an anisotropic material with natural variability (Crolla, 2017; Qi et al., 2021). In 2005, Willis and Woodward suggested design parameters such as material flaws, grain directions and inconsistent densities will make it difficult to achieve a direct correlation between digital data and a constructed building, but note this gap between the building and the model will continue to narrow (Willis & Woodward, 2005). Far from trying to bridge this gap, mainstream architectural design practice operates on *"reduced matter-models designed to behave like pristine, controlled numerical milieu"* (Kwinter, 1996, p. 70). Using a generative design approach to design with full-culm bamboo is situated in a wider discourse within architectural design crystalised by two terms. *Digital materiality* as coined by Fabio Gramazio and Matthias Kohler (Gramazio & Kohler, 2008), and *digital materiallurgy* coined by Adam Fure in 2011 (Fure, 2011). Kohler and Gramazio use the term *digital materiality* to suggest a departure from the design of purely form, but a design that is informed by the constructive organisations and methods of implementation (Willmann, Gramazio, Kohler, & Langenberg, 2013). Instead of realising a design or an image, a comprehensive design and building process is conceived. Constructive principles can be determined that define the production of architectural components as interrelated production steps (Willmann et al., 2013). *Digital materiallurgy* (a play on the ancient craft of metallurgy) builds on this and suggests to intentionally cede limited design control to the material's innate ability to produce and to take advantage of unexpected formal and material complexity (Fure, 2011). Such an attitude can be the pivot point around which we use computational tools with materials with natural variability, where contrary to materials waiting to be formed a *"productive slack between materials and digital form"* emerges (Fure, 2011). Examples of these two terms in use can be seen in the ongoing movement to incorporate bamboo into a design process which utilises computational design tools. This happens on a spectrum of scales from mapping the pole, to looking to model the variable nature of bamboo as part of the building system. Before I highlight some examples and in order to better situate the design process I detail in this paper, I have listed what I believe to be two ways in which bamboo is used in a computational design process (Figure 4). The first is where an inventory of pre-selected bamboo is mapped in order to establish parameters for the design, and the second is where an algorithm determines the specification of bamboo required. In other words a specification as an input (Type 1), or a specification as an output (Type 2). I have split Type 1 into A and B, where B looks to compensate for the variability of bamboo by designing additive components.

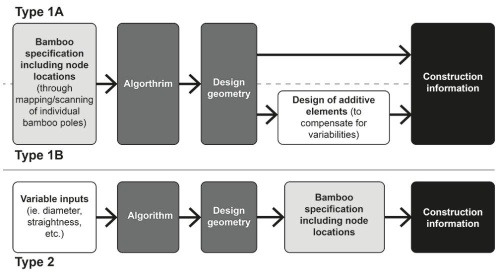


Figure 4
Conceptual representation of a categorisation of how computational design processes address the natural variability of full-culm bamboo in the design process.

An example of Type 1A is the paper *BIM Bamboo*. Here the conceptual details of a framework are presented which use digital modelling and robotic fabrication to enfranchise bamboo poles by mapping them locally (each individual pole) and designing for each distinct characteristic, as opposed to negating the natural variability (Lorenzo, Lee, Oliva-Salinas, & Ontiveros-Hernandez, 2017). An example of Type 1B is the paper *Working with Uncertainties: An Adaptive Fabrication Workflow for Bamboo Structures* which uses vision augmentation research to respond to the deviations between bamboo as built- and designed form in real-time so as to compensate for cumulative deviations caused by material uncertainties (Qi et al., 2021). An example of looking to implement global variabilities of bamboo into a design process, Type 2, is the ZCB Pavilion by the Chinese University of Hong Kong built in October 2015 in Kowloon Bay, Hong Kong (Crolla, 2017). This was an event space for the Zero Carbon Building (ZCB) with a forty-yard span (Crolla, 2018). A physical scale model built from bamboo was brought into Rhinoceros 3D and Grasshopper using the Kangaroo plug in. Bending forces present in the physical model were abstracted into vector forces and applied on a discretised curve network. The digital setup would find its force equilibrium in comparable emerging geometries (Crolla, 2017). Unlike those processes I classify as Type 1, the ZCB Pavilion workflow produced a digital emulation model which embodied variability, not an accurate model of individually digitised culms with their local variances that would be replicated. Using the gablet roof type as the basis of this study, the goal of this paper is to advocate both awareness for protection by design for bamboo structures and demonstrate the applicability and efficiencies of computational design tools when working with bamboo. This paper is not about mapping the eccentricities of bamboo in order to organise their role in a building system. The design process in this paper is situated between Type 1 and 2. The algorithm builds immaterial geometry as a representative roof form in order to test the shading performance against cylindrical geometry which represents the bamboo poles which would be visible externally. This model can be used as both a quantification tool to suggest the curvature of the bamboo that should be used, but the model also allows the input of material parameters. These inputs attempt to standardise pole parameters through allowing the ability to adapt to curvatures and pole diameters in a global manner. The question of building future tolerances into the construction information would occur after the steps identified in Figure 4.

Tools

The software used in this study are widely used in the architecture profession. Firstly Rhinoceros 3D (Version 7) which is a three-dimensional computer graphics and computer-aided design software [2]. Secondly, Grasshopper [1] which is a graphical algorithm editor integrated with Rhinoceros 3D. Grasshopper is used to build generative algorithms. Ladybug [3] is an open source environmental plugin for Grasshopper. Ladybug allows the designer to explore the direct relationship between site specific environmental data through the importation of standard EnergyPlus Weather (EPW) files, and the generation of graphical data outputs which can also act as inputs into the geometry building process (Sadeghipour Roudsari & Pak, 2013). Galapagos is an evolutionary solver embedded within Grasshopper. It is a heuristic solver, which are used when there are a large number of variables to consider and an exact solution cannot be found so a best fitness to the problem is sought.

METHODOLOGY

Constructing the roof geometry in the algorithm

This process starts by drawing a closed quadrilateral shape in Rhinoceros which should have sides no larger than 6m and this *'closed curve'* is assigned in Grasshopper. This allows the roof geometry to be built over any quadrilateral site. The first edge of this quadrilateral will define the location of the planar truss and the truss will be constructed perpendicular to the base plane. The design of the planar truss is based on a design in Building with Bamboo, by Gernot Minke (Minke, 2016). This truss is suggested to be no more than a span of 8m. The choice of a planar truss for roof construction has many advantages for buildability. A planar truss can be built flat on the ground then raised and pivoted into place. This provides a safer work environment due to less working at height.

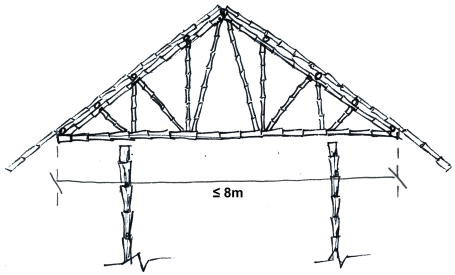


Figure 5
Planar truss spanning up to 8m (Minke, 2016, p. 51). Sketch by author based on truss design referenced from Building with Bamboo by Gernot Minke, 2016.

The truss (Figure 5) is modelled, within the algorithm generating secondary members. Producing the geometry for the individual poles in the truss will allow for drawings to be produced which show bamboo elements to cut with node and bolt locations. This truss defines the transverse section of the roof geometry, where this truss will be replicated and arrayed along the length of the building. The roof type used as the basis of this study (Figure 6), is known in the UK as a Dutch gable roof or gablet roof. For straightforwardness this is the terminology I use in this paper. There are examples of this roof design present in Kerala (Heston, 1996), and Indonesia, known as a Javanese *kampung roof* (Samodra, 2009). A conceptual representation for this process is shown in (Figure 8).

Input parameters

The algorithm which generated the gablet roof geometry was built with a series of variable input parameters (Figure 6): (1) The peak height of the roof truss in meters; (2) The position of the ridge line as a percentage of the width of the building; (3) The height of the gable as a percentage of the height of the roof truss (Input parameter 1); (4) The width of the roof in meters; (5) The depth of the roof overhang in meters which is mirrored on the opposite edge; (6)

The height of the arc segment as a percentage out of straightness which defines the curved rafters; and the additional length of the overhang (each opposite edge can be independently input). (7A) is the extension in meters of the straight rafters in Trial 1, and (7B) is the extension of the arc of the curved rafters used in Trial 2 and 3. Within the input parameter 7A and 7B, minimum values can be set to ensure that the 45 degree guideline roof overhang is maintained, if required. Input parameter 2 allows the truss to become asymmetrical to assist in finding the optimal roof geometry and surface area.

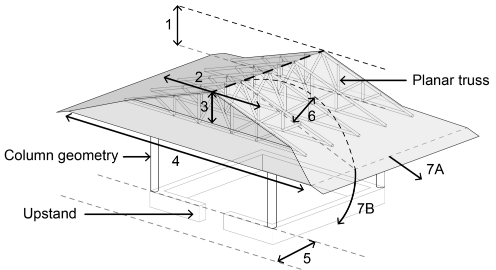


Figure 6
Parameters of the gablet roof design which are input into the algorithm in order to define the gablet roof geometry.

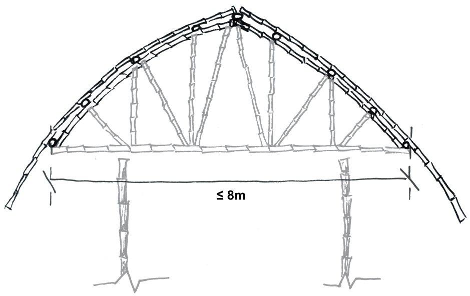


Figure 7
Planar truss design from Figure 5 spanning up to 8m (Minke, 2016, p. 51), with rafters replaced with curved members. Sketch by author, referencing truss design from Building with Bamboo by Gernot Minke, 2016.

Considering the curvature of bamboo culms

Bamboo has a natural arch in growth yet straight poles are often used. This can render the majority of the available bamboo stock an unused latent asset, pushing up the price of available poles and creating an architecture which seeks to find bamboo which fits the design, rather than designing for the natural state of bamboo. The use of curved poles can both perform an aesthetic and performative role. It could be the case that we want to use a species of bamboo which is generally more curved than another. In Trial 1, the algorithm negates any curvature of the bamboo, assuming that the bamboo that would be used in construction would be less than 1% out of straightness (Kaminski, Lawrence, & Trujillo, 2016b). Using curved poles as rafters (Figure 7) is later implemented in the algorithm and in Trial 2 and 3, this is compared to the results of the Trial 1 environmental analysis. Trial 2, generates curved rafters with a 5% out of straightness and Trial 3, connects the input parameters for the rafter curvature to the Evolutionary Solver in order to let the algorithm suggest the optimal curvature of rafters we should use in order to reduce the surface area of the roof.

Selected climates and optimisation methodology

In order to run the solar hours study in Grasshopper we need a series of input geometry and components which are provided in Grasshopper through the Ladybug plug-in (Ladybug Tools LLC, 2020). The geometry to be exposed to the solar study (the bamboo columns), the geometry which will provide the shade, known as the *Context* (the roof), and the locations of the Sun we wish to test which are available through the Ladybug component *'Ladybug_-SunPath'*. This generates a 3D sun path in the Rhinoceros 3D window and with the sun path oriented east to west as default. In all tests in this study the building is positioned north/south, however this can be easily changed by rotating the sun path as necessary. A file path container and the *'ImportEPW'* component is used to link this algorithm to an EPW file. Three sites were chosen to reflect a variety of geographies in which bamboo could be locally sourced and utilised. These were Kunming, China, which is north of the tropics, Bengaluru, India, situated between the Tropic of Cancer and the Equator, and La Libertad, Ecuador, which will be exposed to equatorial sunlight but is characterised by a local steppe climate with little rainfall throughout the year and proximity to local bamboo resources. For Kunming and Bengaluru, the 45 degree guideline roof overhang is set as a minimum value in input 7 given the protection required for rainfall and the script looks to validate or add to this in order to provide full protection from UV light. In La Libertad, given the steppe climate and lack of rainfall, the goal here is to optimise and potentially reduce the roof overhang therefore there is no minimum value set for input 7. EPW weather files were used for each of these three locations. Hourly sun locations for each of these sites were taken from 10:00 to 16:00 for each solstice (21st June and 21st December), which is when the sun would be at extreme angles. This information as well as the input geometries were input into the *'SunlightHoursAnalysis'* component which ran the calculation and output the combined hours of sunlight for both periods and dates.

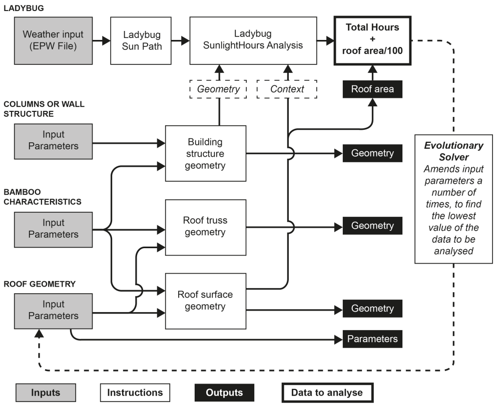


Figure 8
Conceptual representation of the generative design process in this paper, based on Laiserin (2008) and (Tedeschi, 2014).

The optimisation methodology involved the Galapagos evolutionary solver running for 100 steps, with 50 iterations per step, with an additional 50 iterations in the first step. Therefore 5,050 total iterations. The objective function is the minimum value for: one hundredth the value for the roof area plus the hours of direct sunlight on the bamboo poles. The set of variables which define the gablet roof geometry and the objective function are each defined by a range, a start and an end value. The variable sliders which were input as part of the *'genome'* to find this objective function differed in each of the 3 trials. These are referenced individually for each of the three trials in this study.

Baseline geometry: Roof with 45 degree overhang. As a baseline roof geometry to compare the studies to, a gablet roof is modelled which maintains a uniform overhang on all sides of the building of 45 degrees.

Trial 1: Optimised roof using straight poles. For Trial 1, all members in the truss and roof rafters are straight. In this trial, input parameter 6 and 7B (Figure 6) are not used.

Trial 2: Optimised roof with percentage straightness as an input. The goal of Trial 2 and Trial 3 is to compare a roof design with curved rafters to the roof design with straight poles in Trial 1. In Trial 2 the user can input the % out of straightness value that is required. This can be determined from the available material. In this case 5% has been used.

Trial 3: Optimised roof with percentage straightness as an output. It could be the case that we want to find the optimal roof area prior to selecting the bamboo poles we will use in construction. Therefore in Trial 3, the inputs which define the straightness of the bamboo poles used as rafters were input into the Evolutionary Solver to find the most optimal curvature of pole to use.

RESULTS AND ANALYSIS

The resultant geometry is shown in Figure 9 and the resultant values are shown in Table 1. It is interesting to note that in Kunming where the uniform 45 degree overhang was tested, there were still parts of the columns that received hours of direct solar exposure. In order to provide full shade in Kunming, the roof was required to be larger than the uniform baseline roof geometry. In Bengaluru the algorithm validated the required 45 degree overhang as providing enough solar protection. In La Libertad, where the dry climate meant we could overlook the 45 degree guideline roof overhang, the roof was found to

Roof type	Location (EPW file used)	% out of straightness of rafters (%) (Input 6)		Truss height (m) (Input 1)	Roof surface area (sqm)	Change in roof area compared to baseline roof area (sqm)	Max. daily hours of solar exposure to full-culm bamboo columns (hours)
		West	East				
Baseline – Uniform 45 degree roof overhang	Kunming	N/A		1m	114.14	N/A	< 6
	Bengaluru	N/A		1m	114.14	N/A	0
	La Libertad*	N/A		1m	114.14	N/A	0
Trial 1 - Straight rafters	Kunming	N/A		1m	141.25	+24%	0
	Bengaluru	N/A		1m	112.80	-1%	0
	La Libertad*	N/A		1m	88.03	-23%	0
Trial 2 - Rafter curvature as an input	Kunming	5		1m	141.91	+24%	0
	Bengaluru	5		1m	112.88	-1%	0
	La Libertad*	5		1m	89.12	-22%	0
Trial 3 - Optimal rafter curvature as an output	Kunming	1	4	1m	141.60	+24%	0
	Bengaluru	1	2	1m	111.69	-2%	0
	La Libertad*	2	1	1m	87.49	-23%	0

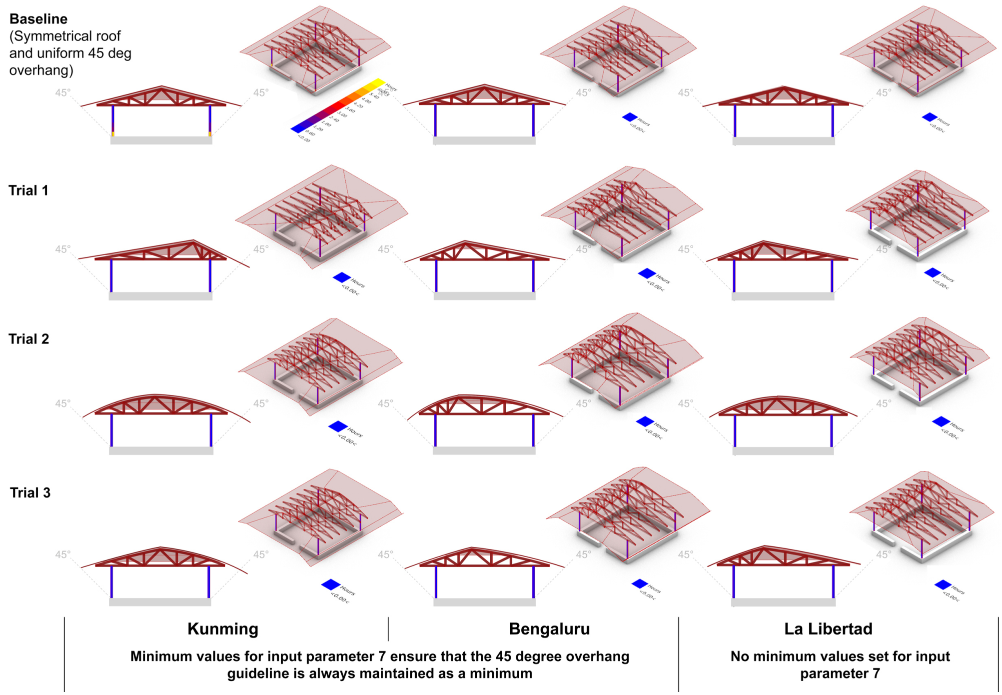
Table 1
Baseline roof information and results of all trials. For clarity, the values of input parameters 2, 3, 4, 5 and 7, as referenced in Figure 6, are not shown. (*the 45 degree guideline roof overhang was not applied and there is no minimum value set for input 7).

be significantly less area yet provide full solar protection to the columns. By implementing curved poles into the algorithm this showed in some cases there could be marginal reduction in the roof surface area whilst still ensuring full solar protection. In all cases an asymmetric truss was found to be optimal with the height at the minimum value of 1m. In Trial 3 which looked to find the most optimal curvature of bamboo pole, the optimal curvature was between 1 and 4 out of 100. Given the many inputs, the evolutionary solver may need more than 100 steps for an improved fitness to be found. A next step could be to run the solver by fixing certain values such as the 1m truss height and the curvature of the bamboo poles at 1% to 4% to reduce the possible combinations of inputs in future tests. The roof structure and joinery is also something which needs to be considered and I have not covered it here given the scope of this paper. In this paper a centre line model was used as the basis of the truss, however this can be taken further to ensure the node, bolt and cut locations are all taken into account when placing secondary members. These can be easily added to the algorithm.

CONCLUSION

Architects should be aware of the low natural durability of bamboo and align their design tools more closely for bamboo to ensure durability. This paper demonstrates one such process. Results also showed that using curved poles instead of straight poles can reduce the surface area of the roof and the material quantity required. Contrary to negating the curvature of bamboo, if a design process following a generative design approach can use the curvature of bamboo as an opportunity this can potentially provide cost savings. If this design was more than a bespoke dwelling, and was a mass building programme, scaling this material reduction over many projects could see substantial cost savings. A next step could be to embed rainfall data to decide whether the minimum 45 degree overhang is required or not as part of the algorithm. The performance of bamboo structures and the societal attitude to bamboo can be greatly improved through the design decisions of architects. At least, this is an awareness of the need to protect exposed bamboo from the sun and rain. At best, architects should follow a design process which balances the formal and functional requirements of a design with the material considerations of using high yield

Figure 9
Screenshot front elevations and axonometric views of output geometry visualisation from Rhinoceros interface, following the Sunlight Hours Analysis in Grasshopper and Ladybug.



cultivated materials such as bamboo. We need to align our tools and processes to consider materials which will provide ecological restoration, particularly in tropical LMIC's in which bamboo is available. If this happens we can see a construction industry as one of the biggest catalysts to improved ecosystems and climate change, instead of the present reverse condition.

REFERENCES

Caetano, I, Santos, L and Leitão, A 2020, 'Computational design in architecture: Defining parametric, generative, and algorithmic design', *Frontiers of Architectural Research*, 9(2), pp. 287-300

Crolla, K 2017, 'Building indeterminacy modelling – the 'ZCB Bamboo Pavilion' as a case study on nonstandard construction from natural materials', *Visualization in Engineering*, 5(1), pp. 1-12

Crolla, K 2018, 'Bending Bamboo Rules: Beyond Century-Old Typologies', *Journal of Architectural Education*, 72(1), pp. 135-145

Fure, A 2011 'Digital Materiallurgy: On the productive force of deep codes and vital matter', *ACADIA 2011*, University of Calgary, pp. 90-97

Gramazio, F and Kohler, M 2008, *Digital materiality in architecture*, Lars Muller / Springer distributor, Baden / London

Harries, K, Sharma, S and Richard, M 2012, 'Structural Use of Full Culm Bamboo: The Path to Standardization', *International Journal of Architecture, Engineering and Construction*, 1(2), pp. 66-75

Heston, M B 1996, 'The Nexus of Divine and Earthly Rule: Padmanābhapuram Palace and Traditions of Architecture and Kingship in South Asia', *Ars Orientalis*, 26, pp. 81-106

Jabi, W 2013, *Parametric design for architecture*, Laurence King Publishing, London

Janssen, JJA 2000, *Designing and Building with Bamboo*, INBAR
Kaminski, S, Lawrence, A and Trujillo, D 2016a, *Engineered Bahareque Technical Report*, INBAR
Kaminski, S, Lawrence, A and Trujillo, D 2016b, 'Structural use of bamboo: Part 1: Introduction to bamboo', *The Structural Engineer*, 94(8), pp. 40-43
Kaminski, S, Lawrence, A, Trujillo, D and King, C 2016, 'Structural use of bamboo: Part 2: Durability and preservation', *The Structural Engineer*, 94(10), pp. 38-43
Kumar, S, Shukla, KS, Dev, T and Dobriyal, PB 1994, *Bamboo preservation techniques: A review*, INBAR
Kwinter, S 1996, 'Flying the bullet, or when did the future begin?', in Kwinter, S (eds) 1996, *Rem Koolhaas: Conversations with students*, Rice University, Princeton Architectural Press, pp. 67-94
Laiserin, J 2008 'Digital Environments for Early Design: Form-Making versus Form-Finding', *First International Conference on Critical Digital: What Matters(s)?*, Cambridge, USA, pp. 235-242
Lehne, J and Preston, F 2018, *Making Concrete Change: Innovation in Low-carbon Cement and Concrete*, Chatham House Report: The Royal Institute of International Affairs, London
Liese, W and Tang, TKH 2015a, 'Preservation and Drying of Bamboo', in Akinlabi, ET, Anane-Fenin, K and Akwada, DR (eds) 2015a, *Bamboo: The Multipurpose Plant*, Springer, pp. 257-297
Liese, W and Tang, TKH 2015b, 'Properties of the Bamboo Culm', in Akinlabi, ET, Anane-Fenin, K and Akwada, DR (eds) 2015b, *Bamboo: The Multipurpose Plant*, Springer, pp. 227-256
Lobovikov, M, Paudel, S, Piazza, M, Ren, H and Wu, J 2007, *World bamboo resources - A thematic study prepared in the framework of the Global Forest Resources Assessment 2005*, FAO, Rome
Lorenzo, R, Lee, C, Oliva-Salinas, JG and Ontiveros-Hernandez, MJ 2017, 'BIM Bamboo: a digital design framework for bamboo culms', *Proceedings of the Institution of Civil Engineers - Structures and Buildings*, 170(4), pp. 295-302
van der Lugt, P 2017, 'Engineered Bamboo Products - A Sustainable Choice?', in Hebel, DE and Heisel, F (eds) 2017, *Cultivated Building Materials: Industrialized Natural Resources for Architecture and Construction*, Birkhäuser, Basel, pp. 86-95
Minke, G 2016, *Building with Bamboo*, Birkhäuser
Pomponi, F, Hart, J, Arehart, JH and D'Amico, B 2020, 'Buildings as a Global Carbon Sink? A Reality Check on Feasibility Limits', *One Earth*, 3(2), pp. 157-161
Qi, Y, Zhong, R, Kaiser, B, Nguyen, L, Wagner, HJ, Verl, A and Menges, A 2021, 'Working with Uncertainties: An Adaptive Fabrication Workflow for Bamboo Structures', in Yuan, PF, Yao, J, Yan, C, Wang, X and Leach, N (eds) 2021, *Proceedings of the 2020 DigitalFUTURES*, Springer Singapore, pp. 265-279
Sadeghipour Roudsari, M and Pak, M 2013 'Ladybug: A parametric environmental plugin for grasshopper to help designers create an environmentally-conscious design', *Proceedings of BS 2013: 13th Conference of the International Building Performance Simulation Association*, pp. 3128-3135
Samodra, FXT 2009, 'Analysis Of Solar Geometry Influences To The Roof Of The Roof Architecture In The Tropical Region', *REGOL - Journal of Architecture and Environment*, 8, pp. 35-48
Sharma, B, Gatoo, A, Bock, M, Mulligan, H and Ramage, M 2015, 'Engineered bamboo: state of the art', *Proceedings of the Institution of Civil Engineers - Construction Materials*, 168(2), pp. 57-67
Tardio, G, Mickovski, SB, Stokes, A and Devkota, S 2017, 'Bamboo structures as a resilient erosion control measure', *Proceedings of the Institution of Civil Engineers - Forensic Engineering*, 170(2), pp. 72-83
Tedeschi, A 2014, *AAD Algorithms-Aided Design: Parametric Strategies using Grasshopper*, Le Penseur
State of the Tropics, Report 2020, *State of the Tropics 2020 Report*, James Cook University, Townsville, Australia
UN-Habitat, Report 2016, *Slum Almanac 2015/2016: Tracking Improvement in the Lives of Slum Dwellers*, UN-Habitat, Nairobi
UNEP, Report 2019, *Sand and Sustainability: Finding new solutions for environmental governance of global sand resources*, UNEP, Geneva, Switzerland
Vélez, S, Vegesack, Av and Kries, M 2000, *Grow your own house: Simón Vélez and bamboo architecture*, Vitra Design Museum, Weil am Rhein, Germany
Willis, D and Woodward, T 2005, 'Diminishing Dificulty: Mass Customization and the Digital Production of Architecture', *Harvard Design Magazine*, 23, pp. 71-83
Willmann, J, Gramazio, F, Kohler, M and Langenberg, S 2013 'Digital by Material', *Rob | Arch 2012*, Vienna, Austria, pp. 12-27
[1] https://www.grasshopper3d.com/
[2] https://www.rhino3d.com/
[3] https://www.ladybug.tools/ladybug.html
[4] https://www.dezeen.com/2020/07/28/amairis-clothing-factory-ruta-4-colombia/

Appendix C: Applying design tools for full-culm bamboo

Conference paper

Published as: Naylor, J. O., et al. (2022). Applying design tools for full-culm bamboo. 18th International Conference on Non-conventional Materials and Technologies (NOCMAT 2022).

International Conference on Non-conventional Materials and Technologies
NOCMAT 2022

APPLYING DESIGN TOOLS FOR FULL-CULM BAMBOO

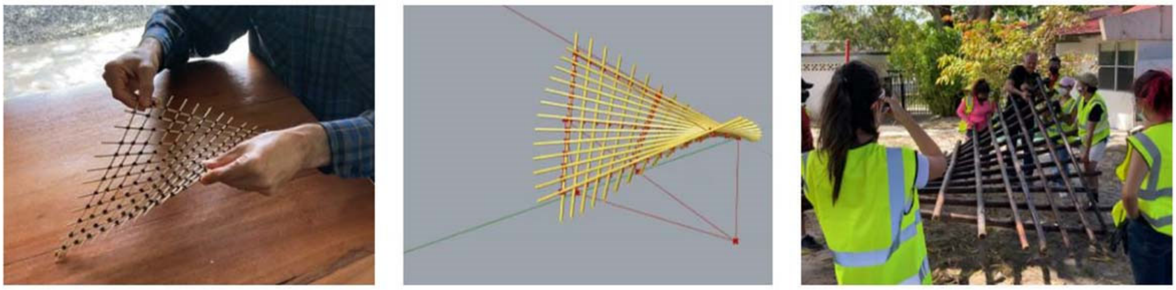
John Osmond Naylor, Architectural Association (AA) School of Architecture, UK, john.naylor@aaschool.ac.uk
Jörg Stamm, Colombia, stammboo@hotmail.com
Munir Vahanvati, Giant Grass, Australia, munir@giantgrass.com

ABSTRACT
Designers use a range of tools to conceive and visualise our built environment. Design for bamboo structures requires an understanding of the material and methods of construction in the initial design stages more so than with standardised man-made materials. This paper discusses and advocates for a mixed media of design tools which includes: concept sketching; physical model-making; computational design, specifically an algorithmic design (AD) approach; and full-scale construction; and discusses the opportunity afforded through the inclusion of an AD approach. Using methods of: self-observation; evaluation; and surveys, this paper reviews the application of this mixed media delivered through participatory action research in Panama in early 2022.

KEYWORDS
Bamboo; architectural design; model-making; design tools; computer aided design; parametric design

INTRODUCTION

Designers use a range of tools to conceive and visualise our built environment (Carpo, 2003; Di Mari & Yoo, 2012; Schilling, 2018). Two dimensional drawings work best for designs using orthogonal shapes but it is difficult to visualise forms that involve complex geometries such as hyperbolic paraboloids and hyperbolic cylinders or organic shapes. It is here another tool, physical model-making, emerges allowing one to explore geometry to find form and design. In recent decades architectural design has seen the emergence of Computer Aided Design (CAD) in the initial design stages (Aish & Bredella, 2017; Wintour, 2018), which in some cases has replaced established tools of design (Fakhry et al., 2021). As Sheil (2008) writes about contemporary practice, "*how we design has become as important as what we design*" (p. 7). This is no more than true than design for full-culm bamboo structures, a latent sustainable alternative to many man-made 'conventional' materials (Harries et al., 2012; Lou et al., 2010; UNEP, 2019), but one which requires a greater understanding of the material performance and methods of construction in the initial design stages. Therefore a greater variety of design tools should be employed to achieve wider application. This paper discusses four tools designers should use to conceive architectural design: concept sketching; physical model-making; computational design, specifically an algorithmic design (AD) approach (Burger, 2012); and full scale construction. This paper reviews literature on these tools in the design process and then reviews their synthesis through participatory action research, in a design curriculum for bamboo. This curriculum was delivered in a workshop given in early 2022 through a series of design and construction activities which took place in Panama City, Panama and the Mamoní Valley Preserve, Panama with 25 participants taking place in-person or online. AD exercises used Rhinoceros 3D (Rhino) CAD (Robert McNeel & Associates, 2020b) and Grasshopper (Robert McNeel & Associates, 2020a) algorithmic modelling software with environmental (Sadeghipour Roudsari & Pak, 2013) and live physics plug-ins (Piker, 2013). The authors both taught at or participated in these activities. This paper reviews these activities with reflections from the authors and discusses the implications of such mixed media on the process of designing with bamboo, a non-standard material with natural variabilities. The impact of these activities on students is assessed and discussed through qualitative surveys and the dialogue between participant and educators outlined in this paper deepens meaning and relevance, and suggests opportunity in utilising these tools in architecture practice and education. The authors believe such multiple perspectives of models (physical and digital), drawings and construction is crucial to better develop awareness about bamboo in architects in bamboo growing regions.



a) Physical model **b) Algorithmic model** **c) Physical construction**

Figure 1: Mixed media used for design exploration of the hyperbolic paraboloid form for bamboo.

DESIGN PROCESSES

Concept sketches and physical modelling

Traditional forms of architectural representation include architectural drawings and architectural models. This can vary from quick concept design sketches and blue foam models to detailed drawings and models. As Schilling (2018) defines sketching, "*Spontaneously an idea is given expression on paper"* (p. 31). Two dimensional drawings work best for designs using orthogonal shapes but it is difficult to visualise forms that involve complex geometries such as hyperbolic paraboloids and hyperbolic cylinders or organic shapes. Here another tool, physical model-making, emerges. This allows one to explore geometry to find form and design. As the role of the architect became one of the thinker and designer, and not builder, the Italian Renaissance saw the emergence of this medium, to visualise the master builder's idea in three dimensions (Schilling, 2018). Concept sketching is often the first in this sequence of tools because lines are easier to construct on paper than physical 3D forms. However, with complex geometries, conceiving this through the medium of bamboo stick models (Figure 1a), the model can begin to be used as an efficient sketching technique to easily visualise and explore various possibilities. The modelling medium of bamboo skewers and elastic bands suggests form but also structure, and construction. Models are tools for design, representation is a simultaneous by-product. This application of models in the design process is exemplified by designers such as Antoni Gaudí and Frei Otto. Their models were used to explore new and innovative designs which facilitated the exploration of new form but could test the structural stability at the same time. This way of designing through models also produces an architecture which is inherently sustainable, efficient, minimal, and ethical (Otto & Rasch, 1995, p. 13). These models were used to, "*make the invisible measurable and the visible calculable"* (Vrachliotis, 2020).

Physical construction

Aforementioned models teach the designer much about structure and form and they start to tell of material. However, to understand the construction logic and material at the scale of the building requires building at full scale. This provides tactility, the feel of the material and the construction logic. Such a process can be termed *'design and build'*, as defined in Storonov (2018) as, *"the act of physically making what is designed at full scale"* (p. 1). This process can generate intuition in designers of material or construction processes. Full-scale building contacts the ground, it endures gravity. A physical object is produced, one which is at the mercy of a fourth dimension, that of time. This dimension is crucially important to experience the environmental factors which can affect the material. For a material like bamboo with low natural durability, experiencing this performance, along with the variabilities, and the eccentricities first hand is so important. Without a *'Ctrl+Z'*, the act of physically making teaches the importance of craft, care and responsibility (Storonov, 2018).

Algorithmic design (AD)
Until now all the tools described are analogue, and these tools can be inadequate to solve complex design problems (Lin, 2001). Eastman (1975) hypothesises the most obvious advantage of using computers in the architectural design process. They offer the *"ideal representation"* of an architectural design (digital drawings and models) producing *"infinite"* drawings, whilst centralising all design changes (Eastman, 1975, p. 46). Almost half a century later, today, computational design brings simulation and analysis into architectural design. When describing the *"ideal representation"*, Eastman (1975) is describing 3D modelling, or explicit modelling. This is the process by which each geometric object is modelled based on explicit coordinates (Burger, 2012). This can however be time-consuming when each small design change could require the remodelling of the entire model (Jabi, 2013). As (Crolla, 2017) writes, *"The assimilation of naturally variability in digital environments is not possible with conventional tools but would be a requirement if we want to use raw materials that don't undergo extensive industrial standardisation."* (p. 10). Algorithmic design (AD) is another paradigm in the use of computers in architecture (Wintour, 2018). AD is based in mathematical thinking in contrast to the explicit nature of Computer Aided Design (CAD) or Building Information Modelling (BIM) (Castelo-Branco et al., 2022). AD involves coding, *"explicit instructions that initiate computational procedures that generate digital forms"* (Oxman, 2017, p. 10). The advantage of such approaches is that through the manipulation of only a few variables, designers can automatically generate almost infinite possibilities (Brown & Mueller, 2018). Processes such as these are efficient and move us closer to a more optimal design solution (Jabi, 2013). The paradigm of AD provides new tools in the wider challenge to bridge the gap between the great accuracies of 3D modelling softwares and full-culm bamboo, an anisotropic material with natural variability.

The digital tools
Rhinoceros 3D (Version 7) is a three-dimensional computer graphics and computer-aided design software which uses Non-uniform rational basis splines (NURBS), to build geometry as opposed to a polygon mesh-based system (Robert McNeel & Associates, 2020b), and widely used in the architecture profession (Stavric et al., 2013). The second is Grasshopper which is a visual programming environment which runs within the Rhino platform. The main interface for algorithm design in Grasshopper is the node-based editor. Algorithms are scripted by dragging components with inputs and outputs onto a canvas (Robert McNeel & Associates, 2020a). A benefit of Grasshopper is the ability to integrate custom plug-ins (Preisinger, 2013), such as environmental (Sadeghipour Roudsari & Pak, 2013) and live physics engines (Piker, 2013). Ladybug is an open source environmental plugin for Grasshopper. Ladybug allows the designer to explore the direct relationship between site specific environmental data and the generation of graphical data outputs. This can act as inputs into the generation of geometry (Sadeghipour Roudsari & Pak, 2013). Bamboo has low natural durability and is susceptible to photodegradation through UV and visible light radiation (Liese & Tang, 2015). Such an environmental analysis tool provides a key means of ensuring the durability of bamboo in an architectural design (Naylor, 2021). In this process another tool, Galapagos, is used. This is an evolutionary solver embedded within Grasshopper. It is a heuristic solver, which are used when there are a large number of variables to consider and an exact solution cannot be found so a best fitness to the problem is sought. It is employed in order to find a best fitness outcome based on testing a variety of input variables. In the case of Naylor (2021) it is used to find the smallest roof area which will provide complete sun protection to exposed bamboo members. Another plug-in is Kangaroo which is a Live Physics engine for interactive simulation, optimization and form-finding directly within Grasshopper (Piker, 2013). An example of the use of Kangaroo to design with full-culm bamboo is seen in Crolla (2017) where it is used to produce a digital model based on previous physical models which would find its force equilibrium and produce a design geometry. On this project AD tools are crucial to accommodate in the design process, *"the variety of material inaccuracies, tolerances, and indeterminacies faced onsite"* (Crolla, 2017, p. 10). This real world information can be fed back into the design process, effectively AD provides a space for the variability of bamboo and design changes even during construction, through changes to input variables in the digital setup.

A palette of design tools – A mixed media approach

Criticisms are levelled at the mainstream use of digital tools in architectural design. Frascari (2009) observes that hand-drafted drawings are often employed as *"persuasive choreographic notations of architectural thinking"* (p. 205). He notes, that the architectural profession has embraced the use of digital information without a proper critical reflection on the conversion of the tradition of architectural drawings into the digital (Frascari, 2009, p. 205). Kwinter (1996) also critiques mainstream architectural design practice stating it operates on *"reduced matter-models designed to behave like pristine, controlled numerical milieu"* (p. 70). Rahim and Jamelle (2020) observe digital architecture has become *"detached"* from its materiality. They argue that the sophisticated use of these tools will appear in the integration of material, structure, building systems and their associated codes (p. 13). It is therefore clear that the computer as a design tool should not be a replacement for other methods. AD becomes a powerful additional tool to physical modelling, concept sketching and full scale construction. It is the belief of the authors that any design process should utilise all of these. In broader terms, given the speed that we can remodel through an AD approach, we can leave design decisions for later into the project. Scripting models which are representative of the internal design logic, rather than the explicit designed form, provide an opportunity to embrace non-conventional materials such as bamboo, and *"reattach"* materiality to the digital design. At the dawn of the use of computers in architectural design process Tom Maver noted that *"…computers were designed to complement, not replace, man. They were potentially much better than people at appraisal and analysis but people were better at synthesis and evaluation."* (AJ, 1970, p. 472). In other words or as Yi-Luen Do (2005) phrases it, *"right tool-right time"* (p. 396). To take a phrase out of context, Algorithmic design (AD) tools are the right tool and our urgent global challenge to use bio-based construction material presents the right time.

METHODOLOGY AND AIM

To discuss the application of this mixed media approach to design, including AD, the methodology is that of participatory action research carried out through a workshop organised by the Architectural Association School of Architecture (AA) in London, in the spring of 2022. This took place in Panama (an example of a country with great potential for bamboo use) with 25 participants. The authors of this paper are both faculty and participants of this workshop. Along with John Naylor and Jörg Stamm in the authorship team, this workshop was jointly conceived and co-directed by Diego Perez Espitia and Cesar Cheng. This workshop was designed as an introduction to the material and the software, therefore most students had not used Rhino, Grasshopper, or worked with the material of bamboo before (with a list of the software students were accustomed to, discussed later in Figure 5). Similar workshops have been organised by the AA which have looked at AD software and bamboo (Kewei et al., 2022; Naylor et al., 2020). The workshop took place online and in-person. The online workshop gave us the ability to deliver all aspects of the curriculum other than physical construction if participants were unable to attend in person. The beginning of 2022 saw a spike in Covid-19 cases of the Omicron variant so the self-isolation of participants was a real possibility. This 10-day workshop in Panama is evaluated through a mixture of qualitative and quantitative evaluation methods. These include self-observation reflections and quantitative surveys. These methods together contribute to the theoretical explanations discussed in this paper. Robson (2000) describes evaluation as assessing, *"…the worth or value of something."* (p. 3) and this is an essential reference in our reflections. To assess the value of a mixed media of design tools which includes AD. The evaluation in this study covers many aspects of the workshop preparation and the tools used. Using notes, sketches, photographs and recordings of sessions from the workshop, a self-observation was used as the method of reflecting on the experience. This evaluation focuses on the process and outcomes of the workshop and in doing this the methodology of a quantitative survey is also used with both closed and open-ended questions. These surveys were self-administered and anonymous which can help to encourage frankness and honesty (Robson, 2002).

PEDAGOGICAL LEARNINGS

Exploration of structural systems

The workshop used three structural systems as the basis of design explorations. These were a: hyperbolic paraboloid; planar truss and columns; and space frame. For this paper we will focus in more detail on the hyperbolic paraboloid.

Case study exercise – Hyperbolic paraboloid

Physical models

Building a physical model using bamboo skewers and rubber bands is a very easy and quick way to build a hyperbolic paraboloid model. Fixed length bamboo skewers are used to create a grid of 10 x 10 skewers tied at each intersection using thin rubber bands. The rubber bands are important component as it keeps the grid flexible allowing it to deform. Once the grid is tied and ready two diagonal ends of the square are pushed together and raised up, this results in the other two corners being pushed together and pushed down. The skewers slide against each other creating a twisted ruled surface. The final shape depends on the amount of pressure applied. Thin string can be tied around the model to fix the shape, or the skewers can be glued together at the intersections, once a desired shape is achieved. Various physical models were shared around the group and participants were encouraged to play with the shape to explore various possibilities. Once the hyperbolic paraboloid form has been found through the model, by pressing the form flat on a surface, the deformation of the grid is highlighted. The length and width of each section of grid is reduced in those at the centre of the grid. Once the pressure is removed from the form which is forcing this flat on a surface, the model will spring back into the hyperbolic paraboloid form. If more than one hyperbolic paraboloid is placed together it is possible to use this as one element in a larger organisation. This creates further complex forms and the physical model provides a level of tactility that is not possible when sketching or using digital tools.

Figure 2: Students integrating physical models and bamboo construction activities.

Physical construction

The hyperbolic paraboloid was constructed using Bambusa Barbatus, zip-ties, steel bolts, nuts and washers. A grid was constructed flat on the ground with zip-ties fastened at each intersection, similar to the process of the physical model. A number of participants were then tasked with deforming the grid into place raising the two opposite vertices and leaving the other two on the ground but pushing them closer together. Given this was outside this was also an opportunity for wider group work, and peer learning given everyone had the opportunity to stand with the structure and form this into place. Once in place and the form was found, holes were drilled at the strap locations and the hyperbolic paraboloid remained static. Bolts, washers and nuts were inserted at most intersections and tightened. Everyone then had an opportunity to add drill and bolt.

The algorithmic model

The experience of building regularly fed into each software exercise at every opportunity. Participants were encouraged to develop scripts which react to their 1:1 scale construction experience. Foote

(2013) describes the scenario well. Instead of *a sequence of designing then building, "… 'design' and 'build' work in a dialectic rather than as a linear process" (p. 53).* The software was taught through a series of exercises which were documented in the textbook given to students. Each exercise would teach the software as well as design awareness for bamboo. Here we are only focussing on one exercise which is that of the hyperbolic paraboloid. The way the physical model, or the 1:1 scale construction is built, informs the way we build the algorithm thanks to the flexibility of AD tools. Clarity and a clear stating of the performance criteria for the algorithmic model is required. In order to build the algorithm we also need a clear idea what information we want as an output. Will this model be used to explore form? If so, then we may not be as dogmatic in the way we construct the algorithm as this is also an opportunity to explore different algorithmic means of producing the form. Or, do we need specific information as an output? These could be material lengths, material quantities, or bolt locations. How the model will be used affects how we will build the algorithm. Identifying the performance criteria and the outputs then allows us to look at our inputs and identify the variables, constants and constraints. For example are we defining one base point and the bamboo pole lengths and then finding the achievable span of the anticlastic hyperbolic paraboloid surface? Or are we defining the span and maximum corner heights of the hyperbolic paraboloid and therefore the lengths and quantities of the bamboo poles will be calculated in the algorithm? In the case of the case study exercise (Figure 3), the constant was the length of poles to be used. The variable was the positions of the upper points. By moving these points the algorithm would deform the geometry based on the way the physical model would deform. These exercises provide the basis of the learning these tools and the parameters which inform the structural system. Examples of these variations in the algorithmic model include changing pole lengths, changing pole diameters, adding poles to the grid and applying force to the form to watch the model deform. Each of these micro-level changes will update the macro-scale. We are not modelling the form, we are finding the form (Figure 3). The algorithmic model can then be *'Baked'* from Grasshopper into Rhino. *'Baking'* is the process of taking the representation of the geometry from Grasshopper into NURBS geometry in Rhino. With this explicit NURBS model within the Rhino platform, we can produce drawings, export to other platforms, and produce visuals such as renders.

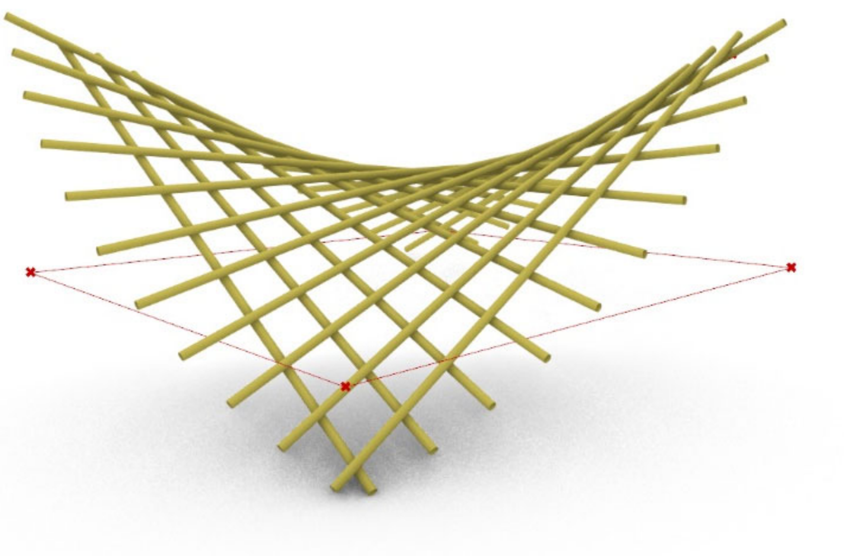


Figure 3: Hyperbolic paraboloid created algorithmically using the Kangaroo plug in for Grasshopper. The user interaction simulates behaviour similar to the physical model.

New possibilities for design and construction with bamboo through AD

The utility of the algorithmic model is increased if the design were to be constructed of more than one hyperbolic paraboloid. AD allows for the design and the construction of complex buildings using bamboo that were once impossible by other design media. An algorithm does not just establish relationships between individual members (poles) in the hyperbolic paraboloid, but can establish the relationship between each hyperbolic paraboloid in a cluster. By embedding the logic of the relationship between a cluster of these forms, it is then possible to see the overall effect of manipulating one hyperbolic paraboloid on the scale of the building (Figure 4). Without AD, to rebuild each individual hyperbolic paraboloid in the cluster and then restitch them together would be time consuming, but it would be almost impossible to visualise and compute the overall form of the multiple hyperbolic paraboloids and make design decisions by any other means. The design and the realisation of such complex buildings would not be possible without the use of AD to adapt and visualise the 3D model in real-time, and obtain and analyse: the 3D data; dimensions; and corner locations. This aspect of form finding on the individual surface then proliferating and observing the effect on several is a unique aspect of AD.

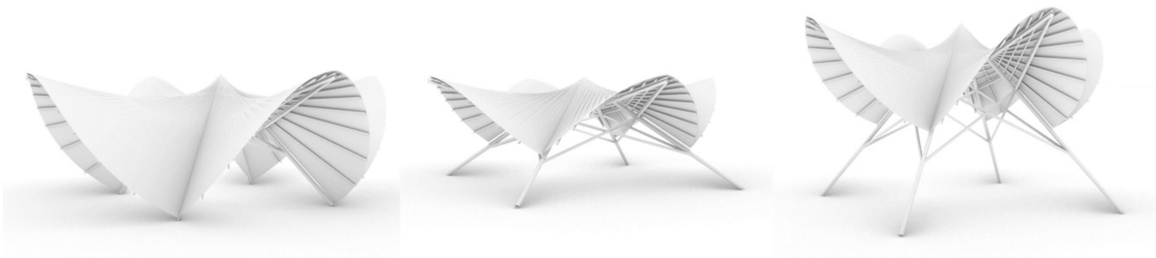


Figure 4: Versions of a design to demonstrate the application of AD to construct and adapt a cluster of hyperbolic paraboloids though the manipulation of the input variables associated with only one hyperbolic paraboloid surface.

The educator experience

Many features of this workshop were influenced by another workshop which runs at the AA directed by one of the co-authors of this paper and Dr Andry Widyowijatnoko and documented in Kewei et al. (2022). The aforementioned workshop was forced to adapt in 2020 and 2021 given the Covid-19 pandemic which meant a focus to online learning and a reduction of peer interaction. Delivering a mixed media approach to designing with bamboo is then a lot more challenging in an online environment as the tactility of the model making and construction are removed and physical group work is impossible. This workshop allowed for a hybrid of these. Course directors produced a textbook prior to the workshop which allowed students to follow step by step instructions for software tutorials and online software tutorials were not recorded. This is crucially important as these sessions are designed to be interactive and private. Any fear in asking questions, or thinking out loud is only made worse if the tutor and participants feel they are being recorded. In order to facilitate this, a maximum tutor to student ratio of 1:10 is required for the software exercises. These software exercises are not just teaching the software but in many cases teaching the material of bamboo. Design decisions which are reflected in the algorithms we build as a class are influenced by the durability or buildability considerations of the material. An example of this was the day when a group built a space frame at 1:1 scale and then modelled the space frame algorithmically later that evening. The construction logic of the space frame became the internal logic of the algorithm. Participants may not know the component in Grasshopper, but they knew what the next step of this process would need to be.

Three didactic considerations when teaching software include: showing the process as a series of steps which is aided by the textbook; showing the outcome at the outset; and showing all representations (name and icon) of each component. A tool which aids the latter is *Bifocals* which is a plug in for Grasshopper. The main tool used for documentation is the platform *Miro* which is an online collaborative whiteboard platform (Miro, 2022) and *Zoom* for online video conferencing. This allowed all in person and online participants to come together. The online format is also something that will no doubt endure beyond the impacts of the Covid-19 pandemic.

The participant experience
One of the co-authors participated in the workshop to learn how to use the digital tools like Rhino and Grasshopper to design structures using bamboo. They had experience in design and building with bamboo so were able to reflect on the use of different design tools and how they influence the design. The online learning environment was suitable for learning digital tools and, although the physical workshop was carried out halfway across the globe, online tools allowed for a global learning environment. The tutorial exercises were well organised and allowed for lots of questions and development. Three different exercises were explored, one of them included building a hyperbolic paraboloid. Further, three different ways of building a hyperbolic paraboloid were also explored including modelling directly in Rhino, scripting in Grasshopper allowing for a parametric design that could be changed and adapted quickly and finally using Grasshopper plugins like Ladybug and Kangaroo to further refine the design. It was surprising easily to get used to working with the software and start scripting in Grasshopper considering there was no previous experience in working with these tools.

Evaluation survey
As part of the evaluation, two self-administered online surveys were issued to participants. The first at the beginning of the workshop activities in January 2022 and then in March 2022. Surveys asked gender, age, and profession, though there was no further information asked which could be used to identify the participants, therefore results were anonymous. Surveys were also used to evaluate the impact of similar architectural design workshops conducted by the AA in Haiti (Naylor et al., 2020). Since the surveys were circulated with our student body, they have already shown an interest in the wider subject matters being evaluated. It is hoped this reduces the issues with external validity. All other questions were single answer multiple choice. Surveys were conducted by an online form in English. Even though some participants did not speak English, the simple nature of the questions we believe allowed for translations and comprehension.

RESULTS

Pre-workshop survey
There was a 68% response rate (17 responses) for the pre-workshop survey.

Existing software use
Responses for software used in both the initial design stages of a project, and for production and outputs are shown in Figure 5.

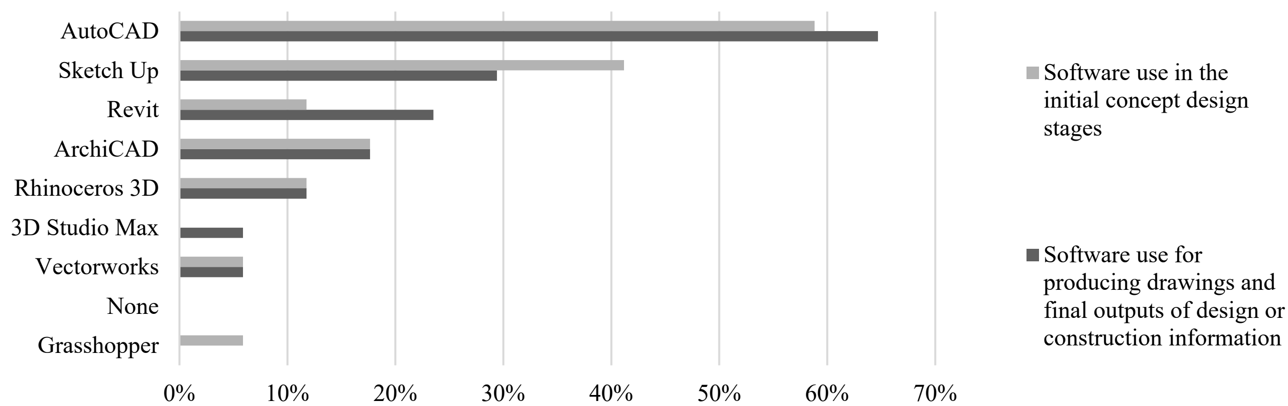


Figure 5: Software use in the initial concept design stages and for final output. (Grasshopper was not available as an option for software use to produce drawings and final output.)

Post-workshop survey
The co-author of this paper who participated in the workshop was not included in the post-workshop survey and another student did not complete the workshop. Therefore there was 23 potential respondents to the post-workshop survey, with 44% (10 respondents) providing a response.

Useful and enjoyable aspects of the workshop in post-workshop survey
Q1 and Q2 in the post-workshop survey also asked students what aspects of the workshop were the most useful to their future needs, and most enjoyable. As shown in Figure 6, 3D modelling software which includes AD tools, scored the highest in both categories.

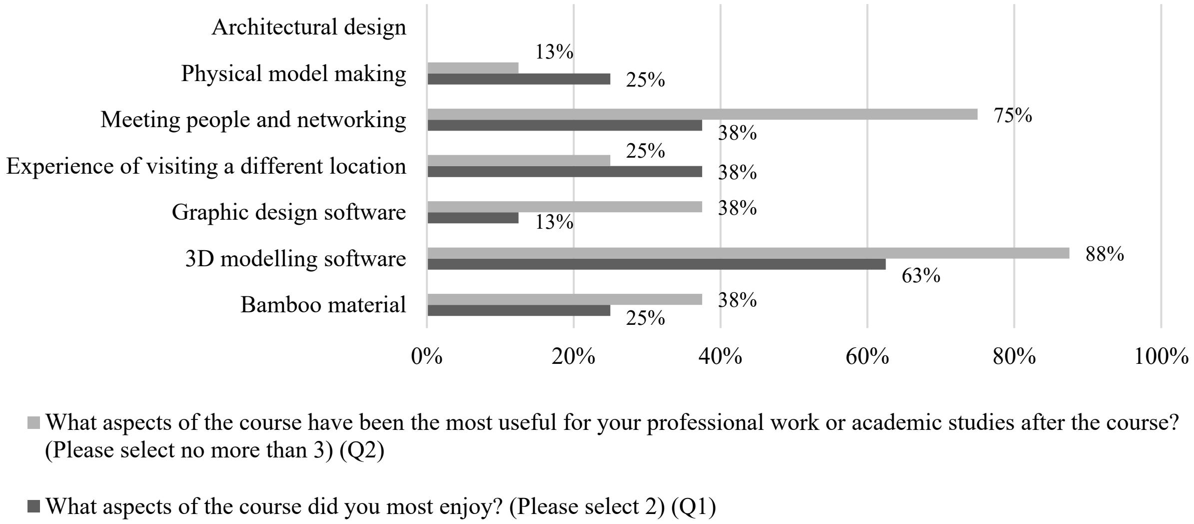


Figure 6: The most useful and most enjoyable aspects of the workshop.

Looking forward: Application of AD tools
A question asked, *"In your own words, can you suggest how the software could be best applied to a design process for full-culm bamboo?"* Comments were as follows. Some have been translated from Spanish to English, with edits only for spelling or grammar:

- *It could focus more in the variability of the material to make it accurate when designing with this natural material.*
- *Explore more the plug-ins and how they can help us to design with bamboo, or how to create different types of structure, not just parabolic or space frame structures.*
- *The software can be used on the process of transcribing the original idea for the project into a more accurate structural process.*
- *Hyperbolic parabola! Following an organic trace.*
- *It allows you to play with the shapes.*
- *Form finding, and ease to model complex forms, and being able also to change them easily.*
- *It would help to change the design in a quick way, with sun orientation facts.*
- *Of course, for all the reasons covered during the course: ensuring durability utilising ladybug plug-in, possibility to measure required material quantity and size, possibility to design for a specific species etc. A smooth process of testing design iterations, time-efficient and science-based decision making.*
- *The best way to design in software is by starting with a sketch and then going digital.*
- *The best way to apply the software is to take it from design to practice in the same course, this way the course would take a greater impact.*

DISCUSSION AND CONCLUSION
This paper firstly outlines the constituent parts of a mixed media design process for full-culm bamboo in architecture. This includes: concept sketching; physical model-making; computational design following an algorithmic design (AD) approach; and full scale prototyping. The paper also posits that the use of AD in the design process presents an opportunity to realise very complex structures, which would be impossible without 3D modelling software and AD software. This is not just in the development of the design, but the construction of such buildings would also be impossible without:

the 3D analysis of each point; the 3D data; the dimensions and corner locations. Therefore it is imperative that such tools are incorporated into the toolset of designers in bamboo growing regions of the world. This paper then reflects on the application of this mixed media approach to design through a participatory action research workshop in Panama in early 2022. The post-workshop survey showed a clear positive response to the role of computers in the design process for bamboo. Results showed both utility and enjoyment from this approach, and showed interesting future directions for the application of these tools to the design process for bamboo. An AD approach does not feature in local architectural education or practice in the respondents. We believe this gap also acts as a barrier to the wider use of bio-based non-conventional materials in local construction. Panama being an example of a country with latent bamboo resource, and a scenario mirrored throughout bamboo growing regions. The workshop in Panama illustrates both the importance of a mixed media design approach, and how the inclusion of AD in a mixed media approach to design for bamboo has the potential to enfranchise new architectural design solutions. This can now incorporate non-conventional materials such as full-culm bamboo to design challenges which until recently would once have been only achievable through the use of standardised materials.

ACKNOWLEDGEMENT
The authors of this paper would like to acknowledge the co-directors of the workshop activities in Panama, Diego Perez Espitia (dpereze@gmail.com) and Cesar Cheng (cheng.cesar@gmail.com) as well as Mia Arias of Taoma Architects, and Erika Schnitter of Isthmus University, although interpretations, conclusions and any errors in this paper are the authors' own. The workshop activities discussed in this paper were partially supported by Isthmus University, Taoma Architects, IMKM Architects, Geoversity, Azulik, Roth Architecture, and the British Embassy in Panama.

CONFLICT OF INTEREST
The authors declare that they have no conflicts of interest associated with the work presented in this paper.

DATA AVAILABILITY
Data on which this paper is based is available from the authors upon reasonable request.

CITATIONS
Aish, R., & Bredella, N. (2017). The evolution of architectural computing: from Building Modelling to Design Computation. *Architectural Research Quarterly*, *21*(1), 65-73. https://doi.org/10.1017/s1359135517000185
AJ. (1970). News: RIBA - Computers and you. *The Architects' Journal (Archive : 1929-2005)*, *151*(8), 472.
Brown, N. C., & Mueller, C. T. (2018). Design variable analysis and generation for performance-based parametric modeling in architecture. *International Journal of Architectural Computing*, *17*(1), 36-52. https://doi.org/10.1177/1478077118799491
Burger, S. M. (2012). Algorithmic Workflows in associative modeling. In M. Scott (Ed.), *Digital Workflows in Architecture: Design - Assembly - Industry* (pp. 132-149). Birkhäuser. https://doi.org/10.1515/9783034612173.132
Carpo, M. (2003). Drawing with Numbers: Geometry and Numeracy in Early Modern Architectural Design. *Journal of the Society of Architectural Historians*, *62*(4), 448-469. https://doi.org/10.2307/3592497
Castelo-Branco, R., Caetano, I., & Leitão, A. (2022). Digital representation methods: The case of algorithmic design. *Frontiers of Architectural Research*, *11*(3), 527-541. https://doi.org/10.1016/j.foar.2021.12.008
Crolla, K. (2017). Building indeterminacy modelling – the 'ZCB Bamboo Pavilion' as a case study on nonstandard construction from natural materials. *Visualization in Engineering*, *5*(1). https://doi.org/10.1186/s40327-017-0051-4
Di Mari, A., & Yoo, N. (2012). *Operative design: A catalogue of spatial verbs*. Amsterdam : BIS.
Eastman, C. (1975). The Use of Computers Instead of Drawings in Building Design. *AIA Journal*, *63*.

Fakhry, M., Kamel, I., & Abdelaal, A. (2021). CAD using preference compared to hand drafting in architectural working drawings coursework. *Ain Shams Engineering Journal*, *12*(3), 3331-3338. https://doi.org/10.1016/j.asej.2021.01.016
Foote, J. (2013). Design-Build :: Build-Design. *Journal of Architectural Education*, *65*(2), 52-58. https://doi.org/10.1111/j.1531-314X.2011.01197.x
Frascari, M. (2009). Lines as Architectural Thinking. *Architectural Theory Review*, *14*(3), 200-212. https://doi.org/10.1080/13264820903341605
Harries, K. A., Sharma, B., & Richard, M. (2012). Structural Use of Full Culm Bamboo: The Path to Standardization. *International Journal of Architecture, Engineering and Construction*, *1*(2), 66-75. https://doi.org/10.7492/ijaec.2012.008
Jabi, W. (2013). *Parametric design for architecture*. London : Laurence King Publishing.
Kewei, L., Jayaramana, D., Yongjiub, S., Harries, K., Jun, Y., Wei, J., Yuechud, S., Junqia, W., Jacomea, P., & Trujillo, D. (2022). "Bamboo: A Very Sustainable Construction Material" - 2021 International Online Seminar summary report. *Sustainable Structures*, *2*(1). https://doi.org/10.54113/j.sust.2022.000015
Kwinter, S. (1996). Flying the bullet, or when did the future begin? In S. Kwinter & R. University (Eds.), *Rem Koolhaas: Conversations with students* (2nd ed.. ed., pp. 67-94). Houston, Tex. : Rice University, School of Architecture, New York : Princeton Architectural Press.
Liese, W., & Tang, T. K. H. (2015). Preservation and Drying of Bamboo. In E. T. Akinlabi, K. Anane-Fenin, & D. R. Akwada (Eds.), *Bamboo: The Multipurpose Plant* (pp. 257-297). Springer, Cham. https://doi.org/10.1007/978-3-319-14133-6_9
Lin, C.-Y. (2001). *A digital Procedure of Building Construction: A practical project* CAADRIA2001, ey Centre of Design Computing and Cognition, University of Sydney.
Lou, Y., Buckingham, K., Henley, G., Li, Y., & Zhou, G. (2010). *Bamboo and Climate Change Mitigation*. https://www.inbar.int/resources/inbar_publications/bamboo-and-climate-change-mitigation/
Miro. (2022). *Miro*. In www.miro.com
Naylor, J. O. (2021). *Protection by Generative Design* Towards a New, Configurable Architecture - Proceedings of the 39th International Hybrid Conference on Education and Research in Computer Aided Architectural Design in Europe, Novi Sad, Serbia. http://ecaade.org/current/wp-content/uploads/2021/08/eCAADe2021_volume1_with_cover.pdf
Naylor, J. O., Leconte, N., & Vendryes, F. R. M. (2020). *Education to practice to ecology: A review and preliminary evaluation of a new architectural design curriculum using computational design tools and bamboo in Haiti* SIGraDi 2020, Medellín, Colombia. https://www.proceedings.blucher.com.br/article-details/education-to-practice-to-ecology-a-review-and-preliminary-evaluation-of-a-new-architectural-design-curriculum-using-computational-design-tools-and-bamboo-in-haiti-35497
Otto, F., & Rasch, B. (1995). *Finding form: Towards an architecture of the minimal* (3rd . ed.). Germany : Axel Menges.
Oxman, R. (2017). Thinking difference: Theories and models of parametric design thinking. *Design Studies*, *52*, 4-39. https://doi.org/10.1016/j.destud.2017.06.001
Piker, D. (2013). Kangaroo: Form Finding with Computational Physics. *Architectural Design*, *83*(2), 136-137. https://doi.org/10.1002/ad.1569
Preisinger, C. (2013). Linking Structure and Parametric Geometry. *Architectural Design*, *83*(2), 110-113. https://doi.org/10.1002/ad.1564
Rahim, A., & Jamelle, H. (2020). Architectural Impact After the Digital. *Architectural Design*, *90*(5), 6-13. https://doi.org/10.1002/ad.2605
Robert McNeel & Associates. (2020a). *Grasshopper 3D*. In https://www.grasshopper3d.com/
Robert McNeel & Associates. (2020b). *Rhinoceros 3D*. In (Version 6) https://www.rhino3d.com/
Robson, C. (2000). *Small-scale evaluation: principles and practice*. Sage.
Robson, C. (2002). *Real world research : a resource for social scientists and practitioner-researchers* (2nd ed.. ed.). Oxford : Blackwell Publishers.
Sadeghipour Roudsari, M., & Pak, M. (2013). Ladybug: A parametric environmental plugin for grasshopper to help designers create an environmentally-conscious design. *Proceedings of BS*

2013: 13th Conference of the International Building Performance Simulation Association, 3128-3135.
Schilling, A. (2018). *Architecture and Modelbuilding: Concepts, Methods, Materials*. Birkhäuser. https://doi.org/10.1515/9783035614732
Sheil, B. (2008). Protoarchitecture: Between the Analogue and the Digital. *Architectural Design*, *78*(4), 6-11. https://doi.org/10.1002/ad.699
Stavric, M., Sidanin, P., & Tepavcevic, B. (2013). *Architectural Scale Models in the Digital Age: design, representation and manufacturing*. Ambra Verlag. https://doi.org/10.1515/9783990435274
Storonov, T. (2018). *The design-build studio: Crafting meaningful work in architecture education*. New York, London : Routledge.
UNEP. (2019). *Sand and Sustainability: Finding new solutions for environmental governance of global sand resources*. http://www.unepgrid.ch/
Vrachliotis, G. (2020). Models, Media, and Methods: Frei Otto's Architectural Research [Exhibition catalogue]. https://www.architecture.yale.edu/publications/128-models-media-and-methods-frei-ottos-architectural-research
Wintour, P. (2018, 08/06/2018). *A brief history of computation*. Parametric Monkey. Retrieved 05/02/2022 from https://parametricmonkey.com/2018/06/08/a-brief-history-of-computation/
Yi-Luen Do, E. (2005). Design sketches and sketch design tools. *Knowledge-Based Systems*, *18*(8), 383-405. https://doi.org/10.1016/j.knosys.2005.07.001

Appendix D: Education to practice to ecology: A review and preliminary evaluation of a new architectural design curriculum using computational design tools and bamboo in Haiti

Conference paper

Published as: Naylor, J. O., et al. (2020). Education to practice to ecology: A review and preliminary evaluation of a new architectural design curriculum using computational design tools and bamboo in Haiti. SIGraDi 2020. N. B. Escobar and D. A. Torreblanca-Díaz. Medellín, Colombia, Blucher Design Proceedings. 8: 643-651.

SI GraDi2020 Transformative design
XXIV International Conference of the Iberoamerican Society of Digital Graphics
Medellín | Colombia

Education to practice to ecology: A review and preliminary evaluation of a new architectural design curriculum using computational design tools and bamboo in Haiti

John Osmond Naylor
University of Newcastle upon Tyne | UK | j.naylor73@newcastle.ac.uk

Nancy Leconte
Haiti | mfnancy.leconte@gmail.com

Franck Reginald Michel Vendryes
Bambutek | Haiti | fvendryes@gmail.com

Abstract

There is an absence of lightweight, sustainable construction materials in contemporary Haitian construction, a fact highlighted in the disproportionate loss of life in the 2010 Port-au-Prince earthquake. Between 2014 and 2017 the authors delivered a series of architectural design workshops in Haiti to raise awareness and develop design skills for bamboo using computational design tools. This paper provides a review of these workshops and a preliminary evaluation from surveys conducted with the course participants. Results showed architectural education had changed perceptions of bamboo and showed potential positive ecological impact due to subsequent reforestation activities instigated by participants. Weaknesses were in the lack of subsequent use of parametric modelling software. Bamboo material knowledge and a new architectural design methodology have been most relevant to their professional or academic work.

Keywords: Haiti; full-culm bamboo; architectural education; sustainable development, parametric design.

INTRODUCTION

In 2010, an earthquake hit Port-au-Prince, Haiti's capital, which caused the deaths of at least 160,000 people and tragically affected many millions more (Kolbe et al., 2010). A lack of lightweight building materials, and lack of enforcement of standards and codes played a significant role in this disproportionate death toll (Haas, 2010). Haiti also suffers chronic deforestation (Dubois, 2016), the results of which are barren hillsides that cause regular flooding and a rural exodus to the capital which increases the proportion of the population living in dense inadequate non-earthquake-resistant housing. This situation is not confined to Haiti. Globally, tropical low- and middle-income countries (LMIC's) are some of the most vulnerable societies to natural disasters, and by 2050, some 50% of the world's population will live in the tropics (State of the Tropics, 2020). The UN Sustainable Development Goal 11 (SDG11), targets by 2030 the access for all to adequate, safe and affordable housing, and suggests that the building of sustainable and resilient buildings utilising local materials should be a catalyst for development (UN-Habitat, 2016a). To achieve this locally available natural renewable materials are required for construction. This challenge should be met by architects to develop new processes to work with natural renewable materials which ensure structural integrity and affordability. Tropical developing economies are large producers of bamboo (Lobovikov, Paudel, Piazza, Ren, & Wu, 2007), a material with good tensile and compressive properties and a low carbon footprint when sourced locally (Lugt, Vogtländer, Vegte, & Brezet, 2015). Bamboo can be worked with simple tools and can be grown locally on a village scale or even a family scale (Janssen, 1995). Bamboo can also absorb CO_2 and stabilise slopes to tackle the effects of deforestation (Tardio, Mickovski, Stokes, & Devkota, 2017). Currently in Haiti, poverty, deforestation, pollution and waste management are growing problems (US AID, 2020). Haiti has seven naturally occurring species of bamboo as many as countries such as El Salvador, and Nicaragua (Akinlabi, Anane-Fenin, & Akwada, 2017). Bamboo is seen by some as a latent economic and ecological asset. The built environment has an opportunity to make bamboo more visible and help convince the most sceptical. Between 2014 and 2017 a series of five architectural design workshops took place in Haiti to develop skills and awareness of the lightweight, sustainable construction material of bamboo as well as teaching a new design process for bamboo involving a parametric design approach (Caetano, Santos, & Leitão, 2020), using parametric modelling software. This paper provides a preliminary evaluation of the impact of these courses and discusses the context of Haiti's architectural education and ecological and construction sector challenges, and the objectives of these courses to build capacity in these areas. By conducting surveys with course participants, the objectives of this paper are to:

1. Identify the perceived strengths and weaknesses of the courses from the participants' perspective.
2. Understand how the courses affected participants' attitude to bamboo.

3. Evaluate the relevance of computational architectural design tools in Haitian architectural education and the Haitian construction industry.
4. Understand how the course has affected participants' architectural design methodologies.
5. Understand how international collaborations between schools of architecture can have a meaningful impact on sustainable development.
6. Understand if these courses resulted in direct or indirect reforestation.
7. Develop a framework for a deeper evaluation of the courses in order to plan the next steps.

BACKGROUND

"Dèyè mòn, gen mòn." or "Beyond mountains, more mountains." This age old Haitian proverb has taken on a new meaning following the political, natural and economic factors which have afflicted Haiti over the past decades. However it was originally intended to describe the unique terrain of the Island nation. This terrain is severely deforested. Approximately only one third of the country has tree coverage. This deforestation amplifies the flooding and landslides caused by hurricanes and storms (Dubois, 2016). Another consequence of a lack of mature trees is that now timber is more expensive and must be imported from abroad. This is a disheartening fact for a construction industry once regional pioneers in timber frame construction, most notably in the Gingerbread architecture of the 19th Century (Columbia University GSAPP, 2016). Early assessments of these historic timber framed buildings undertaken after the earthquake found that traditional construction techniques proved seismically resistant. This prevented many Gingerbread structures from collapsing (Columbia University GSAPP, 2016), while over half of the contemporary built stock of predominantly unreinforced masonry in Port au Prince collapsed or was damaged enough to require repairs (Desroches, Comerio, Eberhard, Mooney, & Rix, 2011). Near the epicentre of the earthquake, in the city of Léogâne, it is estimated that 80%–90% of the buildings were critically damaged or destroyed (Desroches et al., 2011). The need for safe and lightweight buildings in Haiti is critical and this is especially true for urban areas which are home to 57.4% of Haiti's population (UN-Habitat, 2016b). These problems have dogged Haiti for decades and it is urgent that we find realistic solutions to these problems and put emphasis on local production and be innovative.

Figure 1: Student project from the Summer 2016 course and the design selected to be developed as a Bamboo Core house prototype.

How can we involve land owners, architects, entrepreneurs and crafts people into the imperative necessity of a formal bamboo network which will not only bring in substantial revenues but will stop erosion in the areas where bamboo is grown? In answering this question, the focus here is on architectural education, the process of shaping individuals to join the architecture profession, one of the most influential professions in our global society (Salleh, Md Yusoff, & Memon, 2016). A lack of lightweight sustainable construction materials is not the result of architectural education. However current models of education are very much based in training students for the current scenario and recreating the buildings which are to be built from currently widely available materials such as concrete with steel rebar and concrete masonry units (CMU's). Client demands reinforce client perceptions of what a building is. In such an environment, the next generation of students are continuing to lose an appreciation of timber and other natural renewable materials. Haiti needs safe buildings but, for lasting change these need to be designed in Haiti by local architects, and not to "air drop solutions" (Sinclair, 2010). As Merkel and Whitaker (2010) put it, to move away from concrete towards sustainable, lightweight materials, "Haiti would need a new generation of builders adept at pounding nails rather than mixing cement." (p.133) (Merkel & Whitaker, 2010). Architectural education has that ability and a responsibility to train the next generation of architects and engineers to be advocates for lightweight natural renewable materials. Their future professional work can incorporate these materials and step by step begin to identify local supply chains and build local capacity. With enough local demand for lightweight natural renewable materials from clients, inevitably those with barren unproductive land in Haiti will see an economic benefit from planting timbers and bamboos. Also important to note is that architects and engineers are only responsible for a minority of buildings in Port au Prince, since almost 75% of Haiti's urban population, over 4 million people, live in non-adequate housing (UN-Habitat, 2016b) which is built usually without the input of an architect or engineer. These informal buildings are often built in the image of what is considered a balance between perceived functionality, durability and cost by the home owner. If architects and engineers can be successful in promoting alternative natural materials, and demonstrating that these materials are affordable, durable and provide a functional space, over time, these few can act as a beacon to the subsequent informal buildings which are constructed. In this context in 2014, the UK based Architectural Association School of Architecture (AA) established a series of workshops to address this challenge and teach bamboo design and construction skills in Haiti, running for five courses until 2017. These courses were coordinated by the AA with support and guidance from Quisqueya University architecture department in Port au Prince, and the Wynne Farm Ecological Reserve in Kenscoff in which construction took place. They were all roughly two weeks in duration. The workshops were financed by sponsorships received from Government agencies, architecture firms and NGO's based locally in Haiti, as well as the USA, UK, and Switzerland. Fees were also paid by participants. The funding model meant overseas participants provided funding through fees which contributed to the costs of the courses. Almost 90% of the Haitian participants received scholarships for $100 fee places or fee free places. There were 4 wider objectives established for the workshops. These were to: equip local students with computational design tools to increase the capacity to design for climatic and seismic conditions; to develop a portfolio of student work showcasing the aesthetic potential of bamboo buildings; to engage students, design professionals and builders in a construction course using domestically grown bamboo, demonstrating both construction techniques and existing infrastructure so skills can be disseminated; and to create a platform linking bamboo growers, land owners, and the construction industry together in Haiti while showcasing skills of those in Haiti internationally.

PARTICIPANTS

In total, over the five years there were 70 enrolments on the courses, the demographics of which are presented in Table 1 and Figure 2. Since a few Haitian enrolees were returning participants from previous courses, these 45 enrolments from Haitian participants represent 37 individual participants.

Table 1: Number of participants enrolled on each course with bars split to show the Haitian and non-Haitian enrolees. (Note: Participants who studied more than one course as an enrolee are recorded for each of their enrolments).

Course year	Haitian	Enrolees Non-Haitian	Total
2014	7	4	11
2015	6	6	12
2016 Summer	9	9	18
2016 Autumn	7	5	12
2017	16	1	17
Total	**45**	**25**	**70**

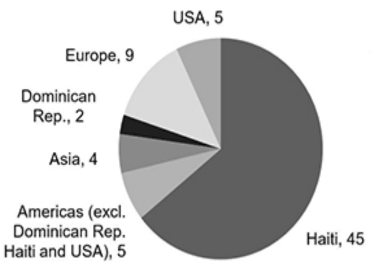


Figure 2: Number of course enrolments over the five courses broken down by geographic location. (Note: Participants who studied more than one course as an enrolee are recorded for each of their enrolments).

TEACHING TEAM

The teaching team was made up of architects from around the world. In 2014 when the course was established we had no Haitian teaching staff, only Haitian visiting lecturers. One main goal with the teaching team was that this would be an opportunity to build capacity within Haiti and over time develop a predominantly Haitian teaching team for the courses, ideally having past participants of the course return as members of the teaching team. The cooperative learning approach to active learning was employed as the means of delivering the curriculum (Keyser, 2000). Tutors acted as design coaches to drop into student groups over the course to provoke and stimulate the emerging design and offer technical support.

PROGRAMME CURRICULUM

Participants would work in groups of three and would develop one design project over the course of each workshop. Groups were designed to ensure they would always be a mix of Haitian and non-Haitian participants. Upon receiving the brief participants were to follow an iterative problem solving process based on one documented by Mitchell and Bevan (1992). Participants were encouraged to identify the problem in the brief from multiple stakeholder perspectives and identify the economic, social and material constraints in which they can design (Mitchell, 1992), with the bamboo material as the exception to this, though in proposing bamboo participants had to argue how this project would be a catalyst to develop a future bamboo infrastructure. Secondly, a method of design, build, test and assess was followed in order to inform design decisions in an iterative process (Mitchell, 1992). This process began with physical model making with bamboo sticks in order to conceptualise initial design responses to the brief. This was supported in parallel with site visits, and lectures on bamboo growth, selection, harvesting, processing and joinery. Following this, 3D modelling software was taught and participants would then build their physical models in Rhinoceros 3D (Robert McNeel & Associates, 2020b). Upon identifying parameters which could be refined, these designs were scripted in Grasshopper (Robert McNeel & Associates, 2020a) in order to efficiently produce new versions which could respond to changing parameters such as a changing site or alternative bamboo species selection. From 2016 onwards participants undertook bamboo harvesting and 1:1 scale bamboo construction which allowed participants to learn more about the buildability of their designs and then use this construction experience to develop the practicality of their design. Graphic design software was then taught to allow participants to properly document their design process and output. Throughout this whole process local and international architects and ecologists would give lectures to the participants presenting a vast palette of issues and ideas from which they could cultivate their design work. This provided the input of outside ideas from other bamboo growing regions of the world and provided networking opportunities for participants. At the end of the course the designs were presented to stakeholders, tutors and their peers in the course.

COMPUTATIONAL DESIGN TOOLS

Computational design brings simulation and analysis into the architectural design process. These tools produce new efficiencies, manage complexity, and explore new forms of aesthetic expression (Senske, 2017). One wider challenge of computational design tools and full-culm bamboo is the difficulties in accurately modelling an anisotropic material with natural variability (Naylor, 2020). In 2005, Willis and Woodward suggested it will be impossible to achieve a direct correlation between digital data and a constructed building. Some design parameters such as material flaws, grain directions and inconsistent densities will be difficult to anticipate in modelling software. However, this gap between the building and the model will continue to narrow (Willis & Woodward, 2005). The design portfolios of the courses in Haiti contributed to the wider discourse and the narrowing of this gap. Participants were taught Rhinoceros 3D (Robert McNeel & Associates, 2020b) which is a three-dimensional computer graphics and computer-aided design software, and Grasshopper (Robert McNeel & Associates, 2020a) which is a graphical algorithm editor integrated with Rhinoceros 3D. Grasshopper is primarily used to build generative algorithms. Such software allows us to specify relationships among parameters and instantly output versions or iterations of a design, based on associative rules set by the designer (Jabi, 2013). These tools and process can ultimately reduce the time in achieving optimal design solutions, and if time is money, then there is no more relevant application of such a design process than in Haiti. We do not expect students to master the software over the course, but simply be introduced to it. By applying computational design tools to a short design brief, we are not just teaching the software but allowing students to autonomously discover their relevance and application.

FULL-CULM BAMBOO

A fundamental principle within the course curriculum was the use of full-culm bamboo as opposed to engineered bamboo products (EBP's). By enfranchising non- or marginally-engineered building materials, we can ensure that the most affordable form of bamboo, 'full culm bamboo', (also named 'round bamboo') can be used (Harries, Sharma, & Richard, 2012; Paraskeva, Pradhan, Stoura, & Dimitrakopoulos, 2019).

WIDER REQUIRED INTERVENTIONS

It is important to note here that the emphasis on architectural education is only one aspect of a plan which needs to take place in order to bring about the restoration of Haitian ecology and the built environment. The authors of this paper believe unless measures are taken right now to stop the destruction of Haiti's meagre forest resources, there will be harsh environmental consequences in the future, and the most important factor in stimulating environmental participation would be providing opportunities to increase incomes (Dolisca, Carter, McDaniel, Shannon, & Jolly, 2006). Non-timber forest products such as bamboo offer this opportunity. Bamboo is *"Un passage obligé"*, in a real quest for sustainable development which will benefit present and future generations of citizens. The future of bamboo in Haiti should be part of a sustainable realistic development plan which considers the wellbeing of all citizens. Faith, discipline, collective work and determination are necessary to bring about and guarantee a long and healthy life to a bamboo endeavour in Haiti. These workshops are an important aspect of what needs to be a wider plan for bamboo.

METHODOLOGY

A self-administered online survey of 18 questions was used (Table 2). Of these 18 questions Q1, Q3, Q10 and Q11 were multiple-answer multiple choice questions and Q18 allowed students to respond with written text. All other questions were single answer multiple choice. Surveys were conducted by an online form in Haitian Creole. This was sent to only Haitian participants of the courses since the goal of this preliminary evaluation is to determine the subsequent local impact. Surveys asked gender, age and which course was attended, however there was no further information asked which could be used to identify the participants. With the lack of further personal information the results were anonymous. There are four key sections to the assessment. These are: attitudes for construction use of bamboo and in the wider context of Haiti; bamboo planting and reforestation activities; software, and networking. Surveys are a relatively straightforward approach to studying attitudes and values, and provide a high degree of data standardisation. Online self-administered surveys such as the one used allow anonymity which can help to encourage frankness and honesty (Robson, 2002).

Table 2: Structure of online self-administered questionnaire. The final survey was translated and answered in Haitian Creole.

Number	Question
Q1	What aspects of the course did you most enjoy?
Q2	Do you think such a course should be offered at a University in Haiti?
Q3	What aspects of the course have been the most useful for your professional work or academic studies after the course?
Q4	Has the course changed your approach to design? If so, in which way?
Q5	Can you see bamboo playing an important role in the future construction industry in Haiti?
Q6	Before the course, had you visited anywhere in which bamboo grows in Haiti?
Q7	After the course, had you visited anywhere in which bamboo grows in Haiti?
Q8	Have you yourself planted bamboo, or been part of any team which has planted bamboo, following the course?
Q9	If you have not participated in planting bamboo, why?
Q10	Before the course, where did you consider bamboo suitable in construction?
Q11	After the course, where do you consider bamboo suitable in construction?
Q12	Have you used RHINOCEROS 3D, following the course?
Q13	Have you used GRASSHOPPER, following the course?
Q14	If not, what were the reason for not using software?
Q15	Have you used any of the following software you were taught following the course?
Q16	Did this course provide an opportunity to meet new people which would not normally be available to you?
Q17	Would you do the course again? If so, which format would be best?
Q18	If you could improve the course, what would you change?

Surveys are also advantageous in their transparency in which the methods, procedures and implementation can be assessed by others (Hakim, 2000). There are internal and external validity problems with surveys. Internal being the questions themselves are incomprehensible or ambiguous resulting in a problem of obtaining the right information, and external being problems with the sampling and securing the involvement of respondents (Robson, 2002). This is particularly true with self-administered surveys which typically have a low response rate and given the anonymity, it is difficult to know how representative the responses are, and any ambiguous questions or misunderstandings by respondents are difficult to detect (Robson, 2002). Similar surveys have been used within the construction industry. In a survey of architects' awareness of sustainability in China, Bing and Yi (2015) noted the non-response bias which could affect the results, in that those who have little interest in this issue may not have replied (Bing & Yi, 2015). Here all respondents were contacted individually. Surveys were also used in a four-year impact study to assess teaching methods for a computational thinking course (Senske, 2017). This methodology of pre- and post- class surveys was successful in that it revealed improved perception of computing and an increased interest in the subject, validating the premise of the course (Senske, 2017). All respondents to our survey had participated in the courses so they had already shown an interest in the wider subject matters being evaluated. It is hoped this reduces the issues with external validity. We also included an initial set of questions before the main survey to understand how the views reflected a broad range of the courses. Respondents were able to state which year they had undertaken the course. In the event a participant had taken the course on more than one occasion they would select each year they had taken the course. We were able to ensure that responses to the survey reflected views over all five courses. As shown in Table 4, the age group of respondents was also recorded with an initial survey question. The majority of those who participated in the course were current students of architecture in Port au Prince, and this younger age group was also reflected in the respondents to the survey.

Table 3: The gender representation of respondents.

Gender	No.	%
Male	11	73.3%
Female	4	26.7%
Total	**15**	**100%**

Table 4: The age demographic of survey respondents .

Age group	No.	%
18-24	4	26.7%
25-32	9	60%
33-40	2	13.3%
41+	0	0%
Total	**15**	**100%**

Figure 3: Construction of a small structure with locally sourced bamboo on the 2017 course.

RESULTS

GENERAL OBSERVATIONS

Q1 and Q3 allowed multiple answers. As shown in Figure 4 respondents noted in Q1 that bamboo material knowledge, networking, the architectural design process, and 3D modelling software had been their most enjoyable parts of the course. The bamboo material knowledge and architectural design process also scored highest when asked what had been the most useful to their subsequent professional work or academic studies (Q3). The least relevant aspect of the course from Q3, was the experience of visiting other parts of Haiti with only 7%.

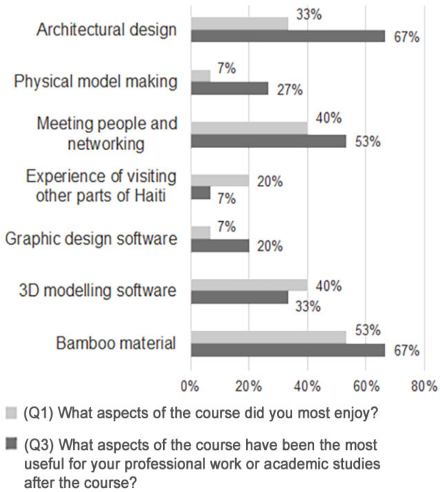


Figure 4: Respondents views on which aspects of the course they most enjoyed (Q1) and which aspects of the course they considered to be most useful to their professional or academic work after the course (Q3).

ATTITUDE TO BAMBOO IN CONSTRUCTION

All respondents responded positively to the question of whether they could see bamboo playing an important role in the future construction industry in Haiti (Q5). Q10 and Q11 allowed multiple answers. The responses are shown in Table 5. Before the course only 27% of respondents thought bamboo could be used for the primary structure whereas this number increased to 93% following the course. Those who think bamboo could be used as a roof more than doubled from 40% before the course to 87% after the course. Those thinking bamboo could be used in the façade also substantially increased from 47% to 73%. In fact in all building applications, more respondents were positive for bamboos application following the course. 20% of respondents noted that bamboo was not suitable for construction. This may seem unusual since at the same time 93% think it can be used in a primary structure and 87% think it can be used in a roof. However this may not necessarily be contradictory to the 93% figure as this could be for other reasons such as cultural or economic. One could think bamboo can work in a structure but also think that it is not suitable to use. This is something to investigate in future evaluation exercises.

Table 5: Respondents' attitudes to the applications of bamboo before (Q10) and after (Q11) the course. (No. of responses and percentage of respondents).

Response	Before the course	After the course
Primary structure	4 (27%)	14 (93%)
Roof	6 (40%)	13 (87%)
Façade	7 (47%)	11 (73%)
Interior finishes	9 (60%)	12 (80%)
Furniture	13 (87%)	15 (100%)
Not suitable for construction	0 (0%)	3 (20%)
No opinion	1 (7%)	0 (0%)

DESIGN METHODOLOGY

Table 6: Responses to Q4. Has the course changed your approach to design? If so, in which way?

Response	No.	(%)
No	1	6.7%
Use of materials	2	13.3%
Conception of form	7	46.6%
The role of design in a social context	4	26.7%
Other	1	6.7%
Total	**15**	**100%**

As shown above in Table 6, all but 1 of the respondents stated the course had in some way changed their approach to design with the role of design in a social context and the conception of form as the highest.

BAMBOO PLANTING

As shown in Table 7, the course had a positive impact on exposing participants to bamboo as a plant and linking participants to reforestation exercises. 20% of respondents had said they had subsequently been part of a team which had planted bamboo in Haiti. For those who answered *'no'*, Q9 was an opportunity to state the reasons for not planting bamboo. The results from 11 responses, as shown in Table 8, were mixed with most respondents recording reasons which were not listed.

Table 7: Responses to Q6, Q7 and Q8.

Response	Yes (%)	No (%)
Have you visited anywhere in which bamboo grows in Haiti?		
Q6. Before the course	7 (46.7%)	8 (53.3%)
Q7. After the course	13 (86.7%)	2 (13.3%)
Q8. Have you yourself planted bamboo, or been part of any team which has planted bamboo, following the course?		
	3 (20%)	12 (80%)

In response to Q9, other reasons for participants not planting bamboo ranged from not finding time to pursue this to not being based anymore in Haiti. However 5 of the 8 other responses such as, *"Did not get opportunities,"* or, *"Because I did not find organizations, groups, teams to participate in these activities,"* could also be categorised as a lack of opportunity. Since no respondents responded with a lack of interest or the feeling that planting bamboo does not make sense, it can be safely deduced that there is a desire of the participants to plant bamboo, but a lack of opportunity stands in the way.

Table 8: Responses to Q9.

Response	Number of Responses	% of responses to Q9
If you have not participated in planting bamboo, why?		
Lack of funding	1	9.1%
No interest in planting bamboo	0	0%
Feel it does not make sense to plant bamboo in Haiti	0	0%
Lack of market for bamboo	1	9.1%
Lack of opportunity to participate	1	9.1%
Other	8	72.7%
Total	**11**	**100%**

SOFTWARE

Participants were asked if they have used Rhinoceros 3D or Grasshopper following the course, and in which capacity (Table 9).

Table 9: Respondents' answers to subsequent use and application of Rhinoceros 3D (Q12), and Grasshopper (Q13) softwares taught on the course.

Response	No. of responses	% of responses
Q.12. Have you used Rhinoceros 3D, following the course?		
Yes, in a university project	0	0%
Yes, in professional work	2	13.3%
Yes, in personal projects	6	40%
No, not used	5	33.3%
Other	2	13.3%
Total	**15**	**100%**
Q13. Have you used Grasshopper, following the course?		
Yes, in a university project	0	0%
Yes, in professional work	0	0%
Yes, in personal projects	1	7.7%
No, not used	11	84.6%
Other	1	7.7%
Total	**13**	**100%**

Responses from the 2016 Autumn course were omitted since Rhinoceros and Grasshopper were not taught on this course. The responses for subsequent use of Rhinoceros 3D showed that roughly half of respondents had used Rhinoceros 3D in their professional work and personal projects. Those who responded to *'Other'* commented in ways which show that they did not continue to use Rhinoceros 3D, with one of these responses stating they would like to with further training. However, subsequent use of Grasshopper was minimal with only one positive response and two respondents not answering this question.

NETWORKING

For Q16, 93% of respondents stated that this course provided an opportunity to meet new people which would not normally be available to them.

COURSE DURATION AND FUTURE FORMATS

Table 10: Respondents' answers to Q17, Would you do the course again? If so, which format would be best?

Response	**No. of resp.**	**(%)**
No	0	0%
Yes, same length and format	2	13.3%
Yes, same format but longer duration	12	80.0%
Yes, a semester length course at University	1	6.7%
Total	**15**	**100%**

There was unanimous agreement from respondents that this course should be offered at a university in Haiti (Q2). Table 10 shows the responses when participants were asked about future formats, most thought the course should be a longer duration. Q18 of the survey was an opportunity for respondents to provide additional comments, with no limit on the size of the text. Of these responses the vast majority reinforced the responses to Q17. Some of these comments included: *"I would make the training last longer so the students would have a better* *understanding of the training and get to use the software better"; "I would increase the amount of time"; "Since the training is built over a very short duration, the time to fully understand and assimilate the software should take more time"; "Our time is spent learning software and the time is not enough to allow us to have a good foundation",* and, *"More time."*

RESPONSE RATE

With 15 responses representing 41% of the 37 participants the response rate was lower than we would have hoped for. The results however still reveal an insight into successes and challenges and provides guidance for further evaluation. That said, a low response rate does not necessarily mean that a survey suffers from a large amount of nonresponse error (Krosnick, Lavrakas, & Kim, 2014).

DISCUSSION

The first objective of this paper was to identify the perceived strengths and weaknesses of the courses from the participant perspective. From the responses it appears the strengths of the course were in the networking opportunities, and learning about bamboo. There was unanimous agreement that bamboo could play an important role in Haitian construction with all respondents responding positively to the question of whether the respondent could see bamboo playing an important role in the future construction industry in Haiti (Q5). The responses to Q10 and Q11 are shown in Table 5. Before the course only 27% of respondents thought bamboo could be used for the primary structure whereas this number increased to 93% following the course. 20% of respondents had said they had subsequently been part of a team which had planted bamboo in Haiti (Q8). Subsequent to the last course, one particular participant was able to harness the lessons from the workshop with real life experience, implementing a reforestation programme which has the self-stated goal of encouraging the rural and urban population to plant bamboo to allow financial independence and stem the problem of Haiti's rural exodus (Facile, 2019a). The authors have also been made aware of the scope and quantity of bamboo planted through this endeavour. This programme received funding to plant 1000 seedlings in phase 1, with 5000 seedlings in phase 2 and claiming to directly impact 10000 people (Facile, 2019b). Two thirds of respondents said that the architectural design methodology and knowledge of bamboo had been useful to their subsequent professional or academic work. Respondents all stated they would do the course again and wished it to be a longer course, unanimously wanting such a course at university (Q2). An apparent weakness from the responses appears to be in the teaching of parametric modelling software without adequate time on the course to do so. 3D modelling software was relevant to respondents (Q3), though subsequent use of Grasshopper showed this not to be relevant (Q13). This begs the question whether it would have been more impactful to not teach parametric modelling software, but focus more on the 3D modelling given the short timeframe we had for each of these courses.

CONCLUSION

Firstly, architectural education when linked to an ecological agenda can impact ecology and can inspire those who do the course to instigate reforestation. 20% of respondents stated they had participated in planting bamboo following the course and we are aware that one participant has implemented a reforestation programme (Facile, 2019b). Perhaps this course has influenced this, whether this was by inspiring the participants to plant bamboo or facilitating the networking which allowed the planting to occur. This should be investigated more as the story of this could have wider relevance to understand how more participants could get involved in planting bamboo and become advocates to landowners to plant bamboo. Access to funds is a key point in following up and setting up a planting programme, and without this know-how, potential interest in bamboo is nipped in the bud. Secondly, architectural education can change perceptions of lightweight sustainable materials such as bamboo. The fact that respondents both enjoyed and found useful the bamboo material information (Q1 and Q3), 100% of respondents thought bamboo had an important role to play in construction (Q5), and there were significant positive changes in the perception of bamboo from the responses to Q10 and Q11. This shows the importance of materials in architectural education, not just for Haiti. In retrospect, the survey could have further investigated bamboo advocacy, to understand how the participants introduced the material to others, from tentatively suggesting it to actively arguing for use in construction with clients. Furthermore, the survey gives no insight on how the participants' university tutors have responded to the suggestion of using bamboo. Indeed, even though this course was open to all ages those who undertook the course were predominantly of university age. As highlighted in Q4, these courses affected participants' attitudes to architectural design and how we see the role of the architect. Nearly a third of respondents noted this course had changed the role of design in a social context. Responses showed that overall the 3D modelling software was relevant, though it is inconclusive the reasons why parametric modelling software was not useful following the course. This could be a lack of knowledge resulting in a lack of use. This could be remedied by a greater length of training as the majority of respondents thought this should be done in response to Q17. It would be beneficial for this evaluation to ask if participants felt these courses had helped in finding employment following the course. However, by engaging with respondents through this study, it is very evident that even before the COVID-19 pandemic of 2020, there was ongoing political unrest in Haiti along with slow devaluation of the currency and economic challenges for the last few years. Therefore it is a difficult time to question participants on their careers. This can be inquired with far more empathy in future personal interviews and will allow us to understand the success of the networking opportunities. These initial survey results should now be backed up by qualitative interviews. In getting this information we can build on these results and the strengths and weaknesses of the course and develop a plan for the future in order to keep the goals of this course alive. One thing is key: the founding principles of these workshops are as relevant today as they were on the first course in January 2014.

ACKNOWLEDGMENTS

Thank you to Jane Wynne, Doria Reyes Córdova, Rose Di Sarno, Aditya Aachi, Diego Perez Espitia and Dr Ben Bridgens who provided insight and expertise although interpretations, conclusions and any errors in this paper are our own.

REFERENCES

Akinlabi, E. T., Anane-Fenin, K., & Akwada, D. R. (2017). Bamboo Taxonomy and Distribution Across the Globe. In Bamboo: The Multipurpose Plant (pp. 1-37). Cham: Springer International Publishing.

Bing, X., & Yi, C. (2015). Chinese Architects' Awareness of, and Attitudes towards, Low-Carbon Architectural Design. Architecture Research, 5(3), 89-96. doi:10.5923/j.arch.20150503.01

Caetano, I., Santos, L., & Leitão, A. (2020). Computational design in architecture: Defining parametric, generative, and algorithmic design. Frontiers of Architectural Research, 9(2), 287-300. doi:10.1016/j.foar.2019.12.008

Columbia University GSAPP. (2016). The Gingerbread Houses of Port-au-Prince, Haiti(pp. 82). Retrieved from https://www.wmf.org/sites/default/files/article/pdfs/haiti-report-.pdf

Desroches, R., Comerio, M., Eberhard, M., Mooney, W., & Rix, G. (2011). Overview of the 2010 Haiti Earthquake. Earthquake Spectra, 27, S1-S21. doi:10.1193/1.3630129

Dolisca, F., Carter, D. R., McDaniel, J. M., Shannon, D. A., & Jolly, C. M. (2006). Factors influencing farmers' participation in forestry management programs: A case study from Haiti. Forest Ecology and Management, 236(2), 324-331. doi:https://doi.org/10.1016/j.foreco.2006.09.017

Dubois, L. (2016, 17/10/2016). Who Will Speak for Haiti's Trees? New York Times. Retrieved from https://www.nytimes.com/2016/10/18/opinion/who-will-speak-for-haitis-trees.html

Facile, J. (2019a). Bamboo: A living green Future in Haiti (Bambou Facile). Retrieved from https://www.youthlead.org/resources/bamboo-living-green-future-haiti-bambou-facile

Facile, J. (2019b). PREBHA (Programme de Reboisement Bambou en Haiti). Retrieved from https://www.youthlead.org/innovations/prebha-programme-de-reboisement-bambou-en-haiti

Haas, P. (2010). When bad engineering makes a natural disaster even worse [Video]. TED Senior Fellows at TEDGlobal 2010. Retrieved from https://www.ted.com/talks/peter_haas_when_bad_engineering_makes_a_natural_disaster_even_worse

Hakim, C. (2000). Ad hoc sample surveys. In C. Hakim (Ed.), Research design : successful designs for social and economic research (2nd ed.. ed., pp. 76-94). London: Routledge.

Harries, K. A., Sharma, B., & Richard, M. (2012). Structural Use of Full Culm Bamboo: The Path to Standardization. International Journal of Architecture, Engineering and Construction, 1(2), 66-75. doi:10.7492/ijaec.2012.008

Jabi, W. (2013). Parametric design for architecture: London : Laurence King Publishing.

Janssen, J. J. A. (1995). Building with bamboo : a handbook (2nd ed.. ed.). London: London : Intermediate Technology Publications.

Keyser, M. W. (2000). Active learning and cooperative learning: understanding the difference and using both styles effectively. Research Strategies, 17(1), 35-44. doi:https://doi.org/10.1016/S0734-3310(00)00022-7

Kolbe, A. R., Hutson, R. A., Shannon, H., Trzcinski, E., Miles, B., Levitz, N., . . . Muggah, R. (2010). Mortality, crime and access to basic needs before and after the Haiti earthquake: a random survey of Port-au-Prince households. Medicine, Conflict and Survival, 26(4), 281-297. doi:10.1080/13623699.2010.535279

Krosnick, J. A., Lavrakas, P. J., & Kim, N. (2014). Survey Research. In C. M. Judd & H. T. Reis (Eds.), Handbook of Research Methods in Social and Personality Psychology (2 ed., pp. 404-442). Cambridge: Cambridge University Press.

Lobovikov, M., Paudel, S., Piazza, M., Ren, H., & Wu, J. (2007). World bamboo resources - A thematic study prepared in the framework of the Global Forest Resources Assessment 2005. Retrieved from Rome: http://www.fao.org/3/a1243e/a1243e00.pdf

Lugt, P. v. d., Vogtländer, J. G., Vegte, J. H. v. d., & Brezet, J. C. (2015). Environmental Assessment of Industrial Bamboo Products - Life Cycle Assessment and Carbon Sequestration. Paper presented at the 10th World Bamboo Congress, Korea.

Merkel, J., & Whitaker, C. (2010). Rebuilding from Below the Bottom: Haiti. Architectural Design, 80(5), 128-134. doi:10.1002/ad.1147

Mitchell, M. (1992). Culture, cash and housing : community and tradition in low-income building. London: London : VSO/IT.

Naylor, J. O. (2020). The Opportunities and Challenges of Using Parametric Architectural Design Tools to Design with Full-Culm Bamboo. In M. Awang & M. R. Meor M Fared (Eds.), Lecture Notes in Civil Engineering. ICACE 2019 (Vol. 59, pp. 9-18). doi:https://doi.org/10.1007/978-981-15-1193-6_2

Paraskeva, T., Pradhan, N. P. N., Stoura, C. D., & Dimitrakopoulos, E. G. (2019). Monotonic loading testing and characterization of new multi-full-culm bamboo to steel connections. Construction and Building Materials, 201, 473-483. doi:10.1016/j.conbuildmat.2018.12.198

Robert McNeel & Associates. (2020a). Grasshopper 3D. Retrieved from https://www.grasshopper3d.com/

Robert McNeel & Associates. (2020b). Rhinoceros 3D (Version 6). Retrieved from http://www.mcneel.com/

Robson, C. (2002). Real world research : a resource for social scientists and practitioner-researchers (2nd ed.. ed.). Oxford: Oxford : Blackwell Publishers.

Salleh, R., Md Yusoff, M. A., & Memon, M. (2016). Attributes of Graduate Architects: An Industry Perspective. The Social Science Journal, 11, 551-556. doi:10.3923/sscience.2016.551.556

Senske, N. (2017). Evaluation and Impact of a Required Computational Thinking Course for Architecture Students. Paper presented at the Proceedings of the 2017 ACM SIGCSE Technical Symposium on Computer Science Education, Seattle, Washington, USA. https://doi.org/10.1145/3017680.3017750

Sinclair, C. (2010). The Role of The Architect in Rebuilding Haiti: To Compete or To Construct? Retrieved from https://www.huffpost.com/entry/the-role-of-the-architect_b_453905

State of the Tropics. (2020). State of the Tropics 2020 Report. Retrieved from Townsville, Australia: https://www.jcu.edu.au/state-of-the-tropics/publications/2020

Tardio, G., Mickovski, S. B., Stokes, A., & Devkota, S. (2017). Bamboo structures as a resilient erosion control measure. Proceedings of the Institution of Civil Engineers - Forensic Engineering, 170(2), 72-83. doi:10.1680/jfoen.16.00033

UN-Habitat. (2016a). SDG-Goal 11 Monitoring Framework. Retrieved from Nairobi: https://unhabitat.org/sites/default/files/download-manager-files/SDG%20Goal%2011%20Monitoring%20Framework.pdf

UN-Habitat. (2016b). Slum Almanac 2015/2016: Tracking Improvement in the Lives of Slum Dwellers. Retrieved from Nairobi: https://unhabitat.org/sites/default/files/download-manager-files/Slum%20Almanac%202015-2016_PSUP.pdf

US AID. (2020). Haiti - Complex Emergency Fact Sheet #2 (2). Retrieved from https://www.usaid.gov/sites/default/files/documents/1866/07.02.20_-_USAD-BHA_Haiti_Complex_Emergency_Fact_Sheet_2.pdf

Willis, D., & Woodward, T. (2005). Diminishing Dificulty: Mass Customization and the Digital Production of Architecture. Harvard Design Magazine(23), 71-83.

Appendix E: Haiti Symposium Discussion: Examining the transformative potential of bamboo construction

Journal article

Published as: Naylor, J. and J. Wynne (2024). "Examining the transformative potential of bamboo construction." Architectural Research Quarterly 27(3): 184-189.

arq (2023), **27.3**, 184–189.
doi: 10.1017/S1359135523000313

Examining the transformative potential of bamboo construction

Developing bamboo in the Haitian built environment

John Naylor and Jane Wynne

Haiti suffers from chronic deforestation that amplifies flooding and landslides caused by hurricanes and storms.[1] More than 60% of Haiti has a slope greater than 20%, and almost 30% of land has slopes less than 10%.[2] The loss of forest cover results in the loss of the topsoil through erosion and increases the probability of flooding,[3] a process that began with the French colonial plantation system.[4] A great number of Haiti's watersheds are entirely deforested and subsequently urbanised, and much of the soil is highly degraded *[1]*.[5] This topsoil from the hillsides around Port-au-Prince has poured down the slopes and added more area to the city due to soil deposits. Such poorly compacted land – the locations presented in the soil classification map in CNBH 2012[6] (the Haitian Building code) – can amplify ground motion and the risk to buildings in earthquakes.[7]

On 12 January 2010, an earthquake hit Port-au-Prince, Haiti's capital, causing a catastrophic death toll.[8] A lack of lightweight building materials, and lack of enforcement of building standards and codes played a significant role in this disproportionately high number.[9] Over half of the contemporary built stock, constructed predominantly of poorly reinforced or unreinforced

1 Steep, deforested hillsides to the south east of Kenscoff, Haiti, south of Port-au-Prince.

masonry, collapsed in the epicentral area, or was damaged enough to require repairs.[10] The need for safe and lightweight buildings in Haiti is critical. Poor quality construction, due to expensive building materials, only exacerbates this problem. Most of these materials need to be imported, and the expensive cost of mineral rich *sab rivyè* leads to the widespread use of calcite sand, which is unsuitable for concrete. Due to a lack of resources, most housing in urban areas in Haiti uses a combination of reinforced concrete columns and unreinforced masonry walls made of concrete masonry units (CMUs) *[2]*.[11] The enforcement of building codes, such as Haiti's national building code, CNBH, are difficult when most low-income homes are built informally and are unlikely to seek building permission.[12]

Haiti grows species of bamboo such as *Guadua angustifolia*, which is codified for structural use in Colombia *[3]*.[13] This species has also been used to construct in Croix-des-Bouquets and Cabaret, in Haiti. The availability of such species makes Haiti an opportune location to apply this lightweight material for construction, to restore ecologies, and support economic development. The name Haiti (or Ayiti) comes from the indigenous pre-Columbus inhabitants, the Taino, and means 'Land of High Mountains'.[14] Even this name highlights the opportunity for bamboo construction, since bamboo grown on slopes can have higher fibre density and increased strength properties.[15] Beyond this, bamboo forests play an important ecological function, enabling soil and water conservation.[16] Bamboo plantations can exacerbate landslides by creating a *weak slip plane* just below the soil surface.[17] But with careful consideration of site, species, and other adjacent plants, such as deep rooted vetiver grass, some bamboo species can help decrease surface soil erosion and can stabilise river banks. The leafy mulch that is common around bamboo clumps protects the topsoil from erosion by the direct impact of rain.[18]

2 Chalky limestone aggregates used in construction in Port-au-Prince, Haiti, in 2012 seen two years after the devastating earthquake of 2010.

3 The bamboo species of Guadua angustifolia is well documented in the Colombia building code. Bamboo is the primary structural material in some campus buildings at the Universidad Tecnológica de Pereira, in Pereira, Colombia.

Prototyping bamboo construction in Haiti

Haiti needs safe buildings. However, for lasting change, these should be designed in Haiti by local design and construction professionals, and should not be so-called 'air drop solutions'.[19] As Merkel and Whitaker put it, to move away from concrete towards sustainable, lightweight materials, 'Haiti would need a new generation of builders adept at pounding nails rather than mixing cement'.[20] Local designers have an important role in creating visions for clients to invest in bamboo buildings, but also in designing practical and durable structures. Bamboo structures need to be desirable, culturally relevant, functional, and strong.

In this vein, between 2014–17, the authors organised five architectural design and build workshops across Haiti focusing on building capacity for design awareness in bamboo. John Naylor from the Architectural Association School of Architecture, London, planned the academic programme. This was based on a theoretical rationale defined by Jane Wynne, from the Wynne Farm Ecological Reserve in Haiti, with a multitude of further individual and institutional support. The AA Haiti Visiting School as it became known (or AAVS Haiti) aimed to foster skills and champion bamboo as a sustainable construction material. Working with Haitian and overseas participants, the curriculum blended computational design and hands-on bamboo construction. Small groups developed concept designs, which displayed the opportunity for bamboo *[4]*.

Awareness of local challenges, practices, and architects' roles is essential when introducing a new

https://doi.org/10.1017/S1359135523000313 Published online by Cambridge University Press

4 Student work produced during the AAVS Haiti 2016 summer workshop. Participants designed core housing to be constructed using a full-culm bamboo primary structure.

material, especially one which might have negative societal attitudes attached to it, particularly so in this instance where building infrastructure is heavily reliant on concrete. Throughout the AAVS Haiti programme, this consistently posed a challenge. A deep understanding of the cultural and social context is pivotal for long-term material cultural change in construction. Attitudes to bamboo construction in Haiti are not dissimilar to those in other bamboo growing regions, which parallel the challenges faced by timber construction in Europe and the US. The way to address this requires localised responses.

On 27 May 2022, a symposium was held as a joint event between the Wynne Farm Ecological Reserve in Haiti, Newcastle University from the UK, and the University of Pittsburgh in the US. This symposium aimed to bring those with knowledge and interest in bamboo together to provide a platform for voices from the Haitian built environment to explore real-world challenges and identify the opportunities for alternative materials to concrete and steel.

Among the participants in the symposium was Jupille Facile, a former alumnus of AAVS Haiti and founder of *Bambou Facile*, a bamboo contractor and advocacy organisation. Isabelle Jolicoeur, a local architect, educator, and founder of *Aetypik*, a media platform that worked closely with the AAVS Haiti throughout the workshops. Nancy Leconte, a course tutor on three workshops in 2016 and 2017, and Rose Di Sarno, a Los Angeles-based architect and course tutor on three workshops from 2014 to 2016. The session was moderated by John Naylor, who asked pre-determined questions, and Elrica Metayer, an architect and educator in Haiti, who moderated the audience questions and contributed to the discussion. Questions were written prior to the event and shared with the participants one week prior to the session. What follows presents a summary of the discussions of the symposium.

Haitian construction and design professionals

It is hard to put an exact percentage on the number of buildings in Haiti that involve an architect or pursue regulatory approval. It is common knowledge, however, that the vast majority of construction in Haiti does not seek approval from a regulatory body. A significant proportion of buildings in Haiti are self-built. An indication of this is the ratio of architects per capita, estimated at one per 40,000. The actual approvals process in Haiti was noted to be geared towards establishing taxable assets, without adequate capacity to enforce code compliance or structural verification.

The public discourse on architecture and design can impact the informal construction sector in Haiti. For example, the architect is often referred to as an engineer: in many cases the word architect does not appear in conversation. When such situations occur, it is an opportunity to educate people and to draw attention to the role of an architect to foster conversation. An example of this is Aetypik, an online platform created in 2015 to showcase Haitian creativity and a virtual library of projects to make the architecture and urban design scene more accessible in Haiti. The Haitian licencing body for architects and engineers, the *Collège National des Ingénieurs et Architectes Haïtiens* (CNIAH), is making efforts to be more present in the public realm and to share training for professionals. The Internet has been an important tool for this, with an online register for architects and engineers. There is also *Kout Kreyon*: an initiative to connect and network young architecture, engineering, and construction professionals in Haiti.

In Haiti, it can be an effort to accompany a client throughout all the steps of design and construction, and to reinforce principles and maintain the needs of the end user, particularly where they are not the same person or organisation. The role of the architect in Haiti is dependent on good communication and interpersonal skills. Software can facilitate this, conveying design intent and reassure the client of progress. The design process followed by practicing architects in Haiti varies. However, there is significant use of Autodesk AutoCAD,[21] and Building Information Modelling (BIM) platforms such as Autodesk Revit. This allows offices to be more efficient and more productive, aiding the management of multiple projects at once. Not every practice in Haiti employs these tools but they are more mainstream than previously. Nevertheless, Haiti does not appear on the list of countries that receive software support, and even credit cards from Haiti are often not accepted. So there are obstacles in mainstreaming software in architecture, engineering, and construction professions in Haiti. The cost of licences is a big issue for the future capacity of designers. This is compounded by basic infrastructural challenges that confront software use such as inconsistent electricity provision or Internet access.

Materials, culture, and cost

Project clients seldom consider sustainability. Life in Haiti is sometimes described as 'urgency living', whereby immediate problems make it difficult to think years into the future. In Haitian building construction, clients typically ask for 'fast' and 'cheap', and rarely make environmental requests. Cost cutting typically impacts quality. A common occurrence, if not checked by professionals onsite, is steel rebar quality, which can, for example, reduce the performance of reinforced concrete columns. Material quality is also impacted by the need to import, which is significantly affected by inflation and currency fluctuations. Additionally, consumer protection is almost non-existent given the distance between producer and user involving imported materials. An example of this is in the imported steel, in which the dimensions of steel rebar are either wrongly advertised, or there is a lack of education in required specifications for use, resulting in the cheapest being ordered. Even those who do have the means to order to a suitable specification will sometimes find the wrong steel is delivered, it is of inadequate quality, or it is non-crenelated.

In Haiti, material purchasing roles are described as 'blurred' and 'informal'. In many cases, whoever the builder is – or, in the case of self-build projects, the end user – may be purchasing materials without any construction or material knowledge. In some cases, the client may have already purchased materials at the outset of the project. There is a suspicion of the contractor or architect purchasing materials, with concerns that contractors inflate prices to take a cut. When clients buy their own construction materials, they do not know the necessary specification or quality. In the case of concrete blocks, these sometimes can just deteriorate in your hand at the point of sale. This highlights the limited role of the architect or engineer to ensure material quality since ultimately the purchasing is going to be done by someone else. Good design, translating to a good quality building, requires a good quality of material. The builder – or *'boss'* – may be onsite all day, but in certain cases the architect or engineer will just come by once or twice a week. Physical absence of the architect or engineer creates a 'mistrust of professionals' that architects have to deal with. Therefore, before the project even kicks off, the architect has to justify and communicate their role.

There is potential for locally sourced materials to alleviate such problems. Locally sourced bamboo becomes an opportunity to decouple material costs from currency fluctuations and import problems. And it permits a proper bamboo preservation treatment and the inspection of material before purchase and delivery to site. The main challenge to bamboo or timber as an alternative to steel and concrete materials is a security concern, because insurance companies will not insure. A prevalent issue is that Haiti (more precisely Port-au-Prince) is experiencing extensive social and economic instability. So, a client may say 'OK, this is nice you've offered something different [bamboo], but, all in all, if someone fires bullet at my house, am I going to die?'.

Lightweight bio-based materials thus remain absent from the material palette of architects and engineers in favour of concrete masonry. A local lack of timber and timber construction expertise has made it more expensive to build with timber and social perceptions changed after major fires throughout Port-au-Prince and Jacmel, which pushed the cities to forbid use of wood in construction.

As seen with the renowned Gingerbread architecture of the nineteenth century,[21] Haiti was once a regional pioneer of timber frame construction *[5]*. Indeed, traditional timber construction has proved seismically resistant and many such structures survived the devastating 2010 Port-au-Prince earthquake. Gingerbread houses were built by skilled Haitian carpenters with an impeccable technique. Though originally an architecture for the elite, the style was influential, was copied and can promote the use of timber.

Haiti needs to diversify the construction material palette and provide inexpensive, locally sourced, quality materials. Lasting change to Haiti's construction sector change needs to be driven by local architects. Gingerbread architecture, indeed, provides a helpful precedent, thinking of Haitian architects who travelled to France in 1895 and returned to adapt the local resort style in response to local climate and culture. Innovation towards a new way of building has thus occurred before.

Bamboo in public and private building

Concrete has become prevalent in the consciousness of Haitian society as a modern, highly efficient, and fast material to build with. There is also the legacy of a 1925 ban on timber construction, which followed a fire in Port-au-Prince.[22] People *like* concrete, and it is perceived as easy to work with. The abundance of professionals who know how to work with concrete, mixed with a lack of alternatives, makes masonry construction a relatively low-cost 'go-to' means of construction. Further, there is a perceived link between natural materials and poverty, and therefore a perceived relationship with social status. This could, perhaps, be changed if bamboo was to be used in major buildings where the bamboo could demonstrate both structural adequacy and aesthetics.

Maintenance and additional costs would be a consideration with

5 A visit to the Gingerbread House, Maison Dufort, in the neighbourhood of Bois Verna, Port-au-Prince, as part of the AAVS Haiti 2016 course. Restoration by Fondasyon Konesans Ak Libète (Foundation for Knowledge and Liberty).

https://doi.org/10.1017/S1359135523000313 Published online by Cambridge University Press

timber and bamboo. As would be material availability, which could delay projects and a project programme already vulnerable to security issues. Another challenge is a current lack of knowledge in the construction sector.

When aware of the seismic risk, roughly 80% of thirty families that a symposium participant worked with responded that they preferred bamboo as a material, but they did not have the necessary skills and could not conceive a bamboo design that they would want to live in. Therefore, they chose concrete.

There is thus a combination of a lack of expertise, trust in new or unfamiliar construction materials, and psychological challenges in envisaging a liveable bamboo space; a series of factors that in combination present significant problems. Establishing design and construction capacity for bamboo, and presenting designs to the public, is critical for bamboo to be accepted by clients and end users alike. There would likely be no push back from clients if bamboo were to be suggested for elements like doors and windows, or shades. But clients are afraid to use it for more structural elements.

A market for bamboo could incentivise those with rural land to make money from planting bamboo. Since many of those who have migrated to the city from rural areas still own land in rural areas, this is an opportunity potentially available to even some of the poorest citizens in urban Haiti. As bamboo is introduced slowly into the public eye through projects, people will be interested in the economic opportunity that it creates. Cost remains a major consideration, but it is important to think too in terms of *value*. Clients in Haiti would invest in what is right, but if a client does not understand bamboo construction, or does not believe in it, a lower cost would not matter. Indeed, a potential first disaster with a bamboo structure risks crushing the whole endeavour instantly. Those who design and build with bamboo need to ensure their buildings are durable and well-constructed. The moment people see bamboo is a material that is accepted, it is easier for it to be trusted and copied.

A key challenge is that architecture in Haiti is not experienced equally

Big houses are hidden behind walls, and even places that are meant to be public are frequently concealed. Many are typically unaware that certain buildings are public. Possibilities have been considered for a bamboo-built culture centre and a current project on the island of La Gonave to the west of the Bay of Port-au-Prince. This project is a small market, and can become a space where visitors could engage with the bamboo itself.

Moving from larger public buildings to an element smaller than building scale, there is also an opportunity to replace basic '2x2' timbers with bamboo in the framing of roofing. This would need to be correctly articulated. Bolts or screws are required, not nails since ISO 22156 makes clear that driven nails or staples shall not be used to connect structural bamboo members unless as part of the construction of bamboo shear walls.[23] This application for bamboo could be significant for the large proportion of Haitians who live in so-called '*tol*', or metal sheet roofing houses. Many in the population are now converting to concrete roofing, particularly in areas with recent memories of hurricane damage to timber roofing, but a well-constructed bamboo roofing frame with metal sheet roofing could be a viable alternative system.

A roadmap for bamboo construction

People who grew up in Cap Haitian, the country's second city, were surrounded by people using bamboo for baskets. Education is the catalyst to convert attitudes from seeing it as a craft material to a building material. As discussed here, a material associated with crafts does not immediately exude construction material strength. Education in, and visibility of, bamboo construction is a potential catalyst to raise awareness, although fears of security remain a barrier.

Bamboo buildings should be seen widely. They could be demonstrated at a public event or fair, although the structures would need to be permanent. If seen only as a one-off novelty, it is difficult to demonstrate how the material reacts to everyday use and how it can be inhabited. The most meaningful application of bamboo in the longer term would be to introduce bamboo into housing, although this should perhaps not be in the poorest neighbourhoods, because of wider societal perceptions. This remains important. Conversely, if someone wealthy or famous were to use bamboo, or an institution or indeed a restaurant, then the wider effects could be positive. A hospital typology could also be a possibility, since society associates hospitals with safety, protection, and care.

In the light of climate change, Haiti has the potential to serve as an exemplar for a wider global shift away from manufactured building materials such as concrete and steel. In Haiti, unique vulnerabilities exacerbate global trends into acute local catastrophes. It may be a distinctively challenging context to introduce bamboo as a construction material, but it could be one of the most impactful and economical. As discussed here, with enough local demand for lightweight natural renewable materials from clients, those with barren unproductive land in Haiti could see an economic benefit from planting trees and bamboos. Design professionals and engineers have capacity to promote non-standard bio-based materials, and demonstrate that these materials are affordable, durable, and provide functional space. Over time, a growing body of built projects can also influence the informal sector. There is huge potential.

The 'Bamboo in Haitian Construction' symposium took place in a hybrid format at the Swanson School of Engineering, Benedum Hall, University of Pittsburgh, Pittsburgh, United States, 27 May 2022, in partnership with Newcastle University, UK and the Wynne Farm Ecological Reserve, Haiti.

Notes

1. Laurent Dubois, 'Who Will Speak for Haiti's Trees?', *New York Times*, 17 October 2016.
2. UNCCD, 'Third National Report of the Republic of Haiti - Executive Summary' (2006).
3. Ose Pauleus and T. Mitchell Aide, 'Haiti Has More Forest Than Previously Reported: Land Change 2000–2015', *PeerJ*, 8 (2020), e9919.4
4 Alex Bellande, 'Haïti Dans Le Marché Mondial Du Bois Aux 19ème Et 20ème Siècles: Commerce Et Environnement', *Journal of Haitian Studies*, 22 (2016), 130–46.
5. Marc J. Cohen, 'Diri Nasyonal Ou Diri Miami? Food, Agriculture and Us-Haiti Relations', *Food Security*, 5 (2013), 597–606.
6. CNBH, 'Code National Du Bâtiment D'haïti', ed. by Ministère

des Travaux Publics Transports et Communications (Ministère des Travaux Publics Transports et Communications, 2012), p. 200.
7. William B. Joyner, Richard E. Warrick, Thomas E. Fumal, 'The Effect of Quaternary Alluvium on Strong Ground Motion in the Coyote Lake, California, Earthquake of 1979', *Bulletin of the Seismological Society of America*, 71 (1981), 1333–49.
8. Athena R. Kolbe, Royce A. Hutson, Harry Shannon, Eileen Trzcinski, Bart Miles, Naomi Levitz, Marie Puccio, Leah James, Jean Roger Noel, Robert Muggah, 'Mortality, Crime and Access to Basic Needs before and after the Haiti Earthquake: A Random Survey of Port-Au-Prince Households', *Medicine, Conflict and Survival*, 26 (2010), 281–97.
9. Peter Haas, 'When Bad Engineering Makes a Natural Disaster Even Worse', TED (2010) <https://www.ted.com/talks/peter_haas_when_bad_engineering_makes_a_natural_disaster_even_worse> [accessed 13 July 2020].
10. Reginald Desroches, Mary Comerio, Marc Eberhard, Walter Mooney, Glenn Rix, 'Overview of the 2010 Haiti Earthquake', *Earthquake Spectra*, 27 (2011), S1–S21.
11. Tracy Kijewski-Correa, Alexandros A. Taflanidis, Dustin Mix, Ryan Kavanagh, 'Empowerment Model for Sustainable Residential Reconstruction in Léogâne, Haiti, after the January 2010 Earthquake', *Leadership & Management in Engineering*, 12 (2012), 271–87.
12. Duong Huynh, Janaki Kibe, Josie McVitty, Delphine Sangodeyi, Surili Sheth, Paul-Emile Simon, David Smith, 'Housing Delivery and Housing Finance in Haiti: Operationalizing the National Housing Policy' (Oxfam America, 2013).
13. NSR-10, 'Nsr-10: Título G – Estructuras De Madera Y Estructuras De Guadua', ed. by Ministerio de Ambiente Vivienda y Desarrollo Territorial (Ministerio de Ambiente Vivienda y Desarrollo Territorial, 2010).
14. Laurent Dubois, *Haiti: The Aftershocks of History* (New York, NY: Henry Holt and Co., 2012).
15. Walter Liese, and Thi Kim Hong Tang, 'Properties of the Bamboo Culm', in *Bamboo: The Plant and Its Uses*, ed. by Walter Liese and Michael Köhl (Springer, Cham, 2015), pp. 227–56.
16. Ratan Lal Banik, 'Bamboo Silviculture', in *Bamboo: The Plant and Its Uses*, ed. by Liese and Köhl, pp. 113–74.
17. Hui Yang, Zhengyi Cao, Xueliang Jiang, Yixian Wang, 'Experimental Study on the Deformation and Mechanical Properties of Bamboo Forest Slopes', *Applied Sciences*, 13 (2022).
18. Ben-Zhi Zhou, Mao-Yi Fu, Jin-Zhong Xie, Xiao-Sheng Yang, Zheng-Cai Li, 'Ecological Functions of Bamboo Forest: Research and Application', *Journal of Forestry Research*, 16 (2005), 143–7.
19. Cameron Sinclair, 'The Role of the Architect in Rebuilding Haiti: To Compete or to Construct?', *Huff Post* (2010) <https://www.huffpost.com/entry/the-role-of-the-architect_b_453905> [accessed 16 July 2020].
20. Jayne Merkel and Craig Whitaker, 'Rebuilding from Below the Bottom: Haiti', *Architectural Design*, 80 (2010), 128–34.
21. Gingerbread timber-framed architecture was designed with raised foundations, shaded and well-ventilated spaces, which align with the modern durability guidelines of ISO 21887:2007 for timber and ISO 22156:2021 for bamboo. Regrettably, in many contemporary timber and bamboo structures seen worldwide today, these techniques are often overlooked. See: Columbia University GSAPP, 'The Gingerbread Houses of Port-Au-Prince, Haiti' (New York, NY: Columbia University, 2016), p. 82.
22. Randolph Langenbach, Stephen Kelley, Patrick Sparks, Kevin Rowell, Martin Hammer, Olsen Jean Julien, 'Preserving Haiti's Gingerbread Houses: 2010 Earthquake Mission Report', ed. by Erica Avrami (World Monuments Fund, 2010).
23. ISO 22156, 'Bamboo Structures – Bamboo Culms – Structural Design (Iso Standard No. 22156:2021)' (ISO/TC 165 Timber structures, 2021).

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The Authors, all images.

Acknowledgements
The 'Bamboo in Haitian Construction' symposium was supported by the Global Partnerships Fund, administered through Newcastle University's International Relations and Partnerships team. The authors would like to thank Dr Kent Harries, Chase Rogers, Nancy Leconte, Isabelle Jolicoeur, Jupille Facile, Rose Di Sarno Elrica Metayer, and Ginette Baussan who provided support, insight and expertise, although interpretations, conclusions, and any errors in this article are the authors' own. Author contributions: writing and editing, JN; conceptualisation and review of published version, JN and JW.

Competing interests
The authors declare none.

Authors' biographies
Jane Wynne was born in Carrefour and is a steward of the Wynne Farm Ecological Reserve in Kenscoff, Haiti. The farm prioritises soil conservation, employing terracing and environmentally friendly cultivation techniques. Building on the farm's foundational practices, Jane addresses Haiti's deforestation and advocates for sustainable agricultural approaches. She studied at Union School in Haiti and 'Anna Maria College, Paxton, Massachusetts, United States, earning a degree in Sociology. She has collaborated with several organisations including the Federation of Friends of Nature, GAFE, Her Many Voices, Earth Givers, and the Smallholder Farmers Alliance.

John Naylor is a UK-based architect and educator at the AA Visiting School. He gained his diploma at the Architectural Association in 2013, winning the Foster's Prize for Sustainable Infrastructure. He has worked at MAD, Beijing and Grimshaw Architects, London. In 2014 he set up the AA's bamboo Visiting School programme in Haiti, which continues as the AA-ITB BambooLab global programme. He is currently studying for a PhD at Newcastle University examining capacity-building design awareness for bamboo, incorporating digital tools, with a continued focus on Haiti.

Authors' affiliations
Jane Wynne, Wynne Farm Ecological Reserve, Haiti.

John Naylor, Newcastle University, United Kingdom.

Authors' addresses
Jane Wynne
jane@wynnefarm.org

John Naylor
j.naylor73@newcastle.ac.uk

https://doi.org/10.1017/S1359135523000313 Published online by Cambridge University Press

Appendix F: Knowledge Gaps and Research Needs for Bamboo in Construction

Conference paper

Published as: Harries, K., et al. (2022). Knowledge Gaps and Research Needs for Bamboo in Construction. 18th International Conference on Non-conventional Materials and Technologies (NOCMAT 2022).

International Conference on Non-conventional Materials and Technologies
NOCMAT 2022

KNOWLEDGE GAPS AND RESEARCH NEEDS FOR BAMBOO IN CONSTRUCTION

Kent A. Harries, University of Pittsburgh, USA, kharries@pitt.edu
Amir Mofidi, Brock University, Canada, amofidi@brocku.ac (formerly Newcastle University, UK)
John Osmond Naylor, Newcastle University, UK
David Trujillo, Coventry University, UK
Luis Felipe Lopez, Base Bahay, The Philippines
Mateo Gutierrez, CLTP Tasmania
Bhavna Sharma, University of Southern California, USA
Chase Rogers, University of Pittsburgh, USA

ABSTRACT
In November 2021, a symposium was held to identify knowledge gaps, and research needs and priorities in the bamboo community. Participants who were asked to complete a post-symposium survey on research gaps, needs and priorities. Both rank-order and open-ended questions were asked covering the broad areas of i) determination of material properties, testing and grading; ii) bamboo connection techniques and technology; iii) bamboo durability and fire performance; and, iv) construction using engineered bamboo. This paper reports the survey and its results. Subsequent discussion identifies priorities for future research that can be leveraged to move the use of bamboo in construction forward.

KEYWORDS
bamboo; connections; construction; durability; engineered bamboo; fire performance; grading; material properties; research needs

INTRODUCTION

In November 2021, a symposium - *Bamboo in the Urban Environment IV* - was held to identify knowledge gaps, and research needs and priorities as perceived by the bamboo community. The symposium attracted 240 unique participants (Table 1) who were asked to complete a post-symposium survey on research gaps, needs and priorities. 42 responses (18%) were received representing a range of stakeholders from at least 12 countries. Both rank-order and open-ended questions were asked covering the broad areas of i) determination of material properties, testing and grading; ii) bamboo connection techniques and technology; iii) bamboo durability and fire performance; and, iv) construction using engineered bamboo. This paper reports the survey and its results. The co-authors include the Symposium organisers and facilitators of each session (Table 1). The objective of the symposium and survey was to identify priorities for future research that can best be leveraged to move the use of bamboo in construction into the mainstream.

Each Symposium session included four invited speakers [1], followed by an open forum from which lists of research gaps and needs were developed – these formed the basis of the survey reported in this paper.

Table 1: Session titles and attendance

Session	attendance in session	views of recorded session[1]
Materials and Systems Testing and Grading	113	112
Connections for Bamboo Structures	140	98
Fire Performance and Durability of Bamboo Structures	104	106
Engineered Bamboo	64[2]	91

[1] as of 19 February 2022
[2] due to a scheduling error, few people attended the fourth session.

Post Symposium Survey
The post symposium survey announcement was distributed to all 240 unique attendees of the Symposium. 42 (18%) responses were received. Not all respondents replied to all questions.

Of the respondents who identified their interest, 24 were academic researchers, 6 were involved in the bamboo construction industry, 8 had an interest in bamboo, and 9 identified as being new to bamboo construction; some respondents identified more than one interest category while some did not respond to this question.

Survey responses came from at least (some respondents did not identify their country of origin): Australia, Brazil, Colombia, Ethiopia, Hungary, Indonesia, Kenya, Malaysia, New Zealand, The Philippines, UK and USA. It is understood that the survey may not have been available in some countries that filter internet activity without use of a foreign VPN.

SURVEY RESULTS
The survey required participants to place in rank order, 1 to 5, their top five perceived gaps and top five research priorities from a list of items generated in the symposium sessions. The eight ranking questions are reported in the following sections; the ranked items are reported in Figures 1 through 4. The weighted score – reported in Figures 1 through 4 – for each item was determined by summing the weighted number of votes received:

$$\text{weighted score} = 5r_1 + 4r_2 + 3r_3 + 2r_2 + r_1$$

where r_n is the number of votes received for rank n. That is, a first rank vote is assigned 5 points, a second rank: 4, etc.

Bamboo material properties, testing and grading

Q1: Rank the top five ***perceived gaps*** *in the current state-of-practice or knowledge of bamboo in* ***determination of material properties, testing and grading****.*

Q2: Assuming reasonable and/or obtainable levels of funding/resources, rank the top five ***research priorities*** *likely to advance the state-of-the-art of bamboo in* ***determination of material properties, testing and grading*** *over the next decade.*

The weighted results for questions 1 and 2 are reported in Figure 1. The ranking in this topic was dominated by the need for higher education to include aspects of engineering design and engineering with bamboo and the need for a global database of bamboo geometric, physical and mechanical properties. The next five ranked items are arguably related to the development of a practical and usable database.

Although at the bottom of the survey rankings, considerable discussion of developing better understanding weak matrix properties of the bamboo was recorded during the symposium open forum. Another issue raised in the symposium and not captured in the survey is investigating the potential for supervised machine learning to be deployed in a database of bamboo geometric, physical and mechanical properties as it develops. Machine learning can be used to discover underlying correlations and derive secondary properties.

Another issue that was raised in the symposium (in multiple sessions) was the need to strengthen the supply chain for bamboo beginning with propagation. Issues of plantation needs were raised to produce enough bamboo of high quality to increase user confidence. As Professor Juan Correal put it, we "need to start the grading from the field".

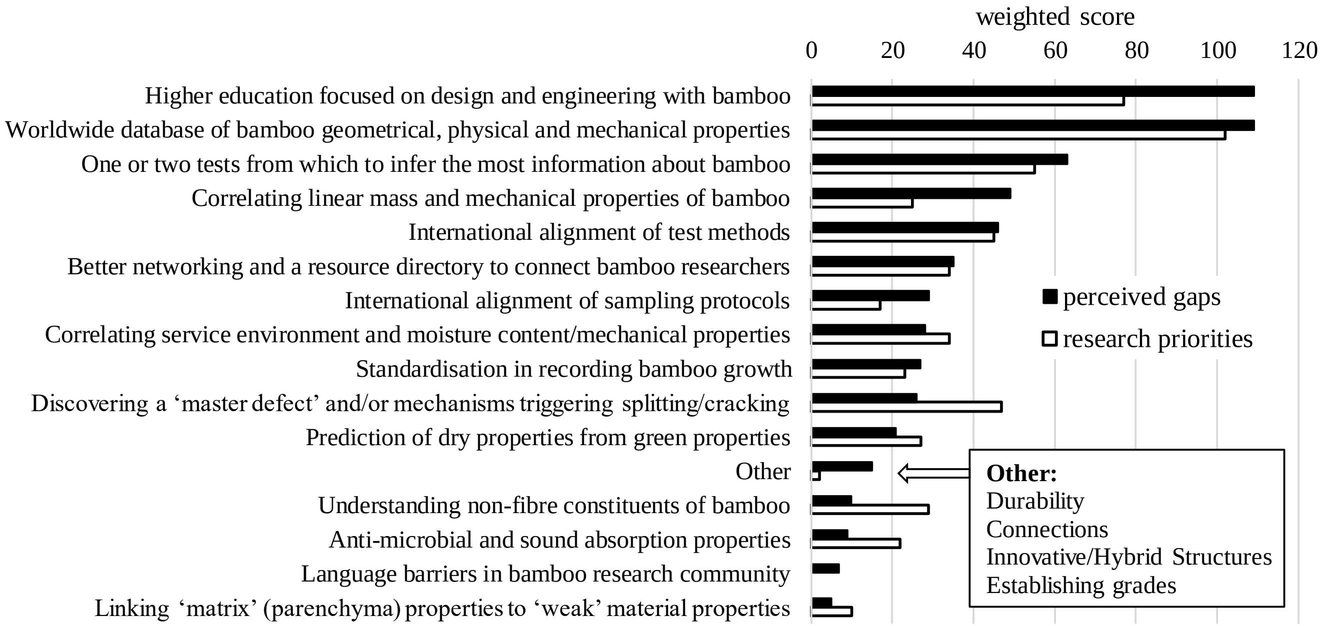

Figure 1: Weighted responses and ranking of Q1 and Q2.

Bamboo connections

*Q3: Rank the top five **perceived gaps** in the current state-of-practice or knowledge of **bamboo connection techniques and technology.***

*Q4: Assuming reasonable and/or obtainable levels of funding/resources, rank the top five **research priorities** likely to advance the state-of-the-art of **bamboo connections** over the next decade.*

The weighted results for questions 3 and 4 are reported in Figure 2. The need for predictability, and ways of avoiding splitting in bamboo connections was identified as a research priority. Otherwise, this ranking was relatively uniform. The second and third ranked items: understanding connection failure modes and correlating these with mechanical properties are intimately related, and thus lead the response. Interestingly, the specific issue of multiple culm elements received little interest in the survey responses. The environmental impact of the materials used in connections was ranked low as both a gap and priority. The potential for collaboration and integration with the [specialty] connector-manufacturing industry was raised in the symposium session.

The question was asked in the symposium *does bamboo **need** to be reinforced?* This led to discussion of identifying appropriate culm infill materials such as bamboo sawdust-resin paste, rather than cementitious grout as is presently used. The issue of potential thermo-mechanical mismatch of such infill materials was raised.

Not having a separate ISO standard for connections was perceived as a research gap, which shows that even though this is not a priority, moving towards this in the future makes sense.

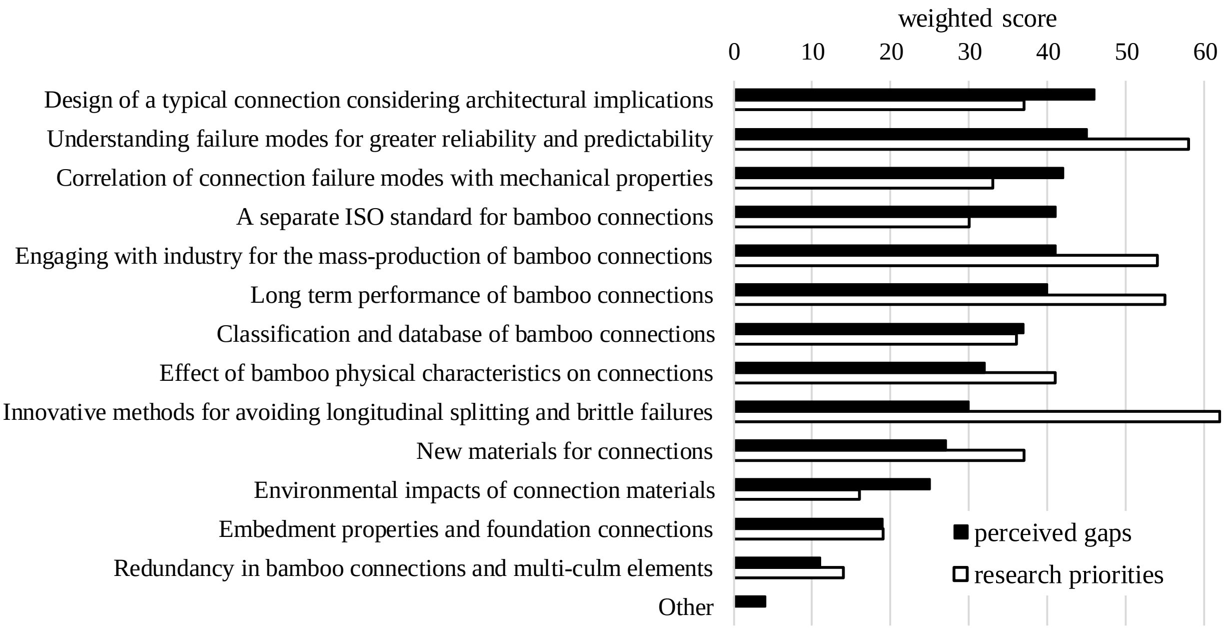

Figure 2: Weighted responses and ranking of Q3 and Q4.

Bamboo durability and fire performance

*Q5: Rank the top five **perceived gaps** in the current state-of-practice or knowledge of **bamboo durability and fire performance.***

*Q6: Assuming reasonable and/or obtainable levels of funding/resources, rank the top five **research priorities** likely to advance the state-of-the-art of **bamboo durability and fire performance** over the next decade.*

The weighted results for questions 5 and 6 are reported in Figure 3. Issues of fire performance were ranked 1, 2, 3 and 5 suggesting greater interest in fire performance or the view that durability is adequately understood but perhaps not integrated into design ('durability by design' was ranked 4). The preponderance of engineers in the group responding the survey may have skewed the results of this question.

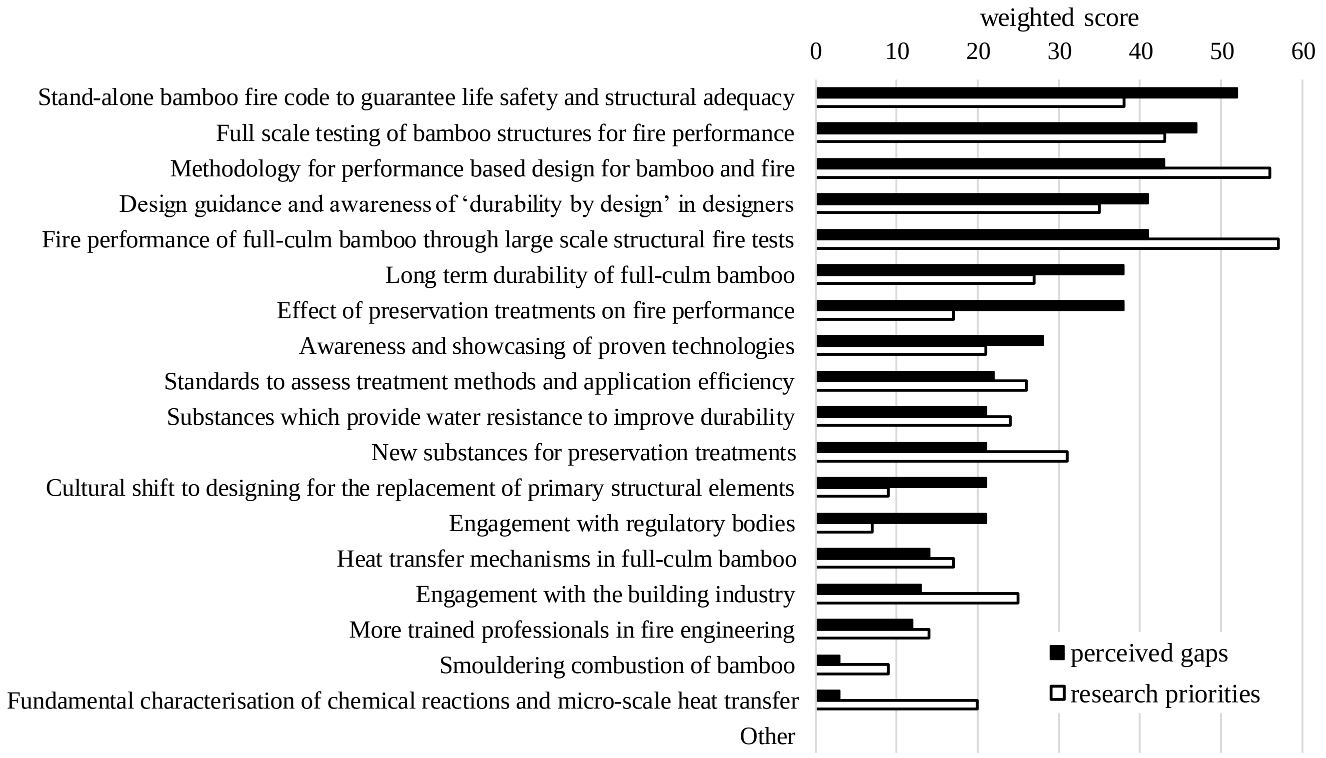

Figure 3: Weighted responses and ranking of Q5 and Q6.

Engineered bamboo construction

*Q7: Rank the top five **perceived gaps** in the current state-of-practice or knowledge of **construction using engineered bamboo.***

*Q8: Assuming reasonable and/or obtainable levels of funding/resources, rank the top five **research priorities** likely to advance the state-of-the-art of **construction using engineered bamboo** over the next decade.*

The weighted results for questions 7 and 8 are reported in Figure 4. When considering engineered bamboo, durability appears to be of primary interest (ranked 1 and 2), and fire performance received a similar score. The fire performance of resins in engineered bamboo products is perceived as a large research gap. In the session it was noted that in the cross-laminated timber (CLT) field there are adhesives which claim to have particular fire performances, but still lack confidence among designers.

Other topics discussed in the symposium session included the potential for chemical modification (in addition, or as an alternative to densification, delignification, and the sustainability of chemicals used in the manufacturing process. Tannin, lignin, polyurethane, and castor oil based resins appear promising for outdoor use since they are stable.

A general need to increase materials efficiency in the manufacture of engineered bamboo was identified**.**

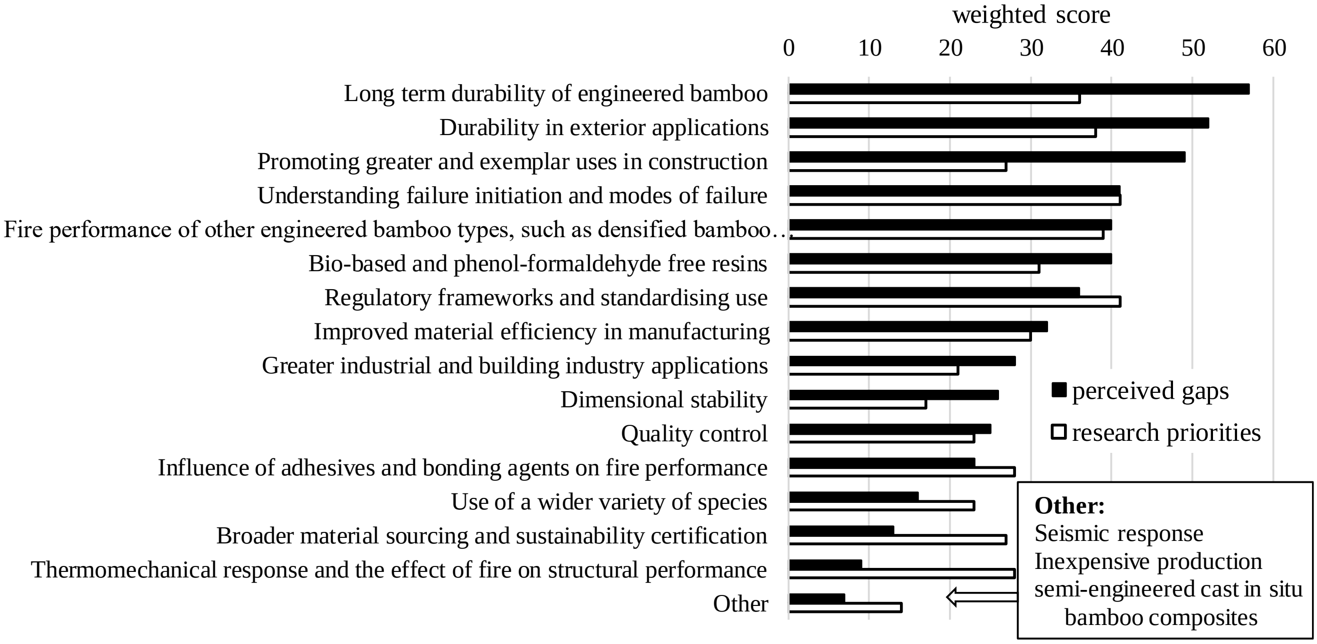

Figure 4: Weighted responses and ranking of Q7 and Q8.

Open-ended questions
Respondents were asked two open-ended questions. The questions and unedited responses received are below:

Q9: Given unlimited resources, please identify a single research priority likely to advance the state-of-the-art of bamboo (including engineered bamboo) construction.

- Simple, universal connections
- Improve joints efficiency, durability, ductile-modes, facility of construction, keeping in mind architectural considerations
- A data mapping of different bamboo species and their maxim[um] construction capability
- Standards connection of engineered bamboo
- Durability of bamboo for exterior use
- Improved fire resistance
- Understanding the impact of moisture content and thermal densification on Engineered bamboo products
- Test Standardization
- Preservation of bamboo used for construction. Information dissemination of bamboo species that are best suited for each climate type
- Bamboo Pole and Engineered Bamboo Connection
- Bamboo potential to decarbonize building construction sector
- Acoustical Properties
- More efficient and cheaper treatment, waterproofing, and adhesive products
- Cast-in-situ semi-engineered bamboo composite structural elements
- Zero Energy Bamboo Buildings
- Commercialisation of universal connectors for bamboo culms
- Material properties database
- Better knowledge and design guidance on bamboo connections

- Large scale pilot testing scheme with international collaboration to cover all major species and engineered bamboo products
- Research integrating bamboo and nanotechnology
- Wide[spread] use and manufacturing of engineered bamboo
- Durability study
- Research mechanical and physical property of bamboo species
- Long term durability
- Development of Codes and curriculum for engineered bamboo construction.
- Finding the cause of splitting and finding the solutions
- Research on mechanical grading of bamboo for industrialization applications
- Mapping the best uses of each bamboo species focusing on creating a world-wide industry capable of supplying the world demand for new buildings (using bamboo to decarbonize civil construction)

Of the 28 responses to this question received: 4 identified connections, 4 identified the need for a database or properties, 3 identified durability and 3 identified the development of codes and standards as the single greatest research needs.

Q10 Please provide any other comments and/or observations on research needs and gaps in the field of bamboo construction.

- Long time behavior of structures
- Advance mapping on the different species of bamboo and their maximum construction potential
- Education of bamboo structures is fundamental for the next decade
- Durability of bamboo in terms of strength, fire resistance, and moisture problem
- Densified bamboo connection to assess its full performance within the building and construction industry
- I really like the idea of one or two (likely would have to be two tests, something simple for E [modulus of elasticity] and deflection, and then a shear test for limiting failure behavior) to get a good understanding of the actual bamboo for design purposes. I would have [given] this more priority in rankings, but I am not sure it has nice solution. It was described as the "holy grail" for bamboo testing and design, and I've not sure anyone has found the Holy Grail, and the difficulty level may be similar.
- Detailed discussion on connections and innovative use of bamboo
- Bamboo Pole Connection
- Connections
- Engineered bamboo is the future, but cheaper machines need to be designed and supplied to encourage the opening of new companies in this field, and even for more researchers to carry out their investigations. Bamboo research must be multidisciplinary. It needs the joint work of engineers, architects, chemists, designers, agronomists, among others.
- The research community might be best to communicate with the manufacturing industry in a more advanced level to take a cut-edge lead rather than usage of the existing industrial products in research.
- How many storeys can be [achieved; is a] bamboo skyscraper [possible]? [*paraphrased by authors*]
- Greater integration with design professions
- Design code and awareness of bamboo construction among professional engineers/ builders
- Science, Technology & Innovation Metrics for non-conventional materials and technologies
- Need for changing public perception
- Workable connection details

- Bamboo bioenergy, Bamboo knowledge share to African Countries
- Standardisation and grading of bamboo per country
- [Much] research had been conducted just for the sake of the research, less relevant to the practice on the field. Action research should be done more often, combining research and practice on the real scale.
- Durability of bamboo and engineered bamboo to fire and water
- The adoption of bamboo in many countries, in special Europe, North America, and Oceania, will depend on the development of sustainable, durable, and non-toxic (throughout the whole processing chain) engineered bamboo products.

Here, 22 additional comments were received. Again, 4 identified connections and 3 identified durability as concerns. 6 respondents added comments regarding collaboration and/or the need for better education, outreach and advocacy for bamboo. These issues were not well captured in the ranking questions.

OTHER OBSERVATIONS

A few responses identified the need for better (less expensive) machining and processing equipment. This is an aspect of bamboo research that tends to be ignored. Most bamboo processing methods are adopted from other industries.

Very few responses identified the sustainability credentials of bamboo as being an important gap or research need. Nonetheless, this is often the basis of the primary argument for adopting bamboo as a construction material. Improved methods of validating the carbon sequestration and embodied carbon information of bamboo would be beneficial to designers, engineers and clients alike.

REFERENCES

[1] Recordings of *Bamboo in the Urban Environment IV* Symposium sessions can be found at: https://conferences.ncl.ac.uk/4th-bamboo-itue/linkstopresentations/

ACKNOWLEDGEMENT

The *Bamboo in the Urban Environment IV* Symposium was supported by the Newcastle University International Partnership Fund in collaboration with the University of Pittsburgh. The authors gratefully acknowledge all Symposium speakers: Dr. Caori Takeuchi, Dr. Juan Francisco Correal, Dr. Patrick Dixon, Dr. Elias Dimitrakopoulos, Dr. Jose Jaime Garcia, Dr. Andry Widyowijatnoko, Dr. Jose Torero Cullen, Dr. Angela Solarte, Mr. Sebastian Kaminski, Dr. Christian Gauss, Mr. Ariel Rabik, Dr. Rory Hadden and Dr. Mahmoud Ashraf. Finally, the authors acknowledge all Symposium participants and survey respondents.

CONFLICT OF INTEREST

The authors declare that they have no conflicts of interest associated with the work presented in this paper.

DATA AVAILABILITY

Data on which this paper is based is available from the authors upon reasonable request.

Appendix G: Survey results: Q1 - Impressions of “bamboo architecture”

Q1 survey response	**Applied theme 1**	**Applied theme 2** ***(if more than one)***
sostenible	Sustainable/Ecological	
Flexibilidad	Flexible	
Revolutionary	Innovation	
vernacular architecture	Vernacular	
sustainable, laborious	Sustainable/Ecological	Challenging
sustainable	Sustainable/Ecological	
Sustainability, Natural	Sustainable/Ecological	Natural
sustainable, underrated	Sustainable/Ecological	Underrated
Sostenible	Sustainable/Ecological	
light and sustainable structure	Sustainable/Ecological	Lightweight
Vernacular Architecture	Vernacular	
Flexible & beautiful	Flexible	Beautiful
tropical	Tropical	
Sustainable	Sustainable/Ecological	
region specific	Region specific	
Natural	Natural	
interesting concept	Interesting	
Unfamiliar, cheap	Cheap	Unfamiliar
Renewable!	Renewable	
Sustainable, renewable	Sustainable/Ecological	
Clean	Clean	
familiarity	Familiarity	
vernacular	Vernacular	
Kengo Kuma	Kengo Kuma	
intriguing	Interesting	
smart & modern	Modern	
sustainable	Sustainable/Ecological	
fast growing	Fast growing	
Material Systems!	Material systems	
Natural / low embodied carbon	Natural	Sustainable
Sustainable	Sustainable/Ecological	
Amazing energy	Positive opinion	
Ecológico	Sustainable/Ecological	
Parametric design	Parametric design	
Tropical	Tropical	
sustainable	Sustainable/Ecological	
Intuitive attraction	Intuitive	
Conexión natural	Natural	
Creativity and warmth	Creative	Warmth
Fascinating, inspiring	Inspiring	
extreme interest	Interesting	
future and flexibility	Flexible	
Amazing energy	Positive opinion	

Structural weaving	Structural	Weaving
vernacular	Vernacular	
Future	Future	
consciousness architecture	Consciousness	
sustainable	Sustainable/Ecological	
Integrity of Nature	Natural	
Sustainable, Low-Cost	Sustainable/Ecological	Cheap
Sustainable, renewable	Sustainable/Ecological	
too hyped	Too-hyped	
Green Wood	Sustainable/Ecological	
Environmental Interventions	Sustainable/Ecological	
tropical	Tropical	
Sustainable design	Sustainable/Ecological	
Amazing potential	Positive opinion	
tropical architecture	Tropical	
organic sustainable	Organic	Sustainable/Ecological
Tropical, light-weight, temporary	Tropical	Lightweight
Sustainable	Sustainable/Ecological	
Sustainable, cheap	Sustainable/Ecological	Cheap
Flexible and natural	Flexible	Natural
ecological	Sustainable/Ecological	
Tiki Bar	Tiki bar	
vernacular, Asia	Vernacular	Asia
Exotic	Exotic	
Sustainable and temporary	Sustainable/Ecological	Temporary
sustainable organic	Sustainable/Ecological	Organic
Sustainable	Sustainable/Ecological	
I have seen spectacular bamboo buildings in south-east Asia. Yes, it can be spectacular but it can also be very simple/simplistic, depending on the design and engineering.	Potential	
lightness and beauty	Lightweight	
Future	Future	
Amazing	Amazing	
Vernacular - ecological	Vernacular	Sustainable/Ecological
impressive	Positive opinion	
Strong; sustainable	Sustainable/Ecological	Strong
Great	Positive opinion	
Ideal for Haiti	Relevant for Haiti	
Flexible	Flexible	
cool	Cool	
amazing	Amazing	
Bamwho?		
Natural	Natural	
Impressive	Positive opinion	
sustainable	Sustainable/Ecological	
Naturaleza	Natural	
Arquitectura sostenible	Sustainable/Ecological	

Acogedor, fresco	Cosy	Cool
Arquitectura sostenible	Sustainable/Ecological	
amigable al medio ambiente	Sustainable/Ecological	
Frescura	New	
Sostenibilidad y Regionalismo	Sustainable/Ecological	Local/Regional
sostenible, local	Sustainable/Ecological	Local/Regional
New World	Future	
Sustainable, green architecture	Sustainable/Ecological	
innovador, lenguaje expresivo	Innovative	Expressive
Sostenible	Sustainable/Ecological	
Sustainable	Sustainable/Ecological	
sustainable green	Sustainable/Ecological	
Sustainability	Sustainable/Ecological	
Versatile	Versatile	
Creative, innovative	Innovation	Creative
structural stability	Stability	
Good	Good	
sustainable	Sustainable/Ecological	
culturally rich	Vernacular	
innovation	Innovation	
Tropical opportunity	Tropical	Opportunity
exciting	Exciting	
Naturaleza	Natural	
Arquitectura Sostenible	Sustainable/Ecological	
Pure nature	Natural	
Como su propia lema dice acero verde.	Sustainable/Ecological	Strong
Eco-friendly architecture	Sustainable/Ecological	
Sustainable	Sustainable/Ecological	
multifunction and flexible	Flexible	
Sustainable , Parametric	Sustainable/Ecological	Parametric design
green material	Sustainable/Ecological	
beauty of nature in architecture material	Natural	
Durability	Durability	
Interesting topic	Interesting	
unique and beautiful	Beautiful	
Sustainable Material	Sustainable/Ecological	
Flexibility	Flexible	
environmental friendly	Sustainable/Ecological	
cool ambience	Cool	
sustainable	Sustainable/Ecological	
Organic	Organic	
vernacular	Vernacular	
Fast	Fast	
Organic form	Organic	
Potential	Potential	
Innovative	Innovation	
interesting	Interesting	
functional	Functional	

flexible design	Flexible	
Impressive	Interesting	
Sostenibilidad	Sustainable/Ecological	
culture	Vernacular	
Elegant	Elegant	
organic form	Organic	
Sustainable	Sustainable/Ecological	
Sustainable and traditional	Sustainable/Ecological	
Sustainable	Sustainable/Ecological	
Interesting	Interesting	
Natural, low carbon	Sustainable/Ecological	Natural
Sustainable, Weak	Sustainable/Ecological	Weak
natural, tropical	Natural	Tropical
Innovative	Innovation	
Lightweight	Lightweight	
Innovative	Innovation	
Sustainable, aesthetic	Sustainable/Ecological	Beautiful
Light, sustainable	Lightweight	Sustainable/Ecological
Tactile	Tactile	
natural building, sustainable	Natural	Sustainable/Ecological
Adaption	Flexible	
Green, Environment Friendly	Sustainable/Ecological	
material that cool	Positive opinion	
green traditional	Traditional	Sustainable/Ecological
Sustainable and cheap	Sustainable/Ecological	Cheap
Sustainable and porous	Sustainable/Ecological	Porous
strong and flexible	Strong	Flexible
Sustainable	Sustainable/Ecological	
Sustainable	Sustainable/Ecological	
So wonderful	Positive opinion	
natural resource	Natural	
sustainable, natural	Sustainable/Ecological	Natural
eco friendly	Sustainable/Ecological	
organic, natural	Organic	Natural
interesting	Interesting	
sustainable, high-maintenance	Sustainable/Ecological	High-maintenance
so flexible in use	Flexible	
Temporary Structure	Temporary	
sustainable	Sustainable/Ecological	
very interesting and amazing	Positive opinion	Interesting
Sustainable	Sustainable/Ecological	
Sustainable Future Material	Sustainable/Ecological	
sustainable	Sustainable/Ecological	
ethnic	Ethnic	
vernacular & sustainable	Vernacular	Sustainable/Ecological
Natural and strong	Natural	Strong
light and sustainable	Sustainable/Ecological	Lightweight
why	Why	
flexible structures	Flexible	
new	New	

interesting, sustainable	Interesting	Sustainable/Ecological
raw , sustainable	Sustainable/Ecological	Natural
Sustainable	Sustainable/Ecological	
Rural	Rural	
Strong structure	Strong	
intriguing	Interesting	
Interesting	Interesting	
Natural	Natural	
Interesting and unique	Interesting	Unique
flexible	Flexible	
Natural & Organic	Natural	Organic
interesting	Interesting	
cheap, sustainable	Cheap	Sustainable/Ecological
Cool and sustainable	Positive opinion	Sustainable/Ecological
eco-friendly, sustainable		Sustainable/Ecological
Renewable Solution	Sustainable/Ecological	
nature product	Natural	
eco-friendly.	Sustainable/Ecological	
traditional	Traditional	
malleable	Flexible	
Natural, raw	Natural	
Weak	Weak	
environmentally friendly	Sustainable/Ecological	
sustainable	Sustainable/Ecological	
traditional	Traditional	
rural, nature	Rural	Natural
organic form	Organic	
Does not look long-lasting	Temporary	
sounds interesting	Interesting	
Strength and Beauty	Beautiful	
Green architecture	Sustainable/Ecological	
natural , organic	Natural	
Natural and Eye-Pleasing	Natural	
Vernacular Architecture	Vernacular	
exceptional	Exceptional	
Flexible architecture	Flexible	
Tropical	Tropical	
The future	Future	
FLEXIBLE	Flexible	
interesting, new	Interesting	New
tropical, low carbon	Tropical	Sustainable
Lightweight. Sustainable.	Lightweight	Sustainable/Ecological
Flexible construction	Flexible	
flexible sustainable	Sustainable/Ecological	Flexible
Natural, respectful	Natural	
Vernacular	Vernacular	

Appendix H: Survey results: Q2 – Responses to “Which do you personally think is the biggest challenge when designing for bamboo?”

Q2 Survey response	Applied theme 1	Applied theme 2 *(if more than one)*	Applied theme 3 *(if more than two)*
A la hora de diseñar el techo es complicado por la posición de las cerchas pero sí es posible.	Natural variability		
A veces la normativa no permite usarlo para estructura	Standardisation	Structural knowledge and calculation	
acceptance by the population and finding skilled workers.	Societal/client attitudes	General knowledge/awarenes s	
Acceptance from construction industries and building regulations	Regulation		
Adapting the material to alternate climates because of the different natural disasters and	Locations of construction	Climate	

varying climate changes.			
attach-joint	Joinery/connections		
Availability	Supply chain		
availability and skilled labor	General knowledge/awareness	Supply chain	
Availability, suiting the surprising areas in the UK	Supply chain		
bamboo material treatment	Treatment		
Bamboo needs to be protected by design.	Durability/maintenance		
bamboo wears out very easily when exposed to rain and sunlight	Durability/maintenance		
Because I have never worked with bamboo so I would not know the functions and uses unless I do my research. The only time I have seen bamboos are used in Singapore are for	General knowledge/awareness		

furniture and drying poles.			
Buckling potention	Structural knowledge and calculation		
Building the project	General knowledge/awareness		
calculating de joints	Joinery/connections		
challenge to imagine	General knowledge/awareness		
Climate and location consideration	Locations of construction		
Comfort	Comfort / Thermal bridging		
competitiveness	Competitiveness		
connection	Joinery/connections		
conocer el material	General knowledge/awareness		
construction capability	General knowledge/awareness		
construction detail	Joinery/connections		

Convincing the client	Societal/client attitudes		
Convincing the clients	Societal/client attitudes		
Convincing the general public to accept it	Societal/client attitudes		
Creating a structure that lasts as long as a steel, concrete and masonry structure.	Durability/maintenance		
Curvature of bamboo when using it to create a structure.	Natural variability		
Curve, resistance	Natural variability	Durability	
Curved in the Bamboo	Natural variability		
cutting bamboo	Supply chain		
Decay	Durability/maintenance		
Don’t know. Willing to learn	General knowledge/awareness		
Double Story structures?	Limited scale of construction		

Durability	Durability/maintenance		
Durability	Durability/maintenance		
durability & shrinkage	Durability/maintenance		
Durability of the material	Durability/maintenance		
durability/ having to maintain once built	Durability/maintenance		
each piece is unique and has a different strength. Knowing how to choose the appropriate pieces to construct with, and when the bamboo is mature to harvest	Natural variability	Supply chain	
Education. Challenging perceptions that bamboo is a weak construction material.	Societal/client attitudes	General knowledge/awareness	
Encontrar cañas aptas a la hora de construir	Supply chain		

Ensamblar	Joinery/connections		
Estabilidad	Structural knowledge and calculation		
Even though it's flexible, the durability and the strength itself is limited. Better treatment and reinforcement is needed to enhance its strength and durability, whether its' steel, concrete, or bamboo itself.	Durability/maintenance	Treatment	
Falta de conocimiento del sistema constructivo	General knowledge/awareness		
Figuring out what type of connection will make the bamboo construction correct and finding the right form that's possible with bamboo	Joinery/connections		

Finding Skilled Labour to construct your systems	General knowledge/awareness		
Finding the right joints for the construction	Joinery/connections		
Finding the source for bamboo(?	Supply chain		
finding ways to make the design look clean and sleek	Societal/client attitudes		
Fire and water resistance	Durability/maintenance	Fire resistance	
Government control and ignorance	Regulation		
Government control and ignorance	Regulation		
Guarantee structural safety	Structural knowledge and calculation		
having t keep it away from moisture and direct sunlight	Durability/maintenance		
High costs for experienced builders	General knowledge/awareness		

How ever piece is different	Natural variability		
How it can be used in repsonse to the tight planning and construction laws of the UK	Regulation		
how others will view the use of bamboo to build the structure	Societal/client attitudes		
I am not very familiar with the material, but I would imagine it's the irregularity of the shape of the material.	Natural variability		
I think it could be how you might want to use it in the design. Since bamboo can be used in many ways and different forms of bamboo is available, it could be challenging to figure out how to design with it.	General knowledge/awareness		

i think it would be the maintenance of bamboo structure	Durability/maintenance		
I think the biggest challenge is that the bamboo poles have heterogeneous dimensions	Natural variability		
I think the biggest challenge we could face designing for bamboo is that as a natural grown vegetation, it could be difficult to standardize the specific cualities of every pole we will use.	Natural variability		
I think the clients	Societal/client attitudes		
in Haiti, people are interested in security. Concrete is viewed in higher regards because it's harder to penetrate.	Material performance	Societal/client attitudes	
in the selection of bamboo, preservation and	Supply chain	Treatment	Durability/maintenance

maintenance of buildings			
Influence people for using bamboo	Societal/client attitudes		
inmunization - access - trained contractors:workforce	Treatment	Supply chain	General knowledge/awareness
Insurnce	Insurance		
irregular diameter and size	Natural variability		
It can decay quite easily when exposed to water and sun	Durability/maintenance		
It can not actually combined with technology	General knowledge/awareness		
It would be combatting the societal impressions the general public has on constructions with bamboo	Societal/client attitudes		
It’s a material that I’m not much familiar with	General knowledge/awareness		

its about durability of material, i think bamboo eventually have to replace	Durability/maintenance		
its external looks to fit certain designs	Aesthetics		
It's hard to predict natural damage done to the bamboo, and those damages may cause serious problems to the bamboo design.	Durability/maintenance		
Its irregularities	Natural variability		
Its preservation after the construction.	Durability/maintenance		
its shapes which is usually not the same with one another	Natural variability		
Its strength	Strength		
Its strength to withstand heavy loads.	Strength		
Its structural design.	Structural knowledge and calculation		

join between bamboo	Joinery/connections		
joinery	Joinery/connections		
Joinery	Joinery/connections		
Joinery	Joinery/connections		
Joinery of bamboo.	Joinery/connections		
joints	Joinery/connections		
knowledge	General knowledge/awareness		
Knowledge - I know nothing about it, particularly potential European supplies and uses.	General knowledge/awareness	Supply chain	
knowledge in consturction	General knowledge/awareness		
Knowledge to design, skills to construct and material cost. Dependant on locality & scale of proposal.	General knowledge/awareness	Supply chain	
La descomposición, es un material orgánico, por eso	Durability/maintenance		

lleva un proceso de curación mas complejo.			
La falta de experiencia para diseñadores y constructores	General knowledge/awareness		
La organizacion de los diversos cortes que se le deben hacer a los bambú para que estos encagen.	Joinery/connections		
lack of know-how	General knowledge/awareness		
Lack of knowledege	General knowledge/awareness		
Lack of knowledge	General knowledge/awareness		
Lack of knowledge about the material	General knowledge/awareness		
lack of knowledge, insurance, innovation adverse construction industry	General knowledge/awareness		

Lack of standardization	Standardisation		
Las normativas de construcción	Standardisation		
Learn about joining and the basic about bamboo	Joinery		
Little information is available about its construction	General knowledge/awareness		
location and context. It makes sense in some context but for example, not in Europe. also, from all you previous questions, I would say the answer always depends on the context: it is never one answer universally.	Locations of construction		
Lograr cambiar la mentalidad de las personas ante el uso del bamboo	Societal/client attitudes		
longevity	Durability/maintenance		

longevity and difference in thickness/size	Durability/maintenance	Natural variability	
maintainence of bamboo structures	Durability/maintenance		
maintaining the durability and longevity	Durability/maintenance		
maintaining the structural integrity of the structure and maintaining it. during the building process it would be finding ways to weave the bamboo to ensure that the final product is durable.	Durability/maintenance		
maintanance	Durability/maintenance		
maintanance	Durability/maintenance		
Maintenance	Durability/maintenance		
maintenance	Durability/maintenance		
Maintenance	Durability/maintenance		

manteinance	Durability/maintenance		
material durability & construction	Durability/maintenance	General knowledge/awareness	
Mechanical analysis	Structural knowledge and calculation		
N.A	N/A		
na	N/A		
NA	N/A		
natural variances	Natural variability		
Need to consider the optimal environments in which the bamboo will operate in	Durability/maintenance		
no	N/A		
Non-standardised sizes	Natural variability		
not being able to expose to sunlight and moisture.	Durability/maintenance		
not enough case-studies introduced to the average leyman, And for different uses of	General knowledge/awareness		

buildings, ie, commercial building, office building etc. So far i see bamboo case studies only for single housing, and pavilions, small bridges, but nothing big to compete with the market.			
not enough common knowledge of the material and its capabilities	General knowledge/awareness		
Not fire resistant	Fire resistance		
Not sure	N/A		
People's mindset	Societal/client attitudes		
Pienso que el mayor desafío está en dar el primer paso y atreverse a diseñar con Bambú, el factor limitante está en la mente.	General knowledge/awareness	Societal/client attitudes	
preconception of the material	Societal/client attitudes		

Preservation, for permanent bamboo buildings.	Durability/maintenance	Treatment	
Preserve	Treatment		
Processing the bamboo	Treatment		
Promoting its use as a globalconvention in building	General knowledge/awareness		
Proper functioning of the structure	Structural knowledge and calculation		
Protection and maintenance	Durability/maintenance		
Providing protection against weather conditions	Durability/maintenance		
Que el resultado final sea lo más parecido al diseño inicial por las formas algo irregulares del bamboo	Natural variability		
Que no hayan aberturas entre las uniones o pares de las cañas de bambú.	Joinery/connections		

reduction of error during building process	General knowledge/awareness		
Renovar la mentalidad de la construcción	General knowledge/awareness		
resistencia y durabilidad	Durability/maintenance	Strength	
shaping it	General knowledge/awareness		
social acceptance	Societal/client attitudes		
Social acceptance	Societal/client attitudes		
Sourcing	Supply chain		
sourcing ?	Supply chain		
sourcing bamboo in non tropical countries	Supply chain		
Sourcing it sustainably and finding skilled workers	Supply chain	General knowledge/awareness	
sourcing of material	Supply chain		

special needs of bamboo material in construction method and maintenance	General knowledge/awareness	Durability/maintenance	
Special treatment and specific construction method for bamboo material before, ongoing and after construction	General knowledge/awareness	Durability/maintenance	
Standardization	Standardisation		
Standards	Standardisation		
Structure	Structural knowledge and calculation		
Su durabilidad y proceso de tratamiento	Durability/maintenance	Treatment	
su rigidez	Strength		
su trabajibilidad	General knowledge/awareness		
sustainability, embodied carbon, transport	Sustainability	Supply chain	

Sustainable sourcing	Supply chain		
Technical data and typical details	Standardisation	Joinery/connections	
Technical Knowledge	General knowledge/awareness		
technical knowledge on how to work with it	General knowledge/awareness		
Technological knowledge is culture-bound.	General knowledge/awareness		
that final user acept it as a trustable material	Societal/client attitudes		
The acceptance of clients that bamboo is a fine material to work with	Societal/client attitudes		
the accuracy of the design vs the actual construction	Structural knowledge and calculation		
the after care of the bamboo structure.	Durability/maintenance		
The association of bamboo homes with poverty	Societal/client attitudes		

the belief that it's not structurally sturdy	Societal/client attitudes	Structural knowledge and calculation	
The biggest Challenge to use bamboo as construction material is the complexity of bamboo itself	General knowledge/awareness		
The biggest challenge in designing bamboo is how to make it more durable	Durability/maintenance		
The biggest challenge is the selection of the type of bamboo including the size to be used and the treatment process	Natural variability	Treatment	
the biggest challenges to design bamboo are the effectiveness and durability of all type of bamboo that has to be consider	Durability/maintenance		
The care needed to prevent bamboo	Durability/maintenance		

from being damaged.			
The challenge of society acepting it and the weather challenges	Societal/client attitudes	Durability	
The challenge when designing for bamboo I think is its curved form.	Natural variability		
The climatic condition	Climate		
the concept of the design using bamboo material that could be difficult to follow all the thumbs rule of how to designing bamboo	General knowledge/awareness	Regulation/codes	
the constant visual net that is created with the bamboo. It is hard to visually purify the look of material.	Societal/client attitudes		
the construction phase	General knowledge/awareness		

The crack	Durability/maintenance		
the curvature of bamboo structure is sometimes cannot be measured by manual/conventional measuring	Natural variability		
the durability of the design	Durability/maintenance		
The fact that all bamboos have a unique form	Natural variability		
the form finding and the joinery	Joinery/connections		
the irregular of bamboo itself (in diameter and in straightness)	Natural variability		
the joint	Joinery/connections		
The lack of experience in the field	General knowledge/awareness		
the lack of industrialised method	Standardisation		
the logistic concerning harvest,	Supply chain	Treatment	

treatment and transport			
The maintenance of bamboo	Durability/maintenance		
The misconception of the material in our and other industries	Societal/client attitudes		
The natural variation in timber means it is difficult to accurately design the structure in digital programmes. Bamboo structures are also very porous and waterproofing needs to be designed carefully. The variation of bamboo may mean it is more difficult to mass-produce bamboo houses in comparison to masonry and concrete for example.	Natural variability	Durability	
the organic aspect makes it difficult to module	Natural variability		

the shape	Shape		
The shape	Shape		
the structural stability and the weather resistance especially in tropical country	Durability/maintenance		
the structure	Structural knowledge and calculation		
The structure of it	Material performance		
the tensile strngth	Strength		
The top/bottom diameter difference	Natural variability		
The union between poles and parts.	Joinery/connections		
The variability in bamboo species	Natural variability		
The years and the strongest of the structure	Durability/maintenance	Strength	
There are fewer people willing to use bamboo compared to timber.	General knowledge/awareness		

Thermal Bridges	Comfort / Thermal bridging		
to go beyond the myths as a poor object for design	Societal/client attitudes		
To have the possibility of making more than two floors with a bamboo structure	Limited scale of construction		
to take in to consideration the weather of the environment	Durability/maintenance		
Treatment, processing, designed joineries,	Treatment	Joinery/connections	
Unavailability of Bamboo	Supply chain		
Understanding the basic principles behind the material	General knowledge/awareness		
understanding the climate conditions of the place where the bamboo will be placed at	Climate		
Understanding the joints to have a	Joinery/connections		

structurally strong building			
unfamiliarity	General knowledge/awareness		
uniformity and aesthetic	Standardisation	Aesthetics	
Upskilling in places where bamboo is not used.	General knowledge/awareness		
variety in pole tension and compression strength	Natural variability		
Ways of acquiring and processing the material	Supply chain	Treatment	
weather conditions and soil type.	Climate		
Yo diría que la disponibilidad, por otro lado pues la falta de información acerca del conocimiento adecuado en cuanto al utilizar el bambú	General knowledge/awareness		

Appendix I: Example exercise taken from Panama workshop textbook

This document is intended for students of the

AA Crossing the Divide 2022 course only.

Although the exercises and information in this document have been researched and tested thoroughly there can be errors. The exercises in this document are applicable only in conjunction with the live taught sessions. The information and exercises in this document should NOT be used for the design and construction of bamboo structures without further input of appropriately qualified engineers and bamboo carpenters on a case by case and site by site basis.

5 Exercise 1 - Hyperbolic paraboloid

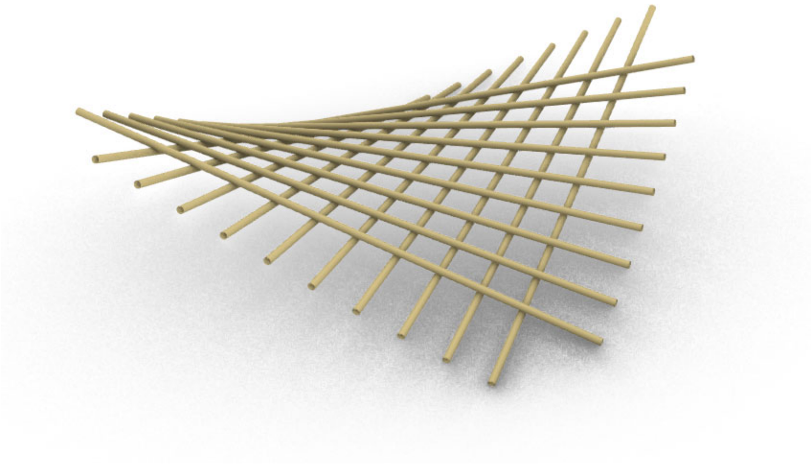

Figure 6

The following exercise is to construct a hyperbolic paraboloid in Rhinoceros and Grasshopper to be built of full culm bamboo. This is an anticlastic roof form which follows a convex curve about one axis and a concave curve about the other.

We begin by drawing our footprint in Rhinoceros 3D as a *'Closed Crv'*. Create a Crv container in the Grasshopper window and assign the Crv from Rhinoceros into Grasshopper as shown in Figure 7.

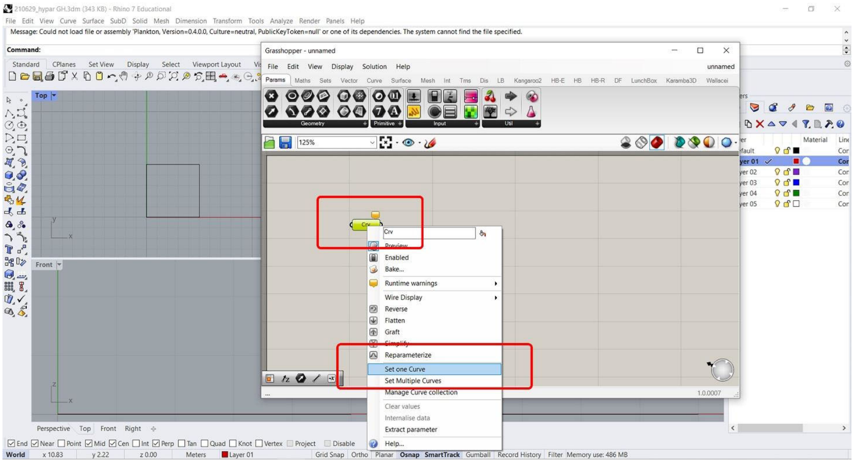

Figure 7

Now the *'Closed Crv'* in Rhinoceros is assigned in Grasshopper. By clicking on the *'Crv'* container, as shown in Figure 8, we will see the *'Closed Crv'* appear as green in the Rhinoceros viewport.

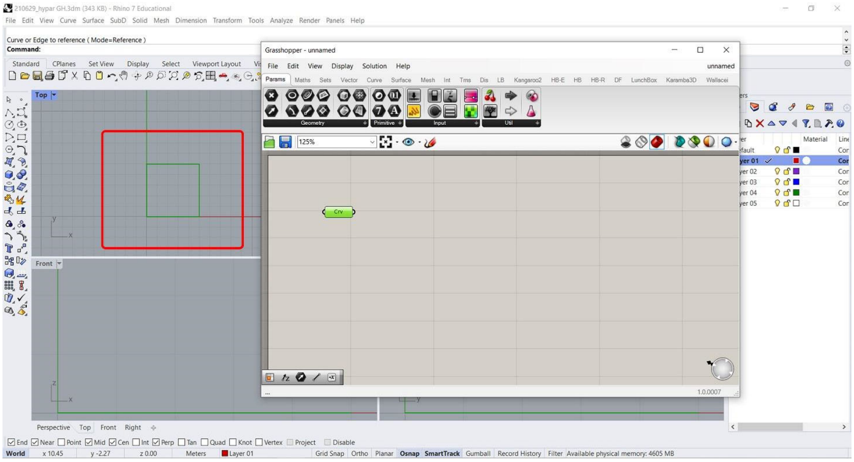

Figure 8

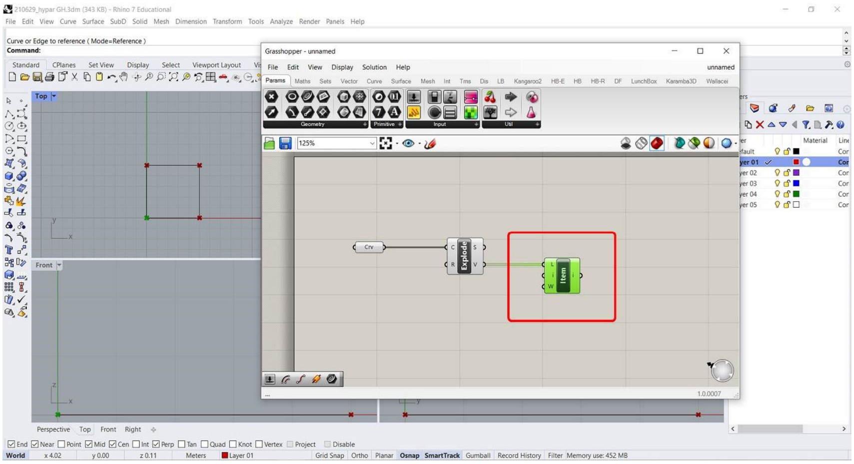

Figure 9

Now we explode the footprint as shown in Figure 9 and use the *'List item'* component to allow us to extract each of the 4 vertices for each corner of the quadrilateral. In order to have the 4 outputs required zoom in and click on the '+' icon shown in Figure 10.

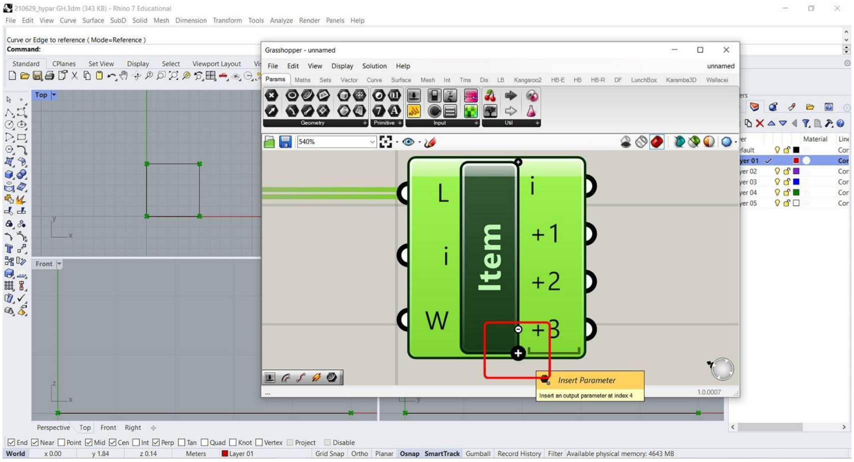

Figure 10

We now move each opposite set of points in the Z axis by a value set by the *'Number slider'* which has values from 1.0 to 10.0 (highlighted in red), as shown in Figure 11.

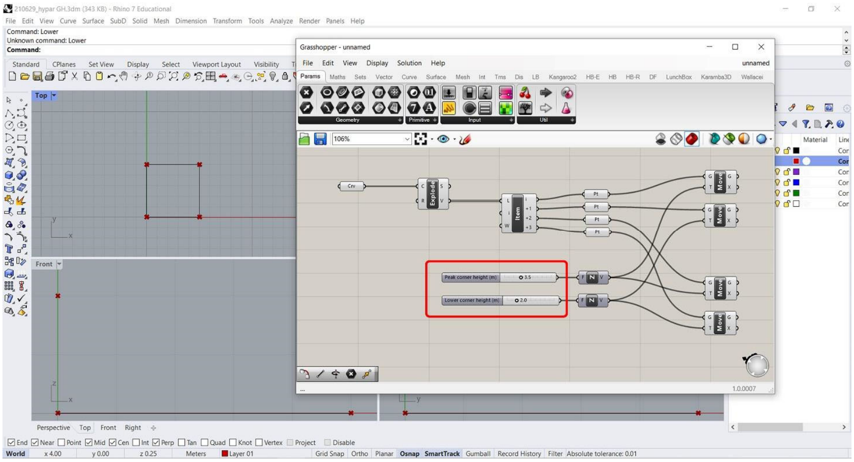

Figure 11

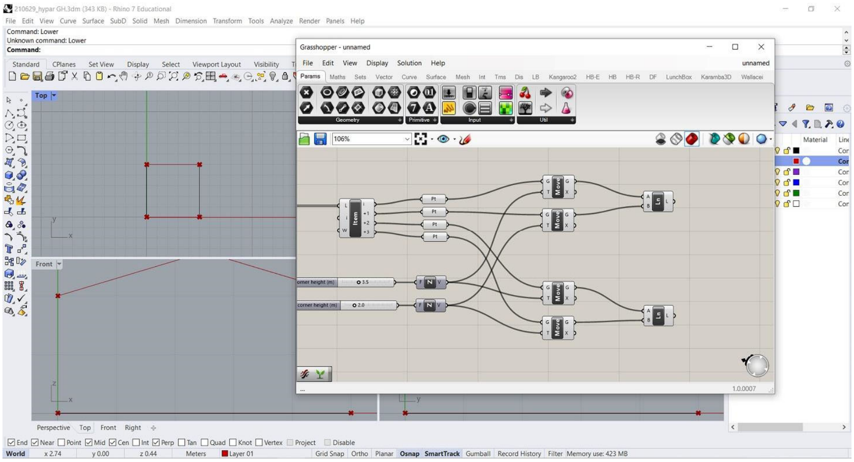

Figure 12

We now create lines between the moved points using the *'Line'* component as shown in Figure 12.

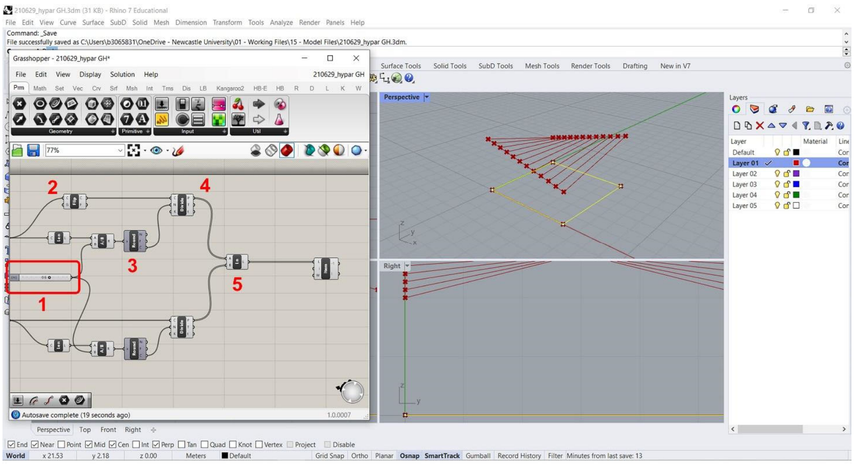

Figure 13

Create the components as shown in Figure 13, this will now allow us to create the roof grid. They are:

1) The *'Number slider'* which will determine the maximum dimensions of the grid;
2) The *'Flip curve'* component is important to ensure that each edge curve is divided in the same direction, so that the start and end of the division sequence occurs from the same side;
3) The *'Round'* component rounds the result of dividing the edge length of the roof by the maximum grid size which is the output of the *'Number slider'*. By

selecting C as the output, this is the 'Ceiling' value which ensures that the grid will never be more than the value set by the 'Number slider'.

4) We then divide the edge line by the number of grids determined by stage 3.
5) Using the *'Line'* component we create lines between each set of points.

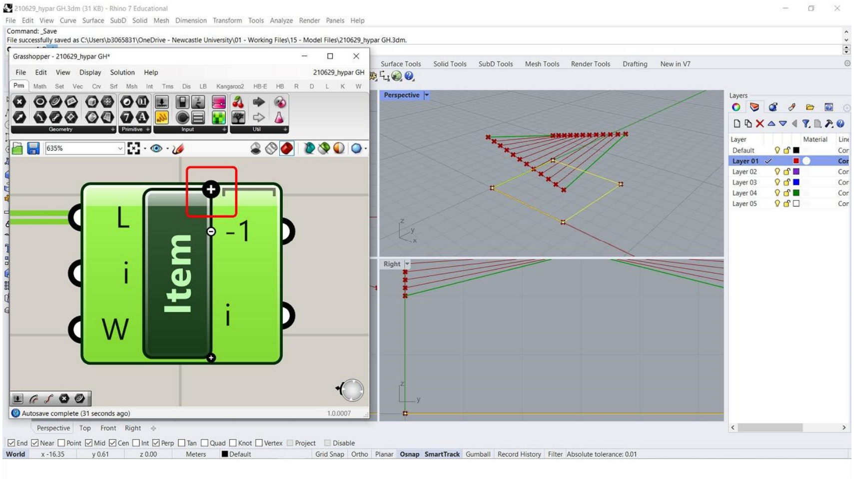

Figure 14

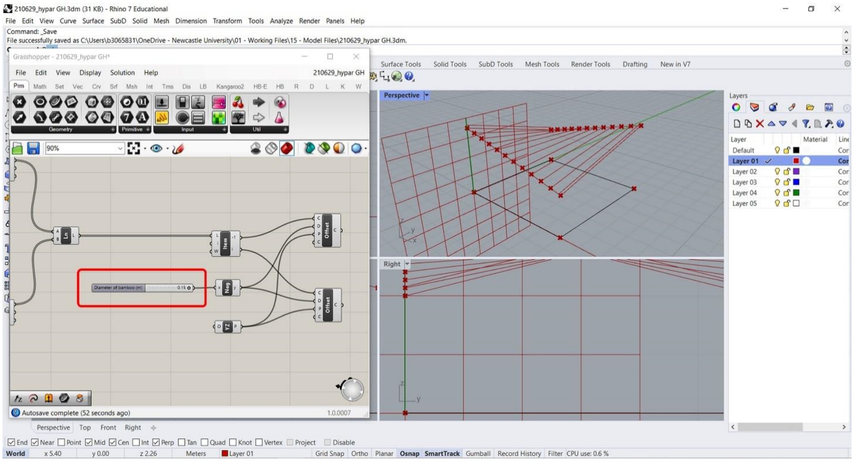

Figure 15

As shown in Figure 15, we now offset the first and last lines which we created between the points in Figure 13. These are offset by the diameter of the bamboo which is created through a *'Number slider'* shown in Figure 15. We can do this by using the *'List item'* component and creating another output to the top of the component as shown in Figure 14.

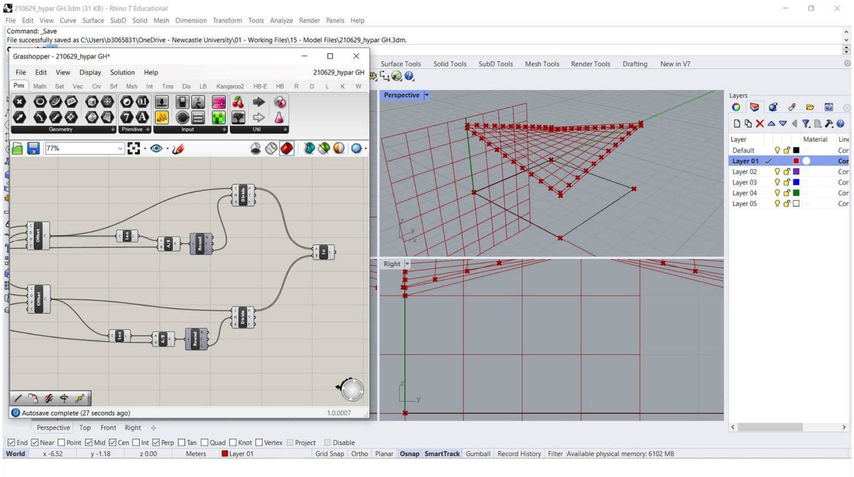

Figure 16

Following the steps in Figure 16, we now do the same as earlier and make a set of points related the maximum grid size we wish and defined in the *'Number slider'* shown in Figure 13. Using the *'Line'* component we can then make lines between the points and this will give us our grid.

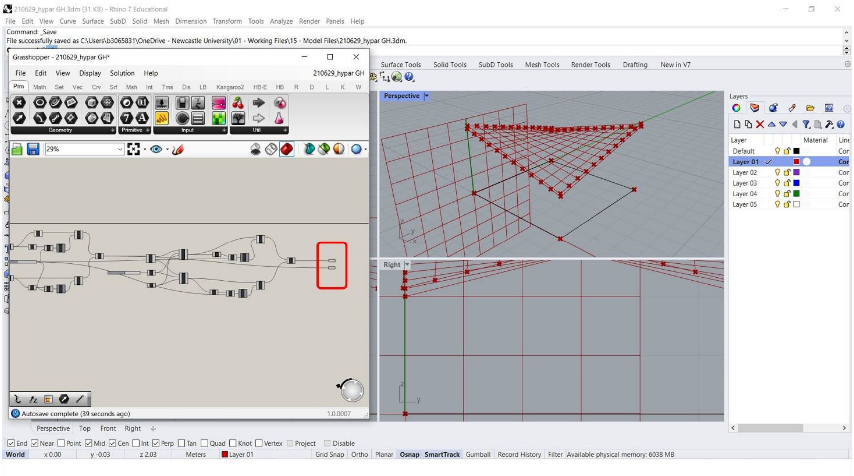

Figure 17

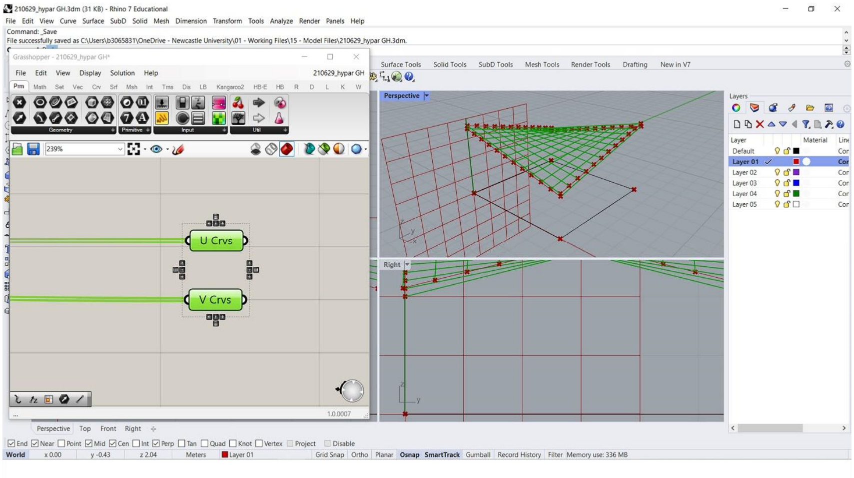

Figure 18

Using the *'Crv'* containers and right clicking on each container, we can rename these appropriately as shown in Figure 18.

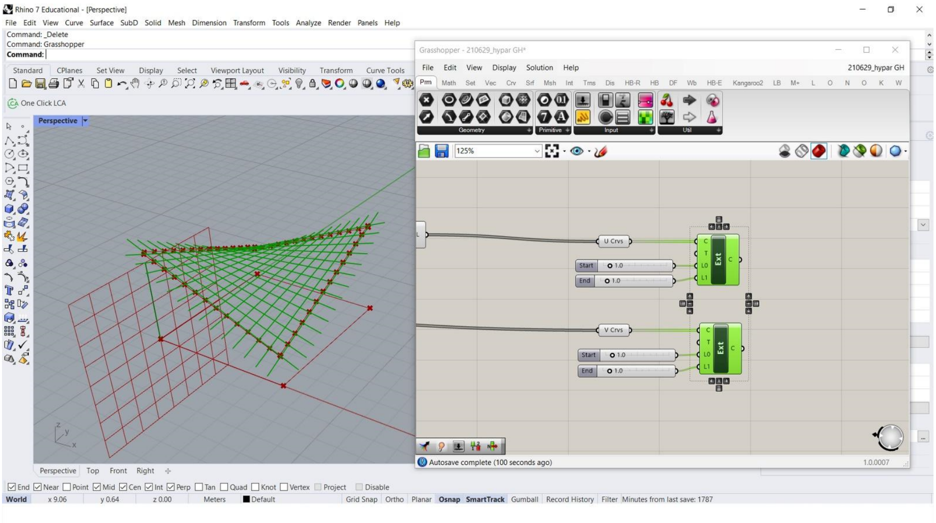

Figure 19

We are now going to extend the curves which form the grid of the hyperbolic paraboloid. We do this with the *'Extend curve'* component as shown in Figure 19.

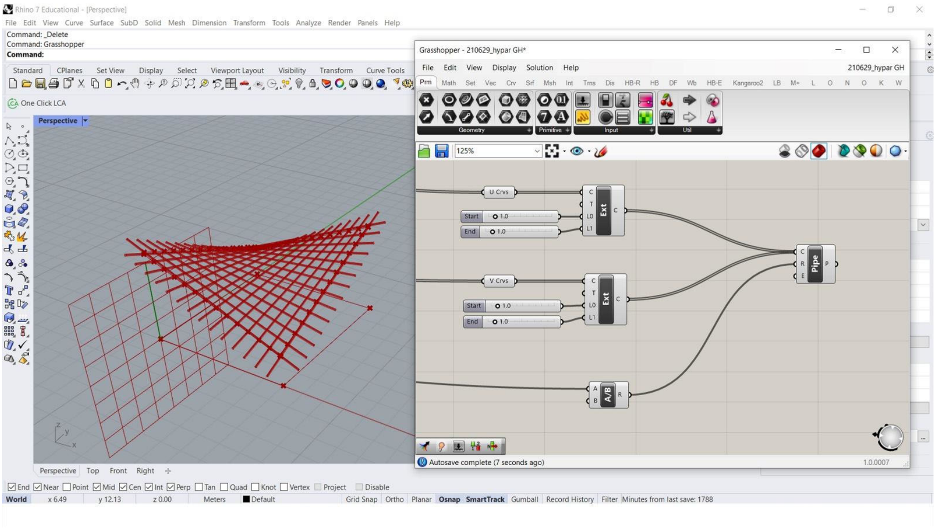

Figure 20

Now to see a representation of the curves as poles, we can use the *'Pipe'* component and we create the pipe by using the radius which is the diameter of the bamboo which we input with the *'Number slider'* shown in Figure 15, divided by 2.

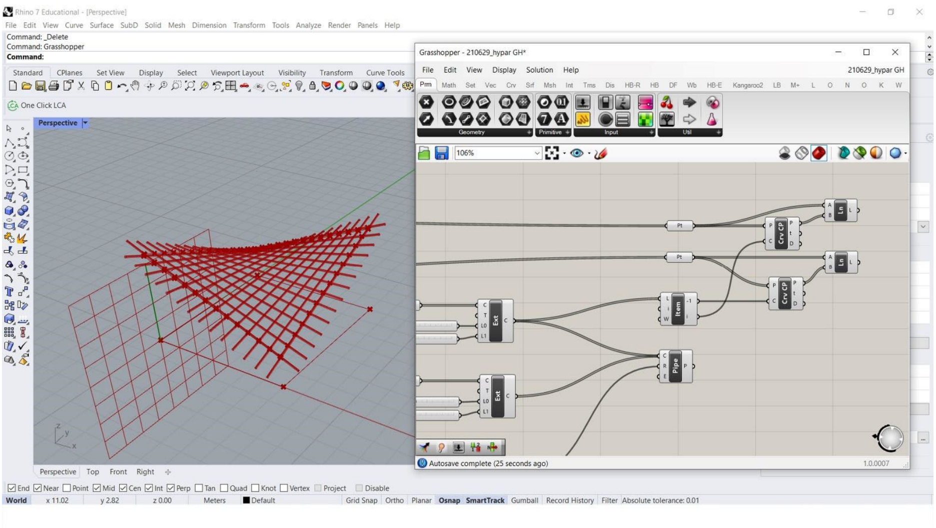

Figure 21

Now we are going to create lines using the *'Line'* component to represent the bolts at the perimeter of the hyperbolic paraboloid. We create the components as shown in Figure 21, and we connect the *'Pt'* containers to the points output earlier when we divided the edge curves. This is shown in Figure 13 and Figure 22.

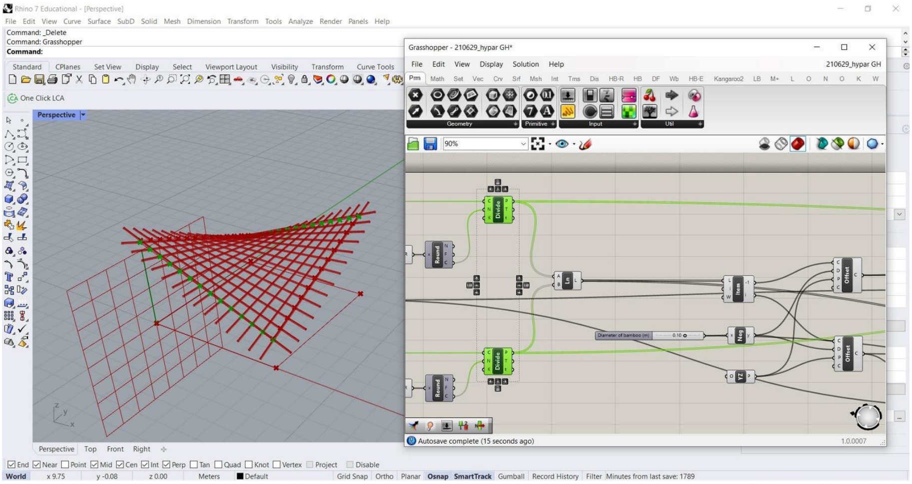

Figure 22

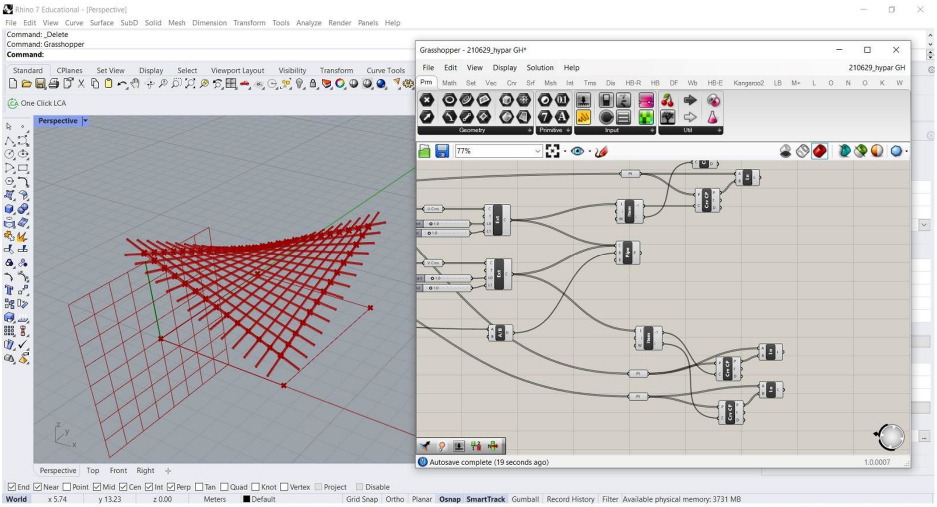

Figure 23

As shown in Figure 23, we do the same with the points of the edge curves in the opposite direction and connect the *'Pt'* containers shown in Figure 23 to the outputs of the *'Divide'* component shown in Figure 16 and Figure 24.

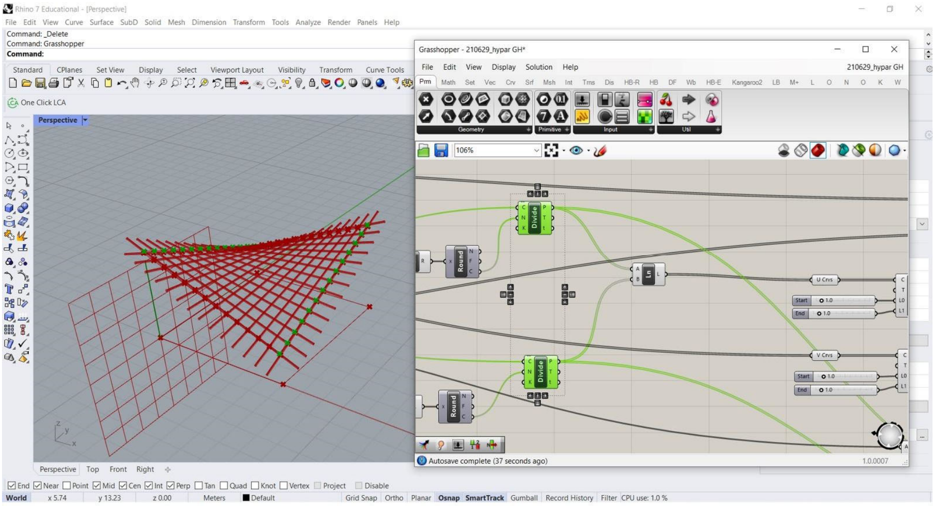

Figure 24

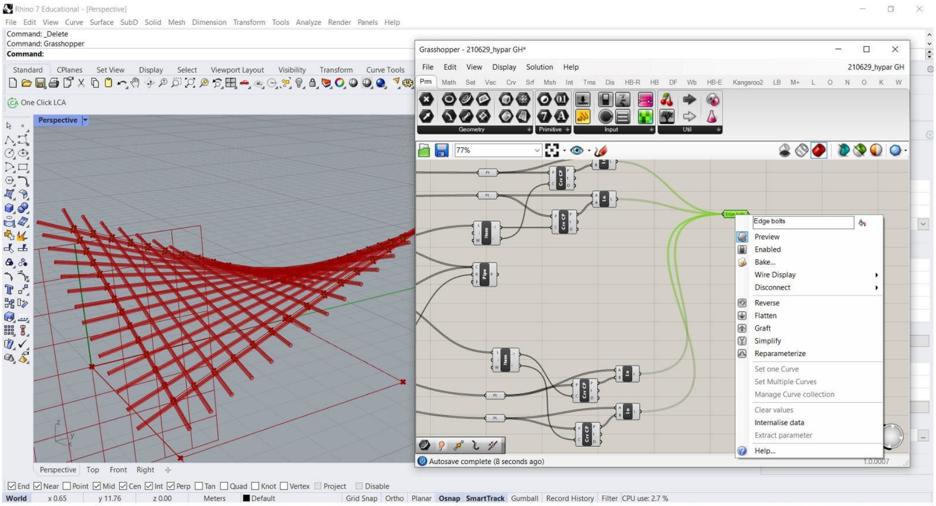

Figure 25

We bring the outputs of the 4 line components together into a *'Crv'* container as shown in Figure 25.

Figure 26: A bolt correctly located around 1 to 2 inches from the node.

At this stage we are now going to extract construction information from the algorithm. We will extract 3 pieces of information. These are:

a. The cut length of each pole;
b. The distance between the first and last node that we will bolt adjacent to;
c. The distance between bolt locations.

As shown in Figure 28, the distance between the bolts can be measured by using the *'Length'* component and measuring the lengths of each line highlighted in Figure 17 and Figure 29. Using a *'Panel'* connected to the *'Length'* component we can see the measurements as a list. As shown in Figure 26, it is important to bolt near to the node roughly 25 to 50mm from a node. It is also important that to mitigate splitting at joints near the ends of culms at least one node should be located between a joint and the end of a culm. Therefore we should ensure there is a node on the outside of each bolt location (as shown in Figure 27). In order to determine the distance between the first and last nodes for each pole in the roof we can add 25mm to each bolt location which is shown in the second set of panels in Figure 28. When selecting the poles we will then measure the distance between the first and last nodes when to determine which poles to use. When bolting a bolt, or threaded-rod should be used and secured with washers and nuts. Nuts shall not be tightened more than “finger tight”. For applications in which vibration is likely, lock washers or some other means of ensuring the nut does not loosen shall be provided.

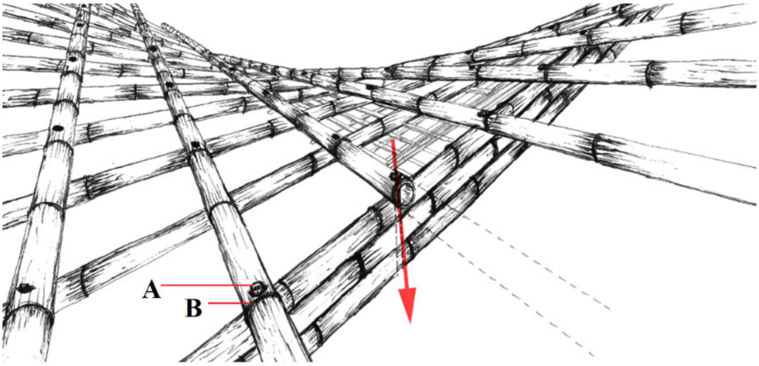

Figure 27: Locations of bolt connections (A) to the beam, adjacent to a node (B) on the internal side.

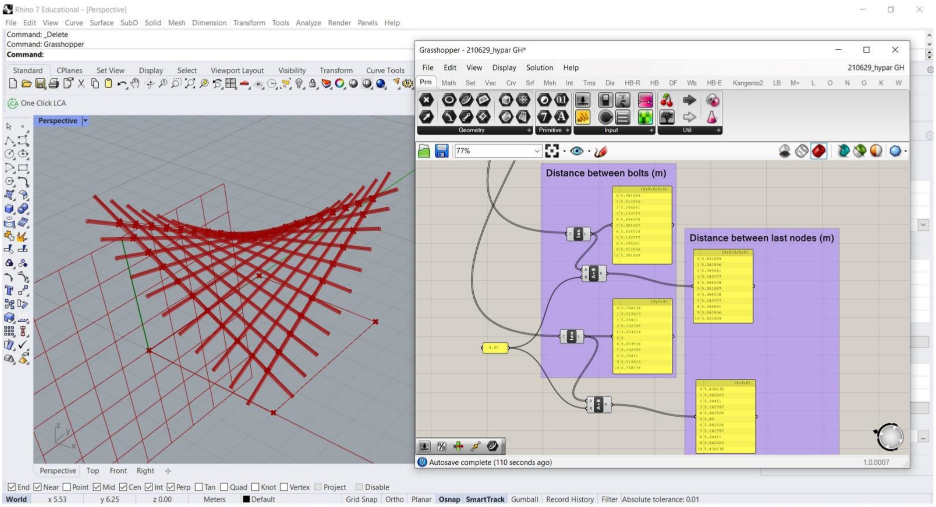

Figure 28

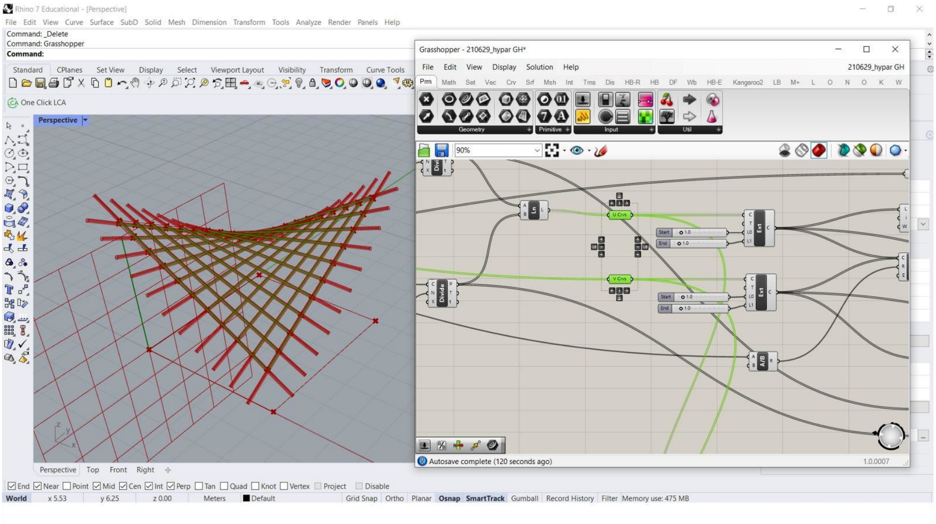

Figure 29

As shown in Figure 30, we will then measure the lengths of the extended poles and this will give us the lengths of the poles required to cut. Using the information in these panels shown in Figure 30, we can also determine if the pole lengths will be available or able to be transported to site.

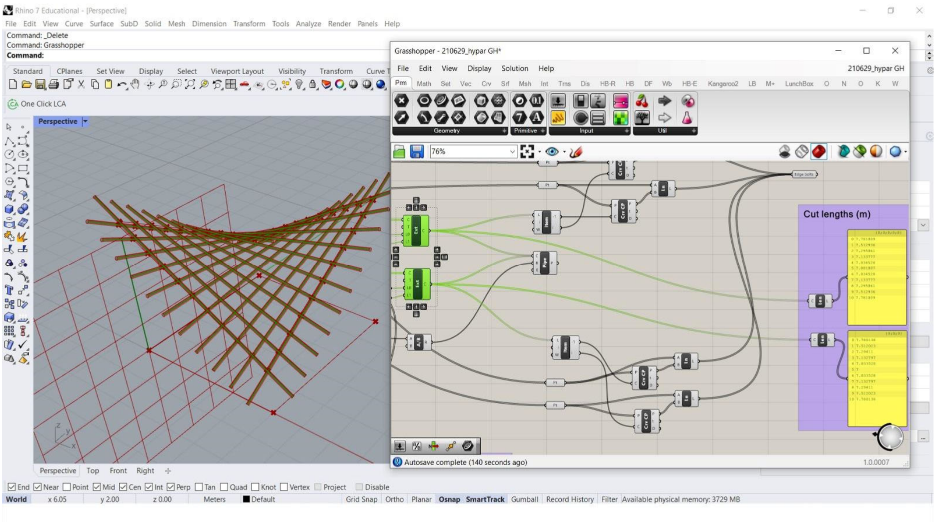

Figure 30

Bibliography

Addleson, L., & Rice, C. (1991). *Performance of Materials in Buildings: A Study of the Principles and Agencies of Change*. Butterworth-Heinemann.

Aditra, R. F., & Widyowijatnoko, A. (2016). Combination of mass customisation and conventional construction: A case study of geodesic bamboo dome. In S.-F. Chien, S. Choo, M. A. Schnabel, W. Nakapan, M. J. Kim, & S. Roudavski (Eds.), *Living Systems and Micro-Utopias: Towards Continuous Designing, Proceedings of the 21st International Conference on Computer-Aided Architectural Design Research in Asia (CAADRIA 2016), 30 March–2 April 2016 Melbourne School of Design The University of Melbourne, Australia* (pp. 777–786). The Association for Computer-Aided Architectural Design Research in Asia (CAADRIA). https://doi.org/10.52842/conf.caadria.2016.777

Agkathidis, A. (2016a). Conclusion: The Digital vs Physical Debate. In *Generative Design (Form + Technique)*. Laurence King Publishing [Kindle Edition].

Agkathidis, A. (2016b). Introduction to Generative Design. In *Generative Design (Form + Technique)*. Laurence King Publishing [Kindle Edition].

Ago, V. (2022). 'Strange Networks': Inhabiting the Boundary Condition A Conversation with Thom Mayne. *Architectural Design*, *92*(2), 68-77. https://doi.org/10.1002/ad.2795

Ahlquist, S., & Menges, A. (2011). Introduction. In S. Ahlquist & A. Menges (Eds.), *Computational Design Thinking* (pp. 10-29). Wiley.

Ahlquist, S., & Menges, A. (2012). Physical Drivers: Synthesis of Evolutionary Developments and Force-Driven Design. *Architectural Design*, *82*(2), 60-67. https://doi.org/10.1002/ad.1380

Aish, R. (2013). First Build Your Tools. In T. Peters & B. Peters (Eds.), *Inside Smartgeometry: Expanding the Architectural Possibilities of Computational Design* (pp. 36-49). Wiley. https://doi.org/10.1002/9781118653074.ch2

Aish, R., & Bredella, N. (2017). The evolution of architectural computing: from Building Modelling to Design Computation. *Architectural Research Quarterly*, *21*(1), 65-73. https://doi.org/10.1017/s1359135517000185

Aish, R., & Woodbury, R. (2005). Multi-level Interaction in Parametric Design. In A. Butz, B. Fisher, A. Krüger, & P. Olivier (Eds.), *Smart Graphics. SG 2005. Lecture Notes in Computer Science* (Vol. 3638, pp. 151-162). Springer. https://doi.org/10.1007/11536482_13

Akin, O., & Moustapha, H. (2004). Strategic use of representation in architectural massing. *Design Studies*, *25*(1), 31-50. https://doi.org/10.1016/S0142-694X(03)00034-6

Akinlabi, E. T., Anane-Fenin, K., & Akwada, D. R. (2017). Bamboo Taxonomy and Distribution Across the Globe. In *Bamboo: The Multipurpose Plant* (pp. 1-37). Springer International Publishing. https://doi.org/10.1007/978-3-319-56808-9_1

Akoto, S. D., Obour, R., Appiah, M. A., & Frimpong, A. P. (2016). Bamboo use for the housing industry in Ghana: Urban Stakeholders' Perception. *Journal of Energy and Natural Resource Management*, *3*(3), 85-91. https://doi.org/10.26796/jenrm.v3i3.93

Alexander, C. (1968). Systems Generating Systems. *Architectural Design*, *38*, 605-610.

Allen, J. G., Bernstein, A., Cao, X., Eitland, E. S., Flanigan, S., Gokhale, M., Goodman, J. M., Klager, S., Klingensmith, L., Guillermo, J., Laurent, C., Lockley, S. W., Macnaughton, P., Pakpour, S., Spengler, J. D., Vallarino, J., Williams, A., Young, A., & Yin, J. (2017). *The 9 Foundations of a Healthy Building*. https://9foundations.forhealth.org/

Allwood, J. M., Cullen, J. M., & Milford, R. L. (2010). Options for Achieving a 50% Cut in Industrial Carbon Emissions by 2050. *Environmental Science & Technology*, *44*(6), 1888-1894. https://doi.org/10.1021/es902909k

Almeida De Araujo, V., Cortez-Barbosa, J., Garcia, J. N., Gava, M., Laroca, C., & César, S. F. (2016). Woodframe: Light framing houses for developing countries. *Revista de la construcción*, *15*(2), 78-87. https://doi.org/10.4067/S0718-915X2016000200008

Amede, E. A., Hailemariama, E. K., Hailemariam, L. M., & Nuramo, D. A. (2021). A Review of Codes and Standards for Bamboo Structural Design. *Advances in Materials Science and Engineering*, *2021*, Article ID 4788381. https://doi.org/10.1155/2021/4788381

Amtsberg, F., Mueller, C., & Raspall, F. (2022). Di-terial – Matching Digital Fabrication and Natural Grown Resources for the Development of Resource Efficient Structures. In P. F. Yuan, H. Chai, C. Yan, & N. Leach (Eds.), *Proceedings of the 2021 DigitalFUTURES. CDRF 2021.* (pp. 330-339). Springer. https://doi.org/10.1007/978-981-16-5983-6_30

Amtsberg, F., & Raspall, F. (2018). Bamboo? In T. Fukuda, W. Huang, P. Janssen, K. Crolla, & S. Alhadidi (Eds.), *Learning, Adapting and Prototyping - Proceedings of the 23rd CAADRIA Conference, Tsinghua University, Beijing, China, 17-19 May 2018* (Vol. 1, pp. 245-254). https://doi.org/10.52842/conf.caadria.2018.1.245

Andrew, R. M. (2018). Global CO2 emissions from cement production. *Earth System Science Data*, *10*(1), 195-217. https://doi.org/10.5194/essd-10-195-2018

Ansys. (2023). *Ansys | Engineering Simulation Software*. In [Computer programme]. https://www.ansys.com/en-gb

Appiah-Kubi, E., Owusu, F. W., Tekpetey, S. L., & Essien, C. (2014). Bamboo for housing in Ghana: Challenges and prospects for the future. *Journal of Bamboo and Rattan*, *13*(3-4), 45-54.

Approved Document F. (2021). Statutory guidance - Ventilation: Approved Document F - Approved Document F: Volume 1 applies to dwellings (in effect from 15 June 2022). In *The Building Regulations*: DLUHC/MHCLG, HM Government, UK.

Aravena, A. (2011). Elemental: A Do Tank. *Architectural Design*, *81*(3), 32-37. https://doi.org/10.1002/ad.1235

Aravena, A. (2016). *Elemental: Incremental Housing and Participatory Design Manual*. Hatje Cantz.

ARB. (2017). *The Architects Code: Standards of Professional Conduct and Practice*. ARB. https://arb.org.uk/architect-information/architects-code-standards-of-conduct-and-practice/

ArchDaily. (2010, October 13). *The Green School / IBUKU*. ArchDaily. Retrieved 16/07/23 from https://www.archdaily.com/81585/the-green-school-pt-bambu

ArchDaily. (2014, November 28). *Timber Frame House / A-Zero Architects*. ArchDaily. Retrieved 19/08/2023 from https://www.archdaily.com/567749/timber-frame-house-a-zero-architects

ArchDaily. (2023, May 31). *Floating Bamboo House / H&P Architects*. Retrieved 18/06/2023 from https://www.archdaily.com/1001723/floating-bamboo-house-h-and-p-architects

Archila, H., Kaminski, S., Trujillo, D., Zea Escamilla, E., & Harries, K. (2018). Bamboo reinforced concrete: a critical review. *Materials and Structures*, *51*(Article number: 102 (2018)). https://doi.org/10.1617/s11527-018-1228-6

Architecture 2030. (2023). *Why the built environment? (Figure data source: Global ABC, Global Status Report 2017)*. Architectrue 2030. Retrieved 23/08/23 from https://architecture2030.org/why-the-built-environment/

Archiweb. (2016). *Parking Garage of the Leipzig Zoo*. Archiweb. https://www.archiweb.cz/en/b/parkovaci-dum-u-zoo-parkhaus-am-zoo-leipzig

Areta, J. I., Bodrati, A., & Cockle, K. (2009). Specialization on Guadua Bamboo Seeds by Three Bird Species in the Atlantic Forest of Argentina. *Biotropica*, *41*(1), 66-73. https://doi.org/10.1111/j.1744-7429.2008.00458.x

Arup, & Shelter/NFI Sector. (2018). *Technical Guidance Note 03: Durability and Treatment of Bamboo in Cox's Bazar* (REP/079032-30/S0001). https://www.arup.com/-/media/arup/files/pdf-downloads/rohingya-refugee-reports/181031-tgn03-bamboo-durability-and-treatment-guidance-note.pdf

Ashaari, Z., & Mamat, N. (2000). Traditional Treatment of Malaysian Bamboos: Resistance Towards White Rot Fungus and Durability in Service. *Pakistan Journal of Biological Sciences*, *3*(9), 1453-1458. https://doi.org/10.3923/pjbs.2000.1453.1458

Ashraf, M. A., Maah, M. J., Bin Yusoff, I., Wajid, A., & Mahmood, K. (2011). Sand Mining Effects, Causes and Concerns: A Case Study from Bestari Jaya, Selangor, Peninsular Malaysia. *Scientific research and essays*, *6*(6), 1216-1231. https://doi.org/10.5897/SRE10.690

Auman, N. B. C., Widyowijatnoko, A., & Wonorahardjo, S. (2018). Technological Contexts in Developing Bamboo Wall System for Housing in Indonesia and Philippines. In ITB (Ed.), *HABITechno 3*

International Conference11 November 2017, Bandung, Indonesia (Vol. 152). IOP Conference Series: Earth and Environmental Science. https://doi.org/10.1088/1755-1315/152/1/012005

Autodesk. (2002). *Autodesk White Paper: Building Information Modeling (Retrieved from https://laiserin.com/features/bim/index.php)*. http://www.laiserin.com/features/bim/autodesk_bim.pdf

Autodesk. (2019). *The Dynamo Primer for Dynamo v2.0*. Autodesk Dynamo. Retrieved 29/07/2023 from https://primer.dynamobim.org/en/index.html

Autodesk. (2022a). *Auto CAD*. In [Computer programme]. https://www.autodesk.co.uk/products/autocad/

Autodesk. (2022b). *Revit*. In (Version 2022) [Computer programme]. https://www.autodesk.co.uk/products/revit/overview

Autodesk. (2023). *Robot Structural Analysis*. In [Computer programme]. Autodesk. https://www.autodesk.co.uk/products/robot-structural-analysis

Bahru, T., & Ding, Y. (2021). A Review on Bamboo Resource in the African Region: A Call for Special Focus and Action. *International Journal of Forestry Research*, *2021*(Article ID 8835673). https://doi.org/10.1155/2021/8835673

Bakker, R. (2020). Smart Materials. In *Smart Buildings: Technology and the Design of the Built Environment* (1 ed., pp. 22-63). RIBA Publishing. https://doi.org/10.4324/9780429348051-4

Banik, R. L. (2015). Bamboo Silviculture. In W. Liese & M. Köhl (Eds.), *Bamboo: The Plant and its Uses* (Vol. 10, pp. 113-174). Springer, Cham. https://doi.org/10.1007/978-3-319-14133-6_5

Bannister, S., & Gledhill, K. (2012). Evolution of the 2010–2012 Canterbury earthquake sequence. *New Zealand Journal of Geology and Geophysics*, *55*(3), 295-304. https://doi.org/10.1080/00288306.2012.680475

Baral, S. K. (2014). *Socio-economic Empowerment of Women by Developing Market Potential of Bamboo Products in Nepal*. INBAR. https://www.inbar.int/resources/inbar_publications/socio-economic-empowerment-of-women-by-developing-market-potential-of-bamboo-products-in-nepal/

Barandy, K. (2020, February 05). *wafai sculpts the 'scandinavian seashell house' as a single organic form*. design boom. Retrieved 29/07/2023 from https://www.designboom.com/architecture/wafai-scandinavian-seashell-house-02-10-2020

Bargout, R. N., & Raizada, M. N. (2013). Soil nutrient management in Haiti, pre-Columbus to the present day: lessons for future agricultural interventions. *Agriculture & Food Security*, *2*(1), 11. https://doi.org/10.1186/2048-7010-2-11

Base Builds. (2023). *Cement-bamboo frame technology: affordable and disaster-resilient housing solution*. Base Builds. Retrieved 23/08/23 from https://base-builds.com/2023/06/20/cement-bamboo-frame-technology-affordable-and-disaster-resilient-housing-solution/

Baydar, G., & Nalbantoḡlu. (1998). Toward Postcolonial Openings: Rereading Sir Banister Fletcher's "History of Architecture". *Assemblage*(35), 7-17. https://doi.org/10.2307/3171235

Beaver. (2022). *Beaver*. In [Computer programme]. Beaver. https://beaver-structures.webflow.io/

Bechthold, M. (2004). Digital Design and Fabrication of Surface Structures. In P. Beesley, N. Y.-W. Cheng, & R. S. Williamson (Eds.), *Fabrication: Examining the Digital Practice of Architecture [Proceedings of the 23rd Annual Conference of the Association for Computer Aidd Design in Architecture and the 2004 Conference of the AIA Technology in Architectural Practice Knowledge Community* (pp. 8-14). University of Waterloo School of Architecture Press. https://doi.org/10.52842/conf.acadia.2004.088

Behrens, K., & Barnes, K. (2016). Wildlife of Madagascar. In *Lemuridae* (pp. 40-55). Princeton University Press. https://doi.org/10.1515/9781400880676-008

Beiser, V. (2018). *The World in a Grain: The Story of Sand and How It Transformed Civilization*. Penguin Publishing Group / Riverhead.

Belcher, B. (1995a). *Bamboo and Rattan Production-to-Consumption Systems: A Framework for Assessing Development Options* (Working Paper Series, Issue 4). https://www.inbar.int/resources/inbar_publications/bamboo-and-rattan-production-to-consumption-systems-a-framework-for-assessing-development-options/

Belcher, B. (1995b). The Role of Bamboo in Development. In I. V. R. Rao, C. B. Sastry, B. Belcher, M. Karki, & T. Williams (Eds.), *Bamboo, People and the Environment - Proceedings of the Vth International Bamboo Workshop: Socio-economics and Culture (Volume 4)* (Vol. 4, pp. 1-9). INBAR.

Benjamin, W. (1968). Paris, Capital of the 19th Century. *New Left review*, *1*(48), 77-88. https://newleftreview.org/issues/i48/articles/walter-benjamin-paris-capital-of-the-19th-century

Berkel, B. V. (2012). Diagrams, design models and mother models. In M. Scott (Ed.), *Digital Workflows in Architecture: Design - Assembly - Industry* (pp. 74-92). Birkhäuser. https://doi.org/10.1515/9783034612173.74

Bernstein, P. G. (2018). *Architecture | Design | Data: Practice Competency in the Era of Computation*. Birkhäuser. https://doi.org/10.1515/9783035610444

Bessa, M. (2009). Algorithmic Design. *Architectural Design*, *79*(1), 120-123. https://doi.org/10.1002/ad.831

Bhatia, P. (2023). Descending into the circles of hell. *New Statesman*, *152*(5716), 24-28. https://www.newstatesman.com/world/americas/2023/05/haiti-descent-into-hell

Bhooshan, S. (2017). Parametric design thinking: A case-study of practice-embedded architectural research. *Design Studies*, *52*, 115-143. https://doi.org/10.1016/j.destud.2017.05.003

BIG. (2022). *Villa Gug*. BIG. Retrieved 29/07/2023 from https://big.dk/projects/villa-gug-2994

Bilham, R. (2010). Lessons from the Haiti earthquake. *Nature*, *463*(7283), 878-879. https://doi.org/10.1038/463878a

Bing, X., & Yi, C. (2015). Chinese Architects' Awareness of, and Attitudes towards, Low-Carbon Architectural Design. *Architecture Research*, *5*(3), 89-96. https://doi.org/10.5923/j.arch.20150503.01

Bliek, B. (2023). *Locality and Identity: Henri Maclaine Pont and the Politics of Representation in the Late Colonial Dutch East Indies* TU Delft]. TU Delft. http://resolver.tudelft.nl/uuid:efcab500-6a3a-4c66-a630-8a3b845b95f0

blueCFD. (2022). *blueCFD-Core 2017-2*. In [Computer programme]. FSD Portugal,. https://bluecfd.github.io/Core/

Böke, J. (2018). Computation in Architecture: Potential and Challenges for Research and Education. In M. Hemmerling & L. Cocchiarella (Eds.), *Informed Architecture: Computational Strategies in Architectural Design* (pp. 105-113). Springer International Publishing. https://doi.org/10.1007/978-3-319-53135-9_10

Booth, L. G. (1997). The design and construction of timber hyperbolic paraboloid shell roofs in Britain: 1957-1975. *Construction History*, *13*, 67-90. https://www.jstor.org/stable/41613779

Borger, J. (2022, October 30). *Haitian ambassador warns criminal gangs may overrun country*. The Guardian. Retrieved 08/07/2023 from https://www.theguardian.com/world/2022/oct/30/haiti-ambassador-usa-criminal-gangs

Borisade, T., Uwalaka, N., Rufai, A., & Odiwe, A. (2020). Carbon Stock Assessment of Bambusa vulgaris stands in a regenerating secondary rainforest, Thirty-four years after Ground fire in Ile-Ife, Nigeria. *Journal of Bamboo and Rattan*, *17*(1), 11-25. https://www.jbronline.org/article.asp?id=294

BRE. (1998). *Timbers: Their natural durability and resistance to preservative treatment* (CI/SfB i(R8)). (Digests, Issue 429). C. R. C. L. b. p. o. B. R. E. Ltd.);.

Brillembourg, A., & Navarro-Sertich, A. (2011). From Product to Process: Building on Urban-Think Tank's Approach to the Informal City. *Architectural Design*, *81*(3), 104-109. https://doi.org/10.1002/ad.1247

Brook, B. W., Bradshaw, C. J. A., Koh, L. P., & Sodhi, N. S. (2006). Momentum Drives the Crash: Mass Extinction in the Tropics. *Biotropica*, *38*(3), 302-305. https://doi.org/10.1111/j.1744-7429.2006.00141.x

Brook, B. W., Sodhi, N. S., & Ng, P. K. L. (2003). Catastrophic extinctions follow deforestation in Singapore. *Nature*, *424*(6947), 420-423. https://doi.org/10.1038/nature01795

Brown, N. C., & Mueller, C. T. (2018). Design variable analysis and generation for performance-based parametric modeling in architecture. *International Journal of Architectural Computing*, *17*(1), 36-52. https://doi.org/10.1177/1478077118799491

Brownell, B. (2019, January 10). *Material Trends to Watch in 2019*. Architect Magazine: The Journal of the American Institute of Architects. Retrieved 29/12/2020 from https://www.architectmagazine.com/practice/material-trends-to-watch-in-2019_o

BS EN 350. (2016). Durability of wood and wood-based products. Testing and classification of the durability to biological agents of wood and wood-based materials. In: BSI Standards Limited.

BS EN 13017-1. (2001). Solid wood panels. Classification by surface appearance. Solid wood panels. Classification by surface appearance. Softwood. In.

Buckingham, K. C., Wu, L., & Lou, Y. (2014). Can't See the (Bamboo) Forest for the Trees: Examining Bamboo's Fit Within International Forestry Institutions. *Ambio*, *43*(6), 770-778. https://doi.org/10.1007/s13280-013-0466-7

Bündnis Entwicklung Hilft. (2022). *World Risk Report 2022*. https://repository.gheli.harvard.edu/repository/10930/

Burchell, J. (1984). *Timber-frame housing*. Longman.

Burger, S. M. (2012). Algorithmic Workflows in associative modeling. In M. Scott (Ed.), *Digital Workflows in Architecture: Design - Assembly - Industry* (pp. 132-149). Birkhäuser. https://doi.org/10.1515/9783034612173.132

Burkart, H. (2016). *Inspeksjonserfaring på trebruer / Learning Experiences from Timber Bridge Inspections (Norwegian)* (468). https://vegvesen.brage.unit.no/vegvesen-xmlui/handle/11250/2624123

Burlotos, C., Kijewski-Correa, T. L., & Taflanidis, A. A. (2020). The Housing Market Value Chain: An Integrated Approach for Mitigating Risk in Informal Residential Construction in Haiti. *Sustainability*, *12*(19). https://doi.org/10.3390/su12198006

Burr, K. L., & Jones, C. B. (2010). The Role of the Architect: Changes of the Past, Practices of the Present, and Indications of the Future. *International Journal of Construction Education and Research*, *6*(2), 122-138. https://doi.org/10.1080/15578771.2010.482878

Burry, M. (2016). Antoni Gaudí and Frei Otto: Essential Precursors to the Parametricism Manifesto. *Architectural Design*, *86*(2), 30-35. https://doi.org/10.1002/ad.2021

Busse, D., & Empelmann, M. (2015). Tragverhalten dünnwandiger Betonhohlbauteile aus hochfestem Feinkornbeton. *Bautechnik*, *92*(1), 46-56. https://doi.org/10.1002/bate.201400055

Butler, A. (2013, January 18). *FR EE / fernando romero enterprise: PH museum*. design boom. Retrieved 31/07/2023 from https://www.designboom.com/art/fr-ee-fernando-romero-enterprise-ph-museum/

Buxton, B. (2007). The Anatomy of Sketching. In B. Buxton (Ed.), *Sketching User Experiences* (pp. 105-114). Morgan Kaufmann. https://doi.org/10.1016/B978-012374037-3/50054-7

Bystriakova, N., Kapos, V., & Lysenko, I. (2004). *Bamboo Biodiversity: Africa, Madagascar and the Americas* (Vol. 19). UNEP-WCMC/INBAR. https://www.unep.org/resources/report/bamboo-biodiversity-africa-madagascar-and-americas

Bystriakova, N., Kapos, V., Stapleton, C., & Lysenko, I. (2003). *Bamboo biodiversity: Information for planning conservation and management in the Asia-Pacific region* (Vol. 14). UNEP-WCMC/INBAR. https://www.unep.org/resources/report/bamboo-biodiversity-information-planning-conservation-and-management-asia-pacific

Caetano, I., Santos, L., & Leitão, A. (2020). Computational design in architecture: Defining parametric, generative, and algorithmic design. *Frontiers of Architectural Research*, *9*(2), 287-300. https://doi.org/10.1016/j.foar.2019.12.008

Calder, B. (2021). *Architecture: From Prehistory to Climate Emergency*. Penguin Books Limited.

Canavan, S., Richardson, D. M., Visser, V., Le Roux, J. J., Vorontsova, M. S., & Wilson, J. R. U. (2017). The global distribution of bamboos: assessing correlates of introduction and invasion. *AoB PLANTS*, *9*(1). https://doi.org/10.1093/aobpla/plw078

Carmo, F. F. d., Kamino, L. H. Y., Junior, R. T., Campos, I. C. d., Carmo, F. F. d., Silvino, G., Castro, K. J. d. S. X. d., Mauro, M. L., Rodrigues, N. U. A., Miranda, M. P. d. S., & Pinto, C. E. F. (2017). Fundão tailings dam failures: the environment tragedy of the largest technological disaster of Brazilian mining in global context. *Perspectives in Ecology and Conservation*, *15*(3), 145-151. https://doi.org/10.1016/j.pecon.2017.06.002

Carpo, M. (2003). Drawing with Numbers: Geometry and Numeracy in Early Modern Architectural Design. *Journal of the Society of Architectural Historians*, *62*(4), 448-469. https://doi.org/10.2307/3592497

Carpo, M. (2014). Ten years of folding. In R. Oxman & R. Oxman (Eds.), *Theories of the digital in architecture* (pp. 35-46). Routledge.

Carpo, M. (2015). The New Science of Form-Searching. *Architectural Design*, *85*(5), 22-27. https://doi.org/10.1002/ad.1949

Carter, P. (1999). *Mies van der Rohe at work*. Phaidon.

Cartwright, M. (2015, April 22). *Vitruvius*. World History Encyclopedia. Retrieved 23/08/23 from https://www.worldhistory.org/Vitruvius/

Castelo-Branco, R., Caetano, I., & Leitão, A. (2022). Digital representation methods: The case of algorithmic design. *Frontiers of Architectural Research*, *11*(3), 527-541. https://doi.org/10.1016/j.foar.2021.12.008

Castelo-Branco, R., Caetano, I., Pereira, I., & Leitão, A. (2022). Sketching Algorithmic Design. *Journal of Architectural Engineering*, *28*(2), 04022010-04022011-04022010-04022011. https://doi.org/10.1061/(ASCE)AE.1943-5568.0000539

Cavallo, E., Powell, A., & Becerra, O. (2010). Estimating the Direct Economic Damages of the Earthquake in Haiti. *The Economic Journal*, *120*(546), F298-F312. https://doi.org/10.1111/j.1468-0297.2010.02378.x

Chakrabarty, D. (2000). *Provincializing Europe: Postcolonial Thought and Historical Difference*. Princeton University Press.

Chaowana, K., Wisadsatorn, S., & Chaowana, P. (2021). Bamboo as a Sustainable Building Material—Culm Characteristics and Properties. *Sustainability*, *13*(13). https://doi.org/10.3390/su13137376

Chard, N. (2005). Drawing Instruments. *Architectural Design*, *75*(4), 22-29. https://doi.org/10.1002/ad.99

Charleson, A. (2014). *Structure As Architecture: A Source Book for Architects and Structural Engineers*. Routledge.

Chaurasia, D., Bhalla, S., Gupta, S., & Gudhakar, P. (2019). 'Bamboo' with reference to Indian context: Potential sustainable building material and awareness. *AIP Conference Proceedings*, *2158*(1), 020004-020001-020004-020005. https://doi.org/10.1063/1.5127128

Chen, C., Noble, I., Hellmann, J., Coffee, J., Murillo, M., & Chawla, N. (2015). *Global Adaptation Index - Country Index Technical Report*. https://gain.nd.edu/

Chen, I.-C., & Hou, J.-H. (2016). Design with bamboo bend: Bridging natural material and computational design. In S.-F. Chien, S. Choo, M. A. Schnabel, W. Nakapan, M. J. Kim, & S. Roudavski (Eds.), *Living Systems and Micro-Utopias: Towards Continuous Designing, Proceedings of the 21st International Conference on Computer-Aided Architectural Design Research in Asia (CAADRIA 2016) / Melbourne 30 March–2 April 2016* (pp. 125-133). The Association for Computer-Aided Architectural Design Research in Asia (CAADRIA). https://doi.org/10.52842/conf.caadria.2016.125

Chen, L., Xu, Q., Leng, Y., Harries, K., & Wang, Z. (2019). Experimental study of performance of engineered bamboo beams exposed to three-sided standard fire. *Fire Safety Journal*, *106*, 52-60. https://doi.org/10.1016/j.firesaf.2019.04.002

Chen, Q., Fang, C., Wang, G., Ma, X., Luo, J., Chen, M., Dai, C., & Fei, B. (2021). Water vapor sorption behavior of bamboo pertaining to its hierarchical structure. *Sci Rep*, *11*(1), 12714. https://doi.org/10.1038/s41598-021-92103-4

Cheng, A. A. (2008). Skin Deep: Josephine Baker and the Colonial Fetish. *Camera Obscura: Feminism, Culture, and Media Studies*, *23*(3 (69)), 35-79. https://doi.org/10.1215/02705346-2008-007

Cheng, I. (2020). Structural Racialism in Modern Architectural Theory. In I. Cheng, C. L. Davis, & M. O. Wilson (Eds.), *Race and Modern Architecture: A Critical History from the Enlightenment to the Present* (pp. 134-152). University of Pittsburgh Press.

Chiganze, T., Buch, M., Lawrence, J., Gore, H., & Jing Lin Ng, F. (2021). Time to decolonise. *RIBA Journal*, *128*(4), 42-43. https://www.ribaj.com/intelligence/takeover-decolonise-architecture-tackling-racism-with-education-and-practice-reform

Chilton, J. (2010). Heinz Isler's Infinite Spectrum: Form-Finding in Design. *Architectural Design*, *80*(4), 64-71. https://doi.org/10.1002/ad.1108

Ching, F. D. K. (2015). *Architecture: Form, Space, and Order* (4 ed.). Wiley.

Chokhachian, A., & Atun, R. A. (2014). A framework for exploring the role of parametric design on design procedure. In Ö. Dinçyürek, Ş. Hoşkara, & S. M. Vural (Eds.), *Unspoken Issues in Architectural Education* (pp. 121-140). Faculty of Architecture -Eastern Mediterranean University.

Chung, K. F., & Siu, Y. C. (2002). *Erection of Bamboo Scaffolds* [INBAR Technical Report 24]. https://www.inbar.int/resources/inbar_publications/erection-of-bamboo-scaffolds/

Chung, K. F., & Yu, W. K. (2002). Mechanical properties of structural bamboo for bamboo scaffoldings. *Engineering Structures*, *24*(4), 429-442. https://doi.org/10.1016/S0141-0296(01)00110-9

Churkina, G., Organschi, A., Reyer, C. P. O., Ruff, A., Vinke, K., Liu, Z., Reck, B. K., Graedel, T. E., & Schellnhuber, H. J. (2020). Buildings as a global carbon sink. *Nature Sustainability*, *3*(4), 269-276. https://doi.org/10.1038/s41893-019-0462-4

Clark, L. G., Londoño, X., & Ruiz-Sanchez, E. (2015). Bamboo Taxonomy and Habitat. In W. Liese & M. Köhl (Eds.), *Bamboo: The Plant and its Uses* (Vol. 10, pp. 1-30). Springer, Cham. https://doi.org/10.1007/978-3-319-14133-6_1

Clark, W. A. V., & Deurloo, M. C. (2005). Categorical Modeling/Automatic Interaction Detection. In K. Kempf-Leonard (Ed.), *Encyclopedia of Social Measurement* (pp. 251-258). Elsevier. https://doi.org/10.1016/B0-12-369398-5/00359-5

CNBH. (2012). Code National du Bâtiment d'Haïti. In M. d. T. P. T. e. Communications (Ed.), (pp. 200): Ministère des Travaux Publics Transports et Communications.

CO-LAB. (2019). *Luum Temple*. Retrieved 01/08/2023 from https://www.co-labdesignoffice.com/luum-temple

Cockle, K. L., & Areta, J. I. (2013). Specialization on Bamboo by Neotropical Birds. *The Condor*, *115*(2), 217-220. https://doi.org/10.1525/cond.2013.120067

Cogley, B. (2019, July 26). *CO-LAB Design Office creates bamboo yoga pavilion in Tulum*. DeZeen. Retrieved 01/08/2023 from https://www.dezeen.com/2019/07/26/luum-temple-co-lab-design-bamboo-yoga-pavilion-tulum/

Cohen, M. J. (2013). Diri Nasyonal ou Diri Miami? Food, agriculture and US-Haiti relations. *Food Security*, *5*(4), 597-606. https://doi.org/10.1007/s12571-013-0283-7

Collins, K., & Nicolson, P. (2002). The Meaning of 'Satisfaction' for People with Dermatological Problems: Reassessing Approaches to Qualitative Health Psychology Research. *Journal of Health Psychology*, *7*(5), 615-629. https://doi.org/10.1177/1359105302007005681

Columbia University GSAPP. (2016). *The Gingerbread Houses of Port-au-Prince, Haiti*. Columbia University. https://www.wmf.org/sites/default/files/article/pdfs/haiti-report-.pdf

Correal, J. F. (2016). Bamboo design and construction. In K. A. Harries & B. Sharma (Eds.), *Nonconventional and Vernacular Construction Materials* (pp. 393-431). Woodhead Publishing. https://doi.org/10.1016/B978-0-08-100038-0.00014-7

Correal, J. F., Calvo, A. F., Trujillo, D. J. A., & Echeverry, J. S. (2022). Inference of mechanical properties and structural grades of bamboo by machine learning methods. *Construction and Building Materials*, *354*. https://doi.org/10.1016/j.conbuildmat.2022.129116

Correal, J. F., Prada, E., Suárez, A., & Moreno, D. (2021). Bearing capacity of bolted-mortar infill connections in bamboo and yield model formulation. *Construction and Building Materials*, *305*. https://doi.org/10.1016/j.conbuildmat.2021.124597

Crabtree, B. F., & Miller, W. L. (1992). *Doing Qualitative Research*. SAGE Publications.

Crane, K., Dobbins, J., Miller, L. E., Ries, C. P., Chivvis, C. S., Haims, M. C., Overhaus, M., Schwartz, H. L., & Wilke, E. (2010). *Building a More Resilient Haitian State*. RAND Corporation.

Crolla, K. (2017). Building indeterminacy modelling – the 'ZCB Bamboo Pavilion' as a case study on nonstandard construction from natural materials. *Visualization in Engineering*, *5*(1). https://doi.org/10.1186/s40327-017-0051-4

Crolla, K. (2018a). Bending Bamboo Rules: Beyond Century-Old Typologies. *Journal of Architectural Education*, *72*(1), 135-145. https://doi.org/10.1080/10464883.2018.1410669

Crolla, K. (2018b). *Building simplexity: The 'more or less' of post-digital architecture practice* (Publication Number 9921864092901341) [Doctor of Philosophy (PhD), RMIT University, RMIT University].

Crolla, K., & Fingrut, A. (2016). Protocol of Error: The design and construction of a bending-active gridshell from natural bamboo. In S.-F. Chien, S. Choo, M. A. Schnabel, W. Nakapan, M. J. Kim, & S. Roudavski (Eds.), *Living Systems and Micro-Utopias: Towards Continuous Designing, Proceedings of the 21st International Conference on Computer-Aided Architectural Design Research in Asia (CAADRIA 2016) / Melbourne 30 March–2 April 2016* (pp. 415-424). The Association for Computer-Aided Architectural Design Research in Asia (CAADRIA). https://doi.org/10.52842/conf.caadria.2016.415

Crolla, K., & Garvin, G. (2020). Designing With Uncertainty: Objectile Vibrancy in the TOROO Bamboo Pavilion. In D. Holzer, W. Nakapan, A. Globa, & I. Koh (Eds.), *Anthropocene, Design in the Age of Humans - Proceedings of the 25th CAADRIA Conference, Chulalongkorn University, Bangkok,* *Thailand, 5-6 August 2020* (Vol. 2, pp. 507-516). CAADRIA. https://doi.org/10.52842/conf.caadria.2020.2.507

Crook, L. (2023, March 29). *Building tall with timber "does not make sense" say experts*. DeZeen. Retrieved 08/08/23 from https://www.dezeen.com/2023/03/29/building-tall-timber-revolution/

CROSS-UK. (2021). *Collaborative Reporting for Safer Structures UK*. https://www.cross-safety.org/

Cross, N. (2000). *Engineering design methods: Strategies for product design* (3 ed.). Wiley.

Cross, N. (2011). *Design Thinking: Understanding How Designers Think and Work*. Bloomsbury Publishing.

Curry, J. A. (2015). Thermodynamics | Humidity Variables. In G. R. North, J. Pyle, & F. Zhang (Eds.), *Encyclopedia of Atmospheric Sciences (Second Edition)* (Vol. 5, pp. 391-393). Academic Press. https://doi.org/10.1016/B978-0-12-382225-3.00162-6

D'Odorico, P., Caylor, K., Okin, G. S., & Scanlon, T. M. (2007). On soil moisture-vegetation feedbacks and their possible effects on the dynamics of dryland ecosystems. *Journal of Geophysical Research*, *112*(G4), 1-10. https://doi.org/10.1029/2006jg000379

Dalbiso, A. D., & Nuramo, D. A. (2019). Ethiopian vernacular bamboo architecture and its potentials for adaptation in modern urban housing: A case study. In Y. Xiao, Z. Li, & K. W. Liu (Eds.), *Modern Engineered Bamboo Structures - Proceedings of the Third International Conference on Modern Bamboo Structures (ICBS 2018), June 25-27, 2018, Beijing, China*. CRC Press. https://doi.org/10.1201/9780429434990-8

DALL·E. (2023). *DALL·E 2*. In [AI image generation model]. Open AI. https://openai.com/dall-e-2

Darke, J. (1979). The primary generator and the design process. *Design Studies*, *1*(1), 36-44. https://doi.org/10.1016/0142-694X(79)90027-9

Datta, S., Hanafin, S., & Pitts, G. (2009). Experiments with Stochastic Processes: Façade Subdivision based on Wind Motion. *International Journal of Architectural Computing*, *7*(3), 389-402. https://doi.org/10.1260/147807709789621239

Daud, N. M., Nor, N. M., Yusof, M. A., Bakhri, A. A. M. A., & Shaari, A. A. (2018). The physical and mechanical properties of treated and untreated Gigantochloa Scortechinii bamboo. *AIP Conference Proceedings - International Conference on Engineering and Technology (IntCET 2017)*, *1930*(1). https://doi.org/10.1063/1.5022910

Davis, A. (2013, September 25). *Blooming Bamboo Home by H&P Architects*. DeZeen. Retrieved 21/07/2019 from https://www.dezeen.com/2013/09/25/blooming-bamboo-house-by-h-and-p-architects

Davis, S. J., Lewis, N. S., Shaner, M., Aggarwal, S., Arent, D., Azevedo, I. L., Benson, S. M., Bradley, T., Brouwer, J., Chiang, Y.-M., Clack, C. T. M., Cohen, A., Doig, S., Edmonds, J., Fennell, P., Field, C. B., Hannegan, B., Hodge, B.-M., Hoffert, M. I., . . . Caldeira, K. (2018). Net-zero emissions energy systems. *Science*, *360*(6396), eaas9793. https://doi.org/10.1126/science.aas9793

de Boissieu, A. (2022). Introduction to Computational Design: Subsets, Challenges in Practice and Emerging Roles. In M. Bolpagni, R. Gavina, & D. Ribeiro (Eds.), *Industry 4.0 for the Built Environment* (Vol. 20, pp. 55-75). Springer, Cham. https://doi.org/10.1007/978-3-030-82430-3_3

De La Rocha, C., & Conley, D. J. (2017). Silica, Be Dammed! In *Silica Stories* (pp. 135-156). Springer, Cham. https://doi.org/10.1007/978-3-319-54054-2_8

DeBoer, D., & Groth, M. (2010). *Bamboo Building Essentials: The Eleven Basic Principles*. Darrel DeBoer and Megan Groth.

DeFries, R. S., Rudel, T., Uriarte, M., & Hansen, M. (2010). Deforestation driven by urban population growth and agricultural trade in the twenty-first century. *Nature Geoscience*, *3*(3), 178-181. https://doi.org/10.1038/ngeo756

DeLanda, M. (2015). The New Materiality. *Architectural Design*, *85*(5), 16-21. https://doi.org/10.1002/ad.1948

Denari, N. (2012). Precise form for an imprecise World. In M. Scott (Ed.), *Digital Workflows in Architecture: Design - Assembly - Industry* (pp. 28-45). Birkhäuser. https://doi.org/10.1515/9783034612173.28

designboom. (2019, October 7). *SEEDS builds community-driven, disaster resilient bamboo housing in india*. designboom. Retrieved 30/09/2021 from https://www.designboom.com/architecture/seeds-disaster-resilient-bamboo-housing-assam-india-10-07-2019/

Desroches, R., Comerio, M., Eberhard, M., Mooney, W., & Rix, G. (2011). Overview of the 2010 Haiti Earthquake. *Earthquake Spectra*, *27*, S1-S21. https://doi.org/10.1193/1.3630129

DETAIL. (2010). Bamboo Pavilion for the Expo Shanghai. *DETAIL inspiration*, *2010*(10), 1046-1052. https://inspiration.detail.de/bamboo-pavilion-for-the-expo-shanghai-103526.html

DETAIL. (2016). Grace Farms Foundation Centre in New Canaan. *DETAIL inspiration*(10), 903-907. https://inspiration.detail.de/grace-farms-foundation-centre-in-new-canaan-113500.html

Deutsch, R. (2019). *Superusers: Design technology specialists and the future of practice*. Routledge.

Di Mari, A., & Yoo, N. (2012). *Operative design: A catalogue of spatial verbs*. BIS.

Di Paola, F., & Mercurio, A. (2023). Algorithmic Modelling and Prototyping of a Connection Joint for Reticular Space Structures. In *Parametric Experiments in Architecture* (pp. 61-87). https://doi.org/10.1007/978-3-030-96276-0_3

Dietsch, D. K. (2002). *Architecture For Dummies*. Wiley.

Dirzo, R., & Raven, P. H. (2003). Global State of Biodiversity and Loss. *Annual Review of Environment and Resources*, *28*(1), 137-167. https://doi.org/10.1146/annurev.energy.28.050302.105532

Disén, K., & Clouston, P. L. (2013). Building with bamboo: A review of culm connection technology. *Journal of Green Building*, *8*(4), 83-93. https://doi.org/10.3992/jgb.8.4.83

Dolisca, F., McDaniel, J. M., Teeter, L. D., & Jolly, C. M. (2007). Land tenure, population pressure, and deforestation in Haiti: The case of Forêt des Pins Reserve. *Journal of Forest Economics*, *13*(4), 277-289. https://doi.org/10.1016/j.jfe.2007.02.006

Dortheimer, J., & Margalit, T. (2020). Open-source architecture and questions of intellectual property, tacit knowledge, and liability. *The Journal of Architecture*, *25*(3), 276-294. https://doi.org/10.1080/13602365.2020.1758950

DPIRD. (2014, June 3). *Growing bamboos*. Department of Primary Industries and Regional Development, Government of Western Australia. Retrieved 15/10/2021 from https://agric.wa.gov.au/n/2830

Dreith, B. (2022, November 16). *How AI software will change architecture and design*. DeZeen. Retrieved 29/07/2023 from https://www.dezeen.com/2022/11/16/ai-design-architecture-product/

Dubois, L. (2012). *Haiti: The aftershocks of history* (1 ed.). Picador.

Dubois, L. (2016, October 17). Who Will Speak for Haiti's Trees? *New York Times*. https://www.nytimes.com/2016/10/18/opinion/who-will-speak-for-haitis-trees.html

Dunkelberg, K., Fritz, J., Gaß, S., Greiner, S., Hennicke, J., Otto, F., Reiner, R., Schaur, E., & Voigt, H. (1985). *IL 31 Bambus Bamboo*. Karl Kramer Verlag.

Easterling, K. (2012). *The Action is the Form: Victor Hugo's TED Talk*. Strelka Press.

Eastman, C. (1975). The Use of Computers Instead of Drawings in Building Design. *AIA Journal*, *63*, 46-50.

Eckstein, D., Künzel, V., & Schäfer, L. (2021). *Global Climate Risk Index 2021*. Germanwatch. https://germanwatch.org/en/19777

Edwards, B. (2013). *Drawing on the Right Side of the Brain: A Course in Enhancing Creativity and Artistic Confidence* (4 ed.). Souvenir Press.

Elhacham, E., Ben-Uri, L., Grozovski, J., Bar-On, Y. M., & Milo, R. (2020). Global human-made mass exceeds all living biomass. *Nature*, *588*(7838), 442-444. https://doi.org/10.1038/s41586-020-3010-5

Elmqvist, T., Fragkias, M., Goodness, J., Güneralp, B., Marcotullio, P. J., McDonald, R. I., Parnell, S., Schewenius, M., Sendstad, M., Seto, K. C., & Wilkinson, C. (2013). *Urbanization, biodiversity and ecosystem services - Challenges and opportunities: A global assessment*. Springer.

Ennemoser, B., & Mayrhofer-Hufnagl, I. (2023). Design across multi-scale datasets by developing a novel approach to 3DGANs. *International Journal of Architectural Computing*, *21*(2), 358-373. https://doi.org/10.1177/14780771231168231

EPFL. (2022). *BamX*. Retrieved 03/02/2023 from https://bamx.epfl.ch/

Erdine, E. (2015). Generative Processes in Tower Design: Simultaneous Integration of Tower Subsystems Through Biomimetic Analogies. In L. Combs & C. Perry (Eds.), *ACADIA 2105: Computational Ecologies: Design in the Anthropocene [Proceedings of the 35th Annual Conference of the Association for Computer Aided Design in Architecture], Cincinnati 19-25 October, 2015)* (pp. 173-184). ACADIA. https://doi.org/10.52842/conf.acadia.2015.173

Escamilla, E. Z., Habert, G., & Lopez, L. F. (2014). Environmental Savings Potential from the Use of Bahareque (Mortar Cement Plastered Bamboo) in Switzerland. *Key Engineering Materials*, *600*, 21-33. https://doi.org/10.4028/www.scientific.net/KEM.600.21

Eskenazi, D. (2015). Architecture's Digital Model Problems. In D. Ruy & L. Sheppard (Eds.), *103rd ACSA Annual Meeting Proceedings, The Expanding Periphery and the Migrating Center* (pp. 636-640). ACSA. https://www.acsa-arch.org/chapter/architectures-digital-model-problems/

Espinosa Trujillo, O., & Wang, T.-H. (2015). Parametric Modeling of Bamboo Pole Joints. In G. Celani, D. Sperling, & J. Franco (Eds.), *Computer-Aided Architectural Design Futures. The Next City - New Technologies and the Future of the Built Environment. CAAD Futures 2015. Communications in Computer and Information Science* (Vol. 527). Springer. https://doi.org/10.1007/978-3-662-47386-3_15

Estrada Meza, M. G., González Meza, E., Chi Pool, D. A., & McNamara Trujillo, J. S. (2022). Design Exploration of Bamboo Shells Structures by Using Parametric Tools. *Applied Sciences*, *12*(7522). https://doi.org/10.3390/app12157522

Fairs, M. (2007, January 2). *UNStudio shows bunker tea house*. DeZeen. Retrieved 29/07/2023 from https://www.dezeen.com/2007/01/02/un-studio-show-tea-house-in-bunker/

Fairs, M. (2015, November 4). *Bamboo fibre is stronger and cheaper than steel says ETH professor*. DeZeen. Retrieved 06/06/2019 from https://www.dezeen.com/2015/11/04/bamboo-fibre-stronger-than-steel-dirk-hebel-world-architecture-festival-2015/

Fakhry, M., Kamel, I., & Abdelaal, A. (2021). CAD using preference compared to hand drafting in architectural working drawings coursework. *Ain Shams Engineering Journal*, *12*(3), 3331-3338. https://doi.org/10.1016/j.asej.2021.01.016

FAO. (2006). *Global Forest Resources Assessment 2005*. FAO. https://www.fao.org/3/a0400e/a0400e00.htm

FAO. (2016). *Promoting sustainable building materials and the implications on the use of wood in buildings: A review of leading public policies in Europe and North America* (Vol. ECE/TIM/SP/38). UN FAO. https://unece.org/fileadmin/DAM/timber/publications/SP-38.pdf

FAO. (2020a). *Global Forest Resources Assessment 2020: Main report*. FAO. https://doi.org/10.4060/ca9825en

FAO. (2020b). *Global Forest Resources Assessment 2020: Terms and Definitions* (Vol. Working Paper 188). FAO. https://www.fao.org/3/I8661EN/i8661en.pdf

Farahani, H., & Bayazidi, S. (2018). Modeling the assessment of socio-economical and environmental impacts of sand mining on local communities: A case study of Villages Tatao River Bank in North-western part of Iran. *Resources Policy*, *55*, 87-95. https://doi.org/10.1016/j.resourpol.2017.11.001

Fawcett, A. P. (1998). *Architecture: Design notebook*. Routledge (Architectural Press).

Fergusson, J. (1855). *The Illustrated Handbook of Architecture: Being a concise and popular account of the different styles of architecture prevailing in all ages and all countries* (Vol. 1). James Murray: Albemarle Street.

Fischer, M., & Tatum, C. B. (1997). Characteristics of design-relevant constructability knowledge. *Journal of Construction Engineering & Management*, *123*(3), 253. https://doi.org/10.1061/(ASCE)0733-9364(1997)123:3(253)

Fletcher, S. B. (1931). Banister Fletcher's A Tree of Architecture (Originally published 1896). In. A History of Architecture on the Comparative Method (9th ed.) [Frontispiece]: London, Batsford.

FOA. (2003). *Phylogenesis: FOA's Ark*. Actar.

Foote, J. (2013). Design-Build :: Build-Design. *Journal of Architectural Education*, *65*(2), 52-58. https://doi.org/10.1111/j.1531-314X.2011.01197.x

Fossey, D., & Harcourt, A. H. (1977). Feeding Ecology of Free-ranging Mountain Gorilla (Gorilla gorilla beringei). In T. H. Clutton-Brock (Ed.), *Primate Ecology: Studies of Feeding and Ranging Behavior in Lemurs, Monkey and Apes* (pp. 415-447). Academic Press. https://doi.org/10.1016/B978-0-12-176850-8.50019-6

Foxx, R. M. (2012). Te Terre a Fatige 'the Earth Is Tired': Reversing Deforestation in Haiti. *Behavioral Interventions*, *27*(2), 105-108. https://doi.org/10.1002/bin.1338

Frampton, K. (1995). *Studies in Tectonic Culture: The Poetics of Construction in Nineteenth and Twentieth Century Architecture*. MIT Press.

Frampton, K. (2020). *Modern Architecture: A Critical History* (5 ed.). Thames and Hudson.

Frascari, M. (2009). Lines as Architectural Thinking. *Architectural Theory Review*, *14*(3), 200-212. https://doi.org/10.1080/13264820903341605

Fraser, I., & Henmi, R. (1993). *Envisioning Architecture: An Analysis of Drawing*. Wiley.

Frazer, J. (2016). Parametric Computation: History and Future. *Architectural Design*, *86*(2), 18-23. https://doi.org/10.1002/ad.2019

Frearson, A. (2014a, January 14). *African children's library with rammed earth walls by BC Architects and Studies*. DeZeen. Retrieved 23/09/2021 from https://www.dezeen.com/2014/01/14/childrens-library-muyinga-africa-rammed-earth-walls-bc-architects/

Frearson, A. (2014b, April 23). *Thomas Heatherwick unveils "sunken oasis" for Abu Dhabi*. DeZeen. Retrieved 29/07/2023 from https://www.dezeen.com/2014/04/23/thomas-heatherwick-unveils-sunken-oasis-for-abu-dhabi/

Frearson, A. (2023, March 16). *"At first we were definitely making concrete buildings out of timber" says Andrew Waugh*. DeZeen. https://www.dezeen.com/2023/03/16/andrew-waugh-interview-timber-revolution/

French, H. W. (1991, September 25). Haitian Fortress Is Saved From Nature's Onslaught. *New York Times*.

Fure, A. (2011). Digital Materiallurgy: On the productive force of deep codes and vital matter. In J. M. Taron (Ed.), *ACADIA 11: Integration through Computation [Proceedings of the 31st Annual Conference of the Association for Computer Aided Design in Architecture (ACADIA), Banff (Alberta) 13-16 October, 2011* (pp. 90-97). ACADIA. https://doi.org/10.52842/conf.acadia.2011.090

Fürnkranz, J. (2010). Decision Tree. In C. Sammut & G. I. Webb (Eds.), *Encyclopedia of Machine Learning* (pp. 263-267). Springer. https://doi.org/10.1007/978-0-387-30164-8_204

Gage, M. F. (2016). A Hospice for Parametricism. *Architectural Design*, *86*(2), 128-133. https://doi.org/10.1002/ad.2034

Garcia, M. (2010). MAXXI, Rome: Zaha Hadid Architects. *Architectural Design*, *80*(3), 132-135. https://doi.org/10.1002/ad.1092

García, M. J. (2019). Discrete Flexibility: Computing Lightness in Architecture. *Architectural Design*, *89*(2), 70-77. https://doi.org/10.1002/ad.2414

Gates, B., & Gates, M. (2019, February 12). *We didn't see this coming: Nine surprises that have inspired us to act.* Gates Notes. Retrieved 23/08/23 from https://www.gatesnotes.com/2019-Annual-Letter

George, B., Suttie, E., Merlin, A., & Deglise, X. (2005). Photodegradation and photostabilisation of wood – the state of the art. *Polymer Degradation and Stability*, *88*(2), 268-274. https://doi.org/10.1016/j.polymdegradstab.2004.10.018

Ghavami, K. (2016). Introduction to nonconventional materials and an historic retrospective of the field. In K. A. Harries & B. Sharma (Eds.), *Nonconventional and Vernacular Construction Materials* (pp. 37-61). Woodhead Publishing. https://doi.org/10.1016/B978-0-08-100038-0.00002-0

Goepel, G., & Crolla, K. (2020). Augmented Reality-based Collaboration - ARgan, a bamboo art installation case study. In D. Holzer, W. Nakapan, A. Globa, & I. Koh (Eds.), *RE: Anthropocene, Design in the Age of Humans - Proceedings of the 25th CAADRIA Conference - Chulalongkorn University, Bangkok, Thailand, 5-6 August 2020* (Vol. 2, pp. 313-322). CAADRIA. https://doi.org/10.52842/conf.caadria.2020.2.313

Goepel, G., & Crolla, K. (2021). Augmented Feedback. In B. Bogosian, K. Dörfler, B. Farahi, J. Garcia del Castillo y López, J. Grant, V. Noel, S. Parascho, & J. Scott (Eds.), *ACADIA 2021: Realignments: Toward Critical Computation: Proceedings of the 41st Annual Conference of the Association for Computer Aided Design in Architecture* (pp. 232-237). ACADIA. https://papers.cumincad.org/cgi-bin/works/paper/acadia21_232

Gold, S., & Rubik, F. (2009). Consumer attitudes towards timber as a construction material and towards timber frame houses – selected findings of a representative survey among the German population. *Journal of Cleaner Production*, *17*(2), 303-309. https://doi.org/10.1016/j.jclepro.2008.07.001

Goldsmith, N. (2016). The physical modeling legacy of Frei Otto. *International Journal of Space Structures*, *31*(1), 25-30. https://doi.org/10.1177/0266351116642071

Gonzalez, E., Estrada, M. G., & Marco, G. D. (2021). Parametric simulation of bamboo structures in Mexico. In S. A. Behnejad, G. A. R. Parke, & O. Samavati (Eds.), *Inspiring the Next Generation - Proceedings of the International Conference on Spatial Structures 2020/21 (IASS2020/21-Surrey7) 23rd – 27th August*

2021 (pp. 371-382). Spatial Structures Research Centre of the University of Surrey. https://doi.org/10.15126/900337

Gonzalez, M. G., Takeuchi, C. P., & Perozo, M. C. (2012). Variation of Tensile Strength Parallel to the Fiber of Bamboo Guadua Angustifolia Kunth in Function of Moisture Content. In *Key Engineering Materials* (Vol. 517, pp. 71-75). https://doi.org/10.4028/www.scientific.net/KEM.517.71

Göswein, V., Arehart, J., Pittau, F., Pomponi, F., Lamb, S., Zea Escamilla, E., Freire, F., Silvestre, J. D., & Habert, G. (2022). Wood in buildings: the right answer to the wrong question. *IOP Conference Series: Earth and Environmental Science*, *1078*(1), 012067. https://doi.org/10.1088/1755-1315/1078/1/012067

Gottron, J., Harries, K., & Xu, Q. (2014). Creep behaviour of bamboo. *Construction and Building Materials*, *66*, 79-88. https://doi.org/10.1016/j.conbuildmat.2014.05.024

Gramazio, F., & Kohler, M. (2008). *Digital materiality in architecture*. Lars Müller.

Greenberg, D. P. (1974). Computer Graphics in Architecture. *Scientific American*, *230*(5), 98-107. https://www.scientificamerican.com/article/computer-graphics-in-architecture/

Greene, R. S. B. (1992). Soil physical properties of three geomorphic zones in a semiarid mulga woodland. *Soil Research*, *30*(1), 55-69. https://doi.org/10.1071/SR9920055

Greene, R. S. B., Kinnell, P. I. A., & Wood, J. T. (1994). Role of plant cover and stock trampling on runoff and soil-erosion from semi-arid wooded rangelands. *Soil Research*, *32*(5), 953-973. https://doi.org/10.1071/SR9940953

Griscom, B. W., & Ashton, P. M. S. (2003). Bamboo control of forest succession: Guadua sarcocarpa in Southeastern Peru. *Forest Ecology and Management*, *175*(1), 445-454. https://doi.org/10.1016/S0378-1127(02)00214-1

Grosser, D., & Liese, W. (1971). On the anatomy of Asian bamboos, with special reference to their vascular bundles. *Wood Science and Technology*, *5*(4), 290-312. https://doi.org/10.1007/BF00365061

Gulay, E., & Lucero, A. (2021). Understanding the Role of Physical and Digital Techniques in the Initial Design Processes of Architecture. In C. Ardito, R. L. A. M. H. Petrie, & A. P. G. D. K. Inkpen (Eds.), *Human-Computer Interaction – INTERACT 2021 18th IFIP TC 13 International Conference, Bari, Italy, August 30 – September 3, 2021, Proceedings, Part II* (Vol. 12933, pp. 312-329). Springer, Cham. https://doi.org/10.1007/978-3-030-85616-8_19

Gutiérrez González, M. (2020). *Fire analysis of load-bearing bamboo structures* [PhD Thesis, The University of Queensland]. The University of Queensland. https://espace.library.uq.edu.au/view/UQ:5974aa1

Gutiérrez González, M., & Briceño Roncancio, P. A. (2015). Equilibrium Moisture Content and Sorption Isotherms determination for different conditions of relative humidity and temperature in the bamboo guadua Angustifolia Kunth. In *Construction for Sustainability - Green Materials & Technologies NOCMAT, 2015 - Winnipeg, Canada, August 10-13, 2015*.

Gutiérrez González, M., Madden, J., & Maluk, C. (2018). *Experimental study on compressive and tensile strength of bamboo at elevated temperatures* World Conference on Timber Engineering 2018, Seoul, South Korea.

Gutiérrez González, M., & Maluk, C. (2020). Mechanical behaviour of bamboo at elevated temperatures – Experimental studies. *Engineering Structures*, *220*, 110997. https://doi.org/10.1016/j.engstruct.2020.110997

Gutiérrez, J., van Vliet, W., Arias, E., & Pujol, R. (1993). In defence of housing: Housing policies and practices in Costa Rica. *Habitat International*, *17*(2), 63-72. https://doi.org/10.1016/0197-3975(93)90005-W

Gutiérrez, J. A. (2000). *Structural Adequacy of Traditional Bamboo Housing in Latin America* (INBAR Technical Report, Issue. INBAR. https://www.inbar.int/resources/inbar_publications/structural-adequacy-of-traditional-bamboo-housing-in-latin-america/

Haas, P. (2010, July). *When bad engineering makes a natural disaster even worse [Video]*. TED. Retrieved 13/07/2020 from https://www.ted.com/talks/peter_haas_when_bad_engineering_makes_a_natural_disaster_even_worse

Hailwood, A. J., & Horrobin, S. (1946). Absorption of water by polymers: analysis in terms of a simple model. *Transactions of the Faraday Society*, *42*, B084-B092. https://doi.org/10.1039/TF946420B084

Hakim, C. (2000). Ad hoc sample surveys. In C. Hakim (Ed.), *Research Design: Succesful Designs for Social Economics Research* (2 ed., pp. 76-94). Routledge. https://doi.org/10.4324/9780203354971-7

Hales, S. (2017). The History of Human Habitation: Ancient Domestic Architecture in Nineteenth-Century Europe. In K. T. v. Stackelberg & E. Macaulay-Lewis (Eds.), *Housing the New Romans: Architectural Reception and Classical Style in the Modern World*. Oxford University Press. https://doi.org/10.1093/acprof:oso/9780190272333.003.0004

Hamdan, H., Hill, C. A. S., Zaidon, A., Anwar, U. M. K., & Abd. Latif, M. (2007). Equilibrium moisture content and volumetric changes of Gigantochloa scortechinii. *Journal of Tropical Forest Science*, *19*(1), 18-24. https://www.frim.gov.my/v1/JTFSOnline/jtfs/v19n1/18-24.pdf

Han, N. N., & Kurniawan, K. R. (2018). Brutalism: The Socio-Political and Technological Effect on Postcolonial Modern Architecture in Indonesia. *International Conference on Civil and Environmental Engineering (ICCEE 2018)*, *65*(2018), 01004. https://doi.org/10.1051/e3sconf/20186501004

Hansen, M. C., Potapov, P., Moore, R., Hancher, M., Turubanova, S., Tyukavina, A., Thau, D., Stehman, S., Goetz, S., Loveland, T., Kommareddy, A., Egorov, A., Chini, L., Justice, C. O., & Townshend, J. (2013). High-Resolution Global Maps of 21st-Century Forest Cover Change. *Science*, *342*, 850-853. https://doi.org/10.1126/science.1244693

Haq, B. (2007). *Battling the Storm - A study on cyclone resistant housing* (2 ed.). German Red Cross.

Hardoy, J. E., & Satterthwaite, D. (1989). *Squatter citizen: Life in the urban third world*. Earthscan.

Harmon, R. S. (2005). An Introduction to the Panama Canal Watershed. In R. S. Harmon (Ed.), *The Río Chagres, Panama* (Vol. 52, pp. 19-28). Springer. https://doi.org/10.1007/1-4020-3297-8_2

Harper, D. (2023). *(n.d.). Etymology of bamboo*. Online Etymology Dictionary. Retrieved 01/09/2023 from https://www.etymonline.com/word/bamboo

Harries, K. A., Ben-Alon, L., & Sharma, B. (2020). Codes and standards development for nonconventional and vernacular materials. In K. A. Harries & B. Sharma (Eds.), *Nonconventional and Vernacular Construction Materials* (2 ed., pp. 81-100). Woodhead Publishing. https://doi.org/10.1016/B978-0-08-102704-2.00004-4

Harries, K. A., Mofidi, A., Naylor, J. O., Trujillo, D., Lopez, L. F., Gutierrez, M., Sharma, B., & Rogers, C. (2022, May 21). *Knowledge Gaps and Research Needs for Bamboo in Construction* 18th International Conference on Non-conventional Materials and Technologies (NOCMAT 2022), http://doi.org/10.5281/zenodo.6569785

Harries, K. A., Rogers, C., & Brancaccio, M. (2022). Bamboo joint capacity determined by ISO 22156 'complete joint testing' provisions. *Advances in Bamboo Science*, *1*. https://doi.org/10.1016/j.bamboo.2022.100003

Harries, K. A., Rogers, C., & Silva, E. (2022). *Experimental demonstration of the poor structural performance of bamboo-reinforced concrete flexural members* 18th International Conference on Non-conventional Materials and Technologies (NOCMAT 2022), http://doi.org/10.5281/zenodo.6569781

Harries, K. A., Sharma, B., & Richard, M. (2012). Structural Use of Full Culm Bamboo: The Path to Standardization. *International Journal of Architecture, Engineering and Construction*, *1*(2), 66-75. https://doi.org/10.7492/ijaec.2012.008

Harries, K. A., Trujillo, D., Kaminski, S., & Lopez, L. F. (2022). Development of load tables for design of full-culm bamboo. *European Journal of Wood and Wood Products*, *80*, 621–634. https://doi.org/10.1007/s00107-022-01798-3

Harris, N. L., Brown, S., Hagen, S. C., Saatchi, S. S., Petrova, S., Salas, W., Hansen, M. C., Potapov, P. V., & Lotsch, A. (2012). Baseline Map of Carbon Emissions from Deforestation in Tropical Regions. *Science*, *336*(6088), 1573-1576. https://doi.org/10.1126/science.1217962

Harvey, C. (2018, July 9). *Cement Producers Are Developing a Plan to Reduce CO2 Emissions*. Scientific American. Retrieved 09/09/20 from https://www.scientificamerican.com/article/cement-producers-are-developing-a-plan-to-reduce-co2-emissions/

Hedges, S. B., Cohen, W. B., Timyan, J., & Yang, Z. (2018). Haiti's biodiversity threatened by nearly complete loss of primary forest. *Proceedings of the National Academy of Sciences*, *115*(46), 11850-11855. https://doi.org/10.1073/pnas.1809753115

Helmore, E. (2008, November 23). *How Haiti hopes to break the cycle of disaster: restoring its lost forests*. The Guardian. Retrieved 07/10/21 from https://www.theguardian.com/environment/2008/nov/23/forests-flooding

Hemmerling, M., & de Falco, C. (2018). Simple Complexities: An Interdisciplinary Approach Towards Computational Design and Architectural Geometry. In *Informed Architecture* (pp. 19-32). https://doi.org/10.1007/978-3-319-53135-9_3

Heying, H. E. (2001). Social and reproductive behaviour in the Madagascan poison frog, Mantella laevigata, with comparisons to the dendrobatids. *Animal Behaviour*, *61*(3), 567-577. https://doi.org/10.1006/anbe.2000.1642

Hidalgo-López, O. (2003). *Bamboo The Gift of the Gods*. Oscar Hidalgo-López.

Hk, T., & Hossiney, N. (2022). A short review on environmental impacts and application of iron ore tailings in development of sustainable eco-friendly bricks. *Materials Today: Proceedings*, *61*, 327-331. https://doi.org/10.1016/j.matpr.2021.09.522

HKBD. (2006). *Guidelines on the Design and Construction of Bamboo Scaffolds*. Hong Kong Buildings Department Retrieved from https://www.bd.gov.hk/doc/en/resources/codes-and-references/code-and-design-manuals/GDCBS.pdf

Hofmeister, S., Schoof, J., & Kaufmann, H. (2021). What is the Future of Timber Construction? Interview with Hermann Kaufmann. *DETAIL*(6), 52-57. https://inspiration.detail.de/hermann-kaufmann-hk-architekten-do-we-have-to-rethink-building-115082.html

Hoinville, G., & Jowell, R. (1978). *Survey Research Practice*. Heinemann Educational Books.

Holl, S. (2000). *Parallax*. Princeton Architectural Press.

Holzer, D., Hough, R., & Burry, M. (2007). Parametric Design and Structural Optimisation for Early Design Exploration. *International Journal of Architectural Computing*, *5*(4), 625-643. https://doi.org/10.1260/147807707783600780

Hone, T., Cahill, L., Robinson, A., Korde, C., & Taylor, D. (2020). The splitting of bamboo in response to changes in humidity and temperature. *J Mech Behav Biomed Mater*, *111*, 103990. https://doi.org/10.1016/j.jmbbm.2020.103990

Huang, J. M. (2017). Integrating Computational Design And Traditional Crafts: A Reinvention of bamboo Structures. In P. Janssen, P. Loh, A. Raonic, & M. A. Schnabel (Eds.), *Protocols, Flows, and Glitches - Proceedings of the 22nd CAADRIA Conference, Xi'an Jiaotong-Liverpool University, Suzhou, China, 5-8 April 2017* (pp. 437-444). CAADRIA. https://doi.org/10.52842/conf.caadria.2017.437

Hughes, R. (2003). *Mies van der Rohe: Less Is More (Episode 3) [Television series episode]*, BBC. https://www.bbc.co.uk/programmes/b0074nxb

Huynh, D., Kibe, J., McVitty, J., Sangodeyi, D., Sheth, S., Simon, P.-E., & Smith, D. (2013). *Housing Delivery and Housing Finance in Haiti: Operationalizing the national housing policy*. Oxfam America. https://www.oxfamamerica.org/explore/research-publications/housing-delivery-and-housing-finance-in-haiti/

Hyun, J. (2005). *Breaking the Bamboo Ceiling: Career Strategies for Asians*. Harper Collins.

ICBO ES. (2000). *AC162 - Acceptance Criteria for Structural Bamboo*. ICBO ES. https://icc-es.org/acceptance-criteria/ac162/

IEA. (2017). *Energy Technology Perspectives 2017*. IEA. https://doi.org/10.1787/energy_tech-2017-en

IEA. (2023). *CO2 Emissions from buildings*. IEA. Retrieved 07/08/2023 from https://www.iea.org/energy-system/buildings

INBAR. (1999). *Socio-economic Issues and Constraints in the Bamboo and Rattan Sectors: INBAR's Assessment*. INBAR. https://www.inbar.int/resources/inbar_publications/socio-economic-issues-and-constraints-in-the-bamboo-and-rattan-sectors-inbars-assessment/

INBAR. (2003). *Proceedings of Bamboo housing workshop*. INBAR. https://www.inbar.int/resources/inbar_publications/proceedings-of-the-bamboo-housing-workshop/

INBAR, & University of Pittsburgh. (2017). *Pittsburgh Declaration*.

Ingram, J. (2020). *Understanding BIM: The past, present and future*. Routledge.

Ioannidou, D., Sonnemann, G., & Suh, S. (2020). Do we have enough natural sand for low-carbon infrastructure? *Journal of Industrial Ecology*, *24*(5), 1004-1015. https://doi.org/10.1111/jiec.13004

IPCC. (2021). *Climate Change 2021: The Physical Science Basis Summary for Policymakers*. https://www.ipcc.ch/report/ar6/wg1/

IRP. (2020). *Mineral Resource Governance in the 21st Century: Gearing extractive industries towards sustainable development*. UNEP. https://www.resourcepanel.org/reports/mineral-resource-governance-21st-century

Isagi, Y., Oda, T., Fukushima, K., Lian, C., Yokogawa, M., & Kaneko, S. (2016). Predominance of a single clone of the most widely distributed bamboo species Phyllostachys edulis in East Asia. *Journal of Plant Research*, *129*(1), 21-27. https://doi.org/10.1007/s10265-015-0766-z

ISO 12944-2. (2017). Corrosion protection of steel structures by protective paint systems - Part 2: Classification of environments (ISO Standard No. 12944-2:2017). In: ISO/TC 35/SC 14.

ISO 19624. (2018). Bamboo structures — Grading of bamboo culms — Basic principles and procedures (ISO Standard No. 19624:2018). In: ISO/TC 165 Timber structures.

ISO 21887. (2007). Durability of wood and wood-based products — Use classes (ISO Standard No. ISO 21887:2007). In: ISO/TC 165 Timber structures.

ISO 22156. (2004). Bamboo structures — Bamboo culms — Structural design (ISO Standard No. 22156:2004). In: ISO/TC 165 Timber structures.

ISO 22156. (2021). Bamboo structures — Bamboo culms — Structural design (ISO Standard No. 22156:2021). In: ISO/TC 165 Timber structures.

ISO 22157. (2019). Bamboo structures — Determination of physical and mechanical properties of bamboo culms — Test methods (ISO Standard No. 22157:2019). In: ISO/TC 165 Timber structures.

ISO 23478. (2022). Bamboo structures — Engineered bamboo products — Test methods for determination of physical and mechanical properties (ISO Standard No. 23478:2022). In: ISO/TC 165 Timber structures.

ISO/CD 7567. (2023). Bamboo Structures — Glued laminated bamboo --Product specification (ISO Standard No. ISO/CD 7567) [Under development]. In: ISO/TC 165 Timber structures.

Jabi, W. (2013). *Parametric design for architecture*. Laurence King Publishing.

Janssen, J. J. A. (1979). *Bamboo: A series of articles on the use of bamboo in building constructions*. Technische Hogeschool Eindhoven.

Janssen, J. J. A. (1981). *Bamboo in building structures* [PhD Thesis (Research TU/e/ Graduation TU/e), Technische Hogeschool Eindhoven]. Technische Hogeschool Eindhoven.

Janssen, J. J. A. (1995). *Building with bamboo: A handbook* (2 ed.). Intermediate Technology Publications.

Janssen, J. J. A. (2000). *Designing and Building with Bamboo* (A. Kumar, Ed.). INBAR. https://www.inbar.int/resources/inbar_publications/designing-and-building-with-bamboo/

Janssen, J. J. A. (2005). International Standards for Bamboo as a Structural Material. *Structural Engineering International*, *15*(1), 48-48. https://doi.org/10.2749/101686605777963288

Jessel, E. (2022, August 17). *Norway's collapsed timber bridge had 'vulnerabilities', says Arup expert*. New Civil Engineer. Retrieved 19/08/2023 from https://www.newcivilengineer.com/latest/norways-collapsed-timber-bridge-had-vulnerabilities-says-arup-expert-17-08-2022/

Jessup, H. (1985). Dutch Architectural Visions of the Indonesian Tradition. *Muqarnas*, *3*, 138-161. https://doi.org/10.2307/1523090

Jolly, C. M., Shannon, D. A., Bannister, M., Flauretin, G., Dale, J., Binns, A., & Lindo, P. (2007). Income efficiency of soil conservation techniques in Haiti. In *26th West Indies Agricultural Economics Conference, July 2006, San Juan, Puerto Rico 36970, Caribbean Agro-Economic Society* (pp. 156-163). https://doi.org/10.22004/ag.econ.36970

Jones, D. T., Sah, J. P., Ross, M. S., Oberbauer, S. F., Hwang, B., & Jayachandran, K. (2006). Responses of twelve tree species common in Everglades tree islands to simulated hydrologic regimes. *Wetlands*, *26*, 830-844. https://doi.org/10.1672/0277-5212(2006)26[830:ROTTSC]2.0.CO;2

Jones, J. C. (1992). *Design methods* (2 ed.). Van Nostrand, Reinhold.

Judziewicz, E. J., Stern, M., Londono, X., & Clark, L. G. (1999). *American Bamboos*. Smithsonian.

Kafle, A., Binfield, L., & Paudel, S. K. (2023). The commercialization of timber bamboo in Nepal: A SWOT-AHP analysis. *Advances in Bamboo Science*, *4*. https://doi.org/10.1016/j.bamboo.2023.100036

Kaiser, A., Holden, C., Beavan, J., Beetham, D., Benites, R., Celentano, A., Collett, D., Cousins, J., Cubrinovski, M., Dellow, G., Denys, P., Fielding, E., Fry, B., Gerstenberger, M., Langridge, R., Massey, C., Motagh, M., Pondard, N., McVerry, G., . . . Zhao, J. (2012). The Mw 6.2 Christchurch earthquake of February 2011: preliminary report. *New Zealand Journal of Geology and Geophysics*, *55*(1), 67-90. https://doi.org/10.1080/00288306.2011.641182

Kamath, A. V. (2013). Digitally Designed Architectural Form Built Using Craft-Based Fabrication: Weaving a complex surface as a bamboo reticulated shell. In R. Stouffs, P. Janssen, S. Roudavski, & B. Tunçer (Eds.), *Open Systems: Proceedings of the 18th International Conference on Computer-Aided Architectural Design Research in Asia (CAADRIA 2013), Singapore 15-18 May 2013* (pp. 623–632). Centre for Advanced Studies in Architecture (CASA), Department of Architecture, National University of Singapore. https://doi.org/10.52842/conf.caadria.2013.623

Kaminski, S. (2013). Engineered bamboo houses for low-income communities in Latin America. *Structural Engineer*, *91*(10), 14-23. https://www.istructe.org/journal/volumes/volume-91-(2013)/issue-10/engineered-bamboo-houses-for-low-income-communitie/

Kaminski, S., Harries, K., Lopez, L. F., Trujillo, D., & Archila, H. (2022). Durability of whole culm bamboo: facts, misconceptions and the new ISO 22156 framework. In *18th International Conference on Non-conventional Materials and Technologies (NOCMAT 2022)*. https://doi.org/10.5281/zenodo.6575090

Kaminski, S., Lawrence, A., Coates, K., & Foulkes, L. (2016). A low-cost vernacular improved housing design. *Proceedings of the Institution of Civil Engineers - Civil Engineering*, *169*(5), 25-31. https://doi.org/10.1680/jcien.15.00041

Kaminski, S., Lawrence, A., & Trujillo, D. (2016a). *Engineered Bahareque Technical Report* (Vol. 38). INBAR. https://www.inbar.int/resources/inbar_publications/design-guide-for-engineered-bahareque-housing/

Kaminski, S., Lawrence, A., & Trujillo, D. (2016b). Structural use of bamboo: Part 1: Introduction to bamboo. *The Structural Engineer*, *94*(8), 40-43. https://doi.org/10.56330/PNSC8891

Kaminski, S., Lawrence, A., Trujillo, D., Feltham, I., & López, L. (2016). Structural use of bamboo: Part 3: Design values. *Structural Engineer*, *94*(12), 42-45. https://doi.org/10.56330/JCLL5610

Kaminski, S., Lawrence, A., Trujillo, D., Feltham, I., & López, L. (2017). Structural use of bamboo: Part 4: Element design equations. *Structural Engineer*, *95*(3), 24-27. https://doi.org/10.56330/SXJG3169

Kaminski, S., Lawrence, A., Trujillo, D., & King, C. (2016). Structural use of bamboo: Part 2: Durability and preservation. *The Structural Engineer*, *94*(10), 38-43. https://doi.org/10.56330/TRBW8039

Kaminski, S., & Low, E. J. (2021, March 9). *Bamboo Buildings in Earthquakes*. Better Bamboo Buildings. Retrieved 09/09/21 from https://www.betterbamboobuildings.com/home/3rn12lawxv5ouxu9gzzyy3ftdhv051

Kaplan, R. D. (2008, September). *Lifting the Bamboo Curtain*. The Atlantic. Retrieved 28/04/2021 from https://www.theatlantic.com/magazine/archive/2008/09/lifting-the-bamboo-curtain/306945/

Karamba3D. (2020). *Karamba3D*. In [Parametric engineering and Finite Element Analysis (FEA) software]. Karamba3D. https://www.karamba3d.com/about

Kaspori, D. (2005). Towards an open-source architectural practice. In M. Shamiyeh (Ed.), *What People Want: Populism in Architecture and Design* (pp. 324-333). Birkhäuser. https://doi.org/10.1007/3-7643-7673-2_26

Kewei, L., Jayaramana, D., Yongjiub, S., Harries, K., Jun, Y., Wei, J., Yuechud, S., Junqia, W., Jacomea, P., & Trujillo, D. (2022). "Bamboo: A Very Sustainable Construction Material" - 2021 International Online Seminar summary report. *Sustainable Structures*, *2*(1). https://doi.org/10.54113/j.sust.2022.000015

Keyser, M. W. (2000). Active learning and cooperative learning: understanding the difference and using both styles effectively. *Research Strategies*, *17*(1), 35-44. https://doi.org/10.1016/S0734-3310(00)00022-7

Khan, S. A. (1994). Bangladesh. In P. B. Durst, W. Ulrich, & M. Kashio (Eds.), *Non-wood forest products in Asia* (pp. 1-8). FAO. http://www.fao.org/3/x5334e/x5334e.pdf

Kijewski-Correa, T., Taflanidis, A. A., Mix, D., & Kavanagh, R. (2012). Empowerment Model for Sustainable Residential Reconstruction in Léogâne, Haiti, after the January 2010 Earthquake [Article]. *Leadership & Management in Engineering*, *12*(4), 271-287. https://doi.org/10.1061/(ASCE)LM.1943-5630.0000201

King, N., Horrocks, C., & Brooks, J. (2019). *Interviews in Qualitative Research* (2 ed.). SAGE.

Kitek Kuzman, M., Klarić, S., Pirc Barčić, A., Vlosky, R. P., Janakieska, M. M., & Grošelj, P. (2018). Architect perceptions of engineered wood products: An exploratory study of selected countries in Central and

Southeast Europe. *Construction and Building Materials*, *179*, 360-370. https://doi.org/10.1016/j.conbuildmat.2018.05.164

KKAA. (2022). *Sana Mane Sauna Sazae*. Retrieved 29/07/2023 from https://kkaa.co.jp/en/project/sana-mane-sauna-sazae/

Klein, J. A. (2022, January 19). *The Connection Between Artisan and Tool*. Retrieved 19/08/2023 from https://www.mortiseandtenonmag.com/blogs/blog/the-connection-between-artisan-and-tool

Kleinn, C., & Morales-Hidalgo, D. (2006). An inventory of Guadua (Guadua angustifolia) bamboo in the Coffee Region of Colombia. *European Journal of Forest Research*, *125*(4), 361-368. https://doi.org/10.1007/s10342-006-0129-3

Klemmt, C., Gheorghe, A., Pantic, I., Hornung, P., & Sodhi, R. (2018). Engineering design tropisms: Utilization of a bamboo-resin joint for voxelized network geometries. In *Recalibration. On imprecisionand infidelity. Proceedings of the 38th Annual Conference of the Association for Computer Aided Design in Architecture (ACADIA)* (pp. 322-327). ACADIA. https://doi.org/10.52842/conf.acadia.2018.322

Knuth, D. E. (1974). Computer Science and Its Relation to Mathematics. *The American Mathematical Monthly*, *81*(4), 323-343. https://doi.org/10.2307/2318994

Koca, G. (2019). Evaluation of Wooden Structures. In *Digital Wood Design* (pp. 761-781). https://doi.org/10.1007/978-3-030-03676-8_30

Koehnken, L., & Rintoul, M. (2018). *Impacts of Sand Mining on Ecosystem Structure, Process and Biodiversity in Rivers*. WWF. https://wwfint.awsassets.panda.org/downloads/sand_mining_impacts_on_world_rivers__final_.pdf

Koenigsberger, O. (1971). Section 6: Wood in housing in developing countries. In *World consultation on the use of wood in housing (Unasylva) 05/07/1971 - 16/07/1971* (Vol. 25). FAO. https://www.fao.org/3/c3848e/c3848e00.htm

Koenigsberger, O. H. (1974). *Manual of tropical housing and building*. Longman.

Kolarevic, B. (2003). Digital Morphogenesis. In B. Kolarevic (Ed.), *Architecture in the Digital Age: Design and Manufacturing*. Taylor & Francis.

Kolarevic, B. (2013). Parametric Evolution. In B. Peters & T. Peters (Eds.), *Inside Smartgeometry* (pp. 50-59). Wiley. https://doi.org/10.1002/9781118653074.ch3

Kolarevic, B. (2014). Computing the performative. In R. Oxman & R. Oxman (Eds.), *Theories of the digital in architecture* (pp. 103-111). Routledge.

Kolbe, A. R., Hutson, R. A., Shannon, H., Trzcinski, E., Miles, B., Levitz, N., Puccio, M., James, L., Noel, J. R., & Muggah, R. (2010). Mortality, crime and access to basic needs before and after the Haiti earthquake: a random survey of Port-au-Prince households. *Medicine, Conflict and Survival*, *26*(4), 281-297. https://doi.org/10.1080/13623699.2010.535279

Kondolf, G. M., Schmitt, R. J. P., Carling, P., Darby, S., Arias, M., Bizzi, S., Castelletti, A., Cochrane, T. A., Gibson, S., Kummu, M., Oeurng, C., Rubin, Z., & Wild, T. (2018). Changing sediment budget of the Mekong: Cumulative threats and management strategies for a large river basin. *Sci Total Environ*, *625*, 114-134. https://doi.org/10.1016/j.scitotenv.2017.11.361

Kossoff, D., Dubbin, W. E., Alfredsson, M., Edwards, S. J., Macklin, M. G., & Hudson-Edwards, K. A. (2014). Mine tailings dams: Characteristics, failure, environmental impacts, and remediation. *Applied Geochemistry*, *51*, 229-245. https://doi.org/10.1016/j.apgeochem.2014.09.010

Kotnik, T., & Weinstock, M. (2012). Material, Form and Force. *Architectural Design*, *82*(2), 104-111. https://doi.org/10.1002/ad.1386

Koyré, A. (1948). Du monde de l'à peu près à l'univers de la précision. In *Etudes d'histoire de la pensée philosophique* (pp. 341-362). Gallimard.

Krahnstöver & Wolf GmbH. (2016). *Parkhausfassade, Zoo Leipzig, Bauen mit Bambus*. Krahnstöver & Wolf GmbH,. Retrieved 29/03/2024 from https://www.krahnstoever-wolf.de/referenzen/bauen-mit-bambus/parkhausfassade-zoo-leipzig/

Krausmann, F., Gingrich, S., Eisenmenger, N., Erb, K.-H., Haberl, H., & Fischer-Kowalski, M. (2009). Growth in global materials use, GDP and population during the 20th century. *Ecological Economics*, *68*(10), 2696-2705. https://doi.org/10.1016/j.ecolecon.2009.05.007

Kumar, S., Shukla, K., Dev, T., & Dobriyal, P. (1994). *Bamboo preservation techniques: A review*. INBAR and ICFRE.

Kwinter, S. (1996). Flying the bullet, or when did the future begin? In S. Kwinter & R. Koolhaas (Eds.), *Rem Koolhaas: Conversations with students* (pp. 67-94). Rice University, School of Architecture.

Kwinter, S. (2003). The Computational Fallacy. *Thresholds*(26), 90-92. https://doi.org/10.1162/thld_a_00366

Ladybug Tools LLC. (2020). *Ladybug*. In [Parametric environmental analysis tools]. https://www.ladybug.tools/ladybug.html

Laiserin, J. (2008). Digital Environments for Early Design: Form-Making versus Form-Finding. In *First International Conference on Critical Digital: What Matters(s)? - 18-19 April 2008* (pp. 235-242). http://papers.cumincad.org/cgi-bin/works/paper/cdc2008_235

Laleicke, P. F., Cimino-Hurt, A., Gardner, D., & Sinha, A. (2015). Comparative carbon footprint analysis of bamboo and steel scaffolding. *Journal of Green Building*, *10*(1), 114-126. https://doi.org/10.3992/jgb.10.1.114

Larsen, O. P. (2022). Learning from Physical Models: Design Through Experimentation. In *Conceptual Structural Design: Bridging the gap between architects and engineers* (3 ed., pp. 73-90). https://doi.org/10.1680/csd.65987.073

Lawrence, A. (2021, September 9). *Where can timber truly excel in a building's design? (Interview with the RIBA)*. RIBA. Retrieved 19/08/2023 from https://www.architecture.com/knowledge-and-resources/knowledge-landing-page/where-can-timber-truly-excel-in-a-buildings-design

Lawson, B. (1994). *Design in Mind*. Butterworth Architecture.

Laxamana, M. (1985). Drying of some commercial Philippine bamboos. *FPRDI Journal (Philippines)*.

Le Corbusier. (1925/1987). *The Decorative Art of Today (J. Dunnett, Trans.)*. Architectural Press (Original work published 1925).

Le Corbusier. (1927/1946). *Towards a New Architecture (F. Etchells Trans.)*. Architectural Press (Original work published 1927).

Le Moniteur. (1974). The National College of Haitian Engineers and Architects, Decree-Law. *Le Moniteur*, *129*(30), 197-199. http://cniah.org/historique-du-cniah.html

Leal Filho, W., Hunt, J., Lingos, A., Platje, J., Vieira, L. W., Will, M., & Gavriletea, M. D. (2021). The Unsustainable Use of Sand: Reporting on a Global Problem. *Sustainability*, *13*(6), 3356. https://doi.org/10.3390/su13063356

Leavenworth, S. (2020, November 5). *China May Shelve Plans to Build Dams on Its Last Wild River*. National Geographic. Retrieved 15/01/22 from https://www.nationalgeographic.com/science/article/160512-china-nu-river-dams-environment

Lee, J. H., & Ostwald, M. J. (2022). The relationship between divergent thinking and ideation in the conceptual design process. *Design Studies*, *79*. https://doi.org/10.1016/j.destud.2022.101089

Lehne, J., & Preston, F. (2018). *Making Concrete Change: Innovation in Low-carbon Cement and Concrete* (Chatham House Report, Issue. https://www.chathamhouse.org/sites/default/files/publications/2018-06-13-making-concrete-change-cement-lehne-preston-final.pdf

Lewis, L. A., & Coffey, W. J. (1985). The Continuing Deforestation of Haiti. *Ambio*, *14*(3), 158-160. https://www.jstor.org/stable/4313133

Leyton, M. (2003). *A Generative Theory of Shape*. Springer.

Liang, Z., Neményi, A., Kovács, G. P., & Gyuricza, C. (2023). Potential use of bamboo resources in energy value-added conversion technology and energy systems. *GCB Bioenergy*, *15*(8), 936-953. https://doi.org/10.1111/gcbb.13072

Liese, W. (1987). Research on bamboo. *Wood Science and Technology*, *21*, 189-209. https://doi.org/10.1007/BF00351391

Liese, W. (1998). *The Anatomy of Bamboo Culms [Technical Report 18]*. INBAR. https://www.inbar.int/resources/inbar_publications/the-anatomy-of-bamboo-culms/

Liese, W. (2009). Bamboo as carbon sink-fact or fiction? *Journal of Bamboo and Rattan*, *8*(3/4), 103-114.

Liese, W. (2019). A glimpse on 65 years of passion-driven work for bamboo. *By-Products of Palm Trees and Their Applications*, *11*, 62-68. https://doi.org/10.21741/9781644900178-2

Liese, W. (2020). Booming bamboo. *Bamboo and Rattan Update*, *1*(1), 4-5. https://www.inbar.int/resources/inbar_publications/bamboo-and-rattan-update-volume-1-issue-1/

Liese, W., Kumar, S., Society, A. B., Resource, C. f. I. B., Technology, Bamboo, I. N. f., & Rattan. (2003). *Bamboo Preservation Compendium*. Centre for Indian Bamboo Resource and Technology.

Liese, W., & Tang, T. K. H. (2015a). Preservation and Drying of Bamboo. In W. Liese & M. Köhl (Eds.), *Bamboo: The Multipurpose Plant* (pp. 257-297). Springer, Cham. https://doi.org/10.1007/978-3-319-14133-6_9

Liese, W., & Tang, T. K. H. (2015b). Properties of the Bamboo Culm. In W. Liese & M. Köhl (Eds.), *Bamboo: The Plant and its Uses* (pp. 227-256). Springer, Cham. https://doi.org/10.1007/978-3-319-14133-6_8

Liese, W., Welling, J., & Tang, T. K. H. (2015). Utilization of Bamboo. In W. Liese & M. Köhl (Eds.), *Bamboo: The Plant and its Uses* (pp. 299-346). https://doi.org/10.1007/978-3-319-14133-6_10

Lin, C.-Y. (2001). A digital procedure of building construction: A practical project. In J. S. Gero, S. Chase, & M. Rosenman (Eds.), *CAADRIA 2001* (pp. 459-468). Key Centre of Design Computing and Cognition, Faculty of Architecture, University of Sydney. https://doi.org/10.52842/conf.caadria.2001.459

Liu, C., Kuchma, O., & Krutovsky, K. V. (2018). Mixed-species versus monocultures in plantation forestry: Development, benefits, ecosystem services and perspectives for the future. *Global Ecology and Conservation*, *15*. https://doi.org/10.1016/j.gecco.2018.e00419

Liu, K., Demartino, C., Li, Z., Liu, Q., & Xiao, Y. (2022). The 2019 International Bamboo Construction Competition. In *2019 International Bamboo Construction Competition* (pp. 1-13). https://doi.org/10.1007/978-3-030-91990-0_1

Liu, K., Wu, J. Q., & King, C. (2021). Editorial. *Bamboo and Rattan Update*, *2*(1), 2. https://www.inbar.int/resources/inbar_publications/vernacular-bamboo-architecture-tradition-or-future-bamboo-and-rattan-update-volume-2-issue-1/

Liu, W., Hui, C., Wang, F., Wang, M., & Liu, G. (2018). Review of the Resources and Utilization of Bamboo in China. In A. Khalil (Ed.), *Bamboo*. IntechOpen. https://doi.org/10.5772/intechopen.76485

Liu, Z., Jiang, Z., Cai, Z., Fei, B., Yu, Y., & Liu, X. e. (2012). Dynamic Mechanical Thermal Analysis of Moso Bamboo (Phyllostachys Heterocycla) at different moisture content. *BioRes*, *7*(2), 1548-1557. https://doi.org/10.15376/biores.7.2.1548-1557

Lloyd Thomas, K. (2007). Introduction: Architecture and material practice. In K. Lloyd Thomas (Ed.), *Material matters: Architecture and material practice* (pp. 1-12). Routledge.

Lobovikov, M., Paudel, S., Piazza, M., Ren, H., & Wu, J. (2007). *World bamboo resources - A thematic study prepared in the framework of the Global Forest Resources Assessment 2005* (Vol. 18). FAO. https://www.fao.org/4/a1243e/a1243e00.htm

Lobovikov, M., Schoene, D., & Yping, L. (2011). Bamboo in climate change and rural livelihoods. *Mitigation and Adaptation Strategies for Global Change*, *17*(3), 261-276. https://doi.org/10.1007/s11027-011-9324-8

Łochnicki, G., Kalousdian, N. K., Leder, S., Maierhofer, M., Wood, D., & Menges, A. (2021). Co-Designing Material-Robot Construction Behaviors. In B. Bogosian, K. Dörfler, B. Farahi, J. G. del Castillo y López, J. Grant, V. Noel, S. Parascho, & J. Scott (Eds.), *ACADIA 2021: Realignments: Toward Critical Computation Proceedings of the 41st Annual Conference of the Association of Computer Aided Design in Architecture (ACADIA)* (pp. 470-479). ACADIA. https://papers.cumincad.org/cgi-bin/works/paper/acadia21_470

Loo, Y. M. (2017). Towards a decolonisation of architecture. *The Journal of Architecture*, *22*(4), 631-638. https://doi.org/10.1080/13602365.2017.1338412

Lopez, M., Bommer, J., & Mendez, P. (2004). The Seismic Performance of Bahareque Dwellings in El Salvador. In *13th World Conference on Earthquake Engineering Vancouver, B.C., Canada August 1-6, 2004 [Paper No. 2646]*. https://www.iitk.ac.in/nicee/wcee/article/13_2646.pdf

Lorenzo, R., Godina, M., & Mimendi, L. (2020). Determination of the physical and mechanical properties of moso, guadua and oldhamii bamboo assisted by robotic fabrication. *Journal of Wood Science*, *66*. https://doi.org/10.1186/s10086-020-01869-0

Lorenzo, R., Lee, C., Oliva-Salinas, J. G., & Ontiveros-Hernandez, M. J. (2017). BIM Bamboo: a digital design framework for bamboo culms. *Proceedings of the Institution of Civil Engineers - Structures and Buildings*, *170*(4), 295-302. https://doi.org/10.1680/jstbu.16.00091

Lorenzo, R., & Mimendi, L. (2019). Digital workflow for the accurate computation of the geometric properties of bamboo culms for structural applications. In H. Li, M. Ashraf, O. Corbi, P. Yang, L. Wang, & I. Corbi (Eds.), *Proceedings of the 1st International Conference on Advances in Civil Engineering and Materials (ACEM1) and 1st World Symposium on Sustainable Bio-composite Materials and Structures (SBMS1) (ACEM2018 and SBMS1)* (Vol. 275, pp. 1-11). EDP Sciences. https://doi.org/10.1051/matecconf/201927501024

Lorenzo, R., & Mimendi, L. (2020). Digitisation of bamboo culms for structural applications. *Journal of Building Engineering*, *29*, 101193. https://doi.org/10.1016/j.jobe.2020.101193

Lorenzo, R., Mimendi, L., Godina, M., & Li, H. (2020). Digital analysis of the geometric variability of Guadua, Moso and Oldhamii bamboo. *Construction and Building Materials*, *236*. https://doi.org/10.1016/j.conbuildmat.2019.117535

Lorenzo, R., Mimendi, L., Yang, D., Li, H., Mouka, T., & Dimitrakopoulos, E. G. (2021). Non-linear behaviour and failure mechanism of bamboo poles in bending. *Construction and Building Materials*, *305*, 124747. https://doi.org/10.1016/j.conbuildmat.2021.124747

Lou, Y., Buckingham, K., Henley, G., Li, Y., & Zhou, G. (2010). *Bamboo and Climate Change Mitigation*. INBAR. https://www.inbar.int/resources/inbar_publications/bamboo-and-climate-change-mitigation/

Louridas, P. (2020). *What is an algorithm?* MIT Press.

Louton, J., Gelhaus, J., & Bouchard, R. (1996). The Aquatic Macrofauna of Water-Filled Bamboo (Poaceae: Bambusoideae: Guadua) Internodes in a Peruvian Lowland Tropical Forest. *Biotropica*, *28*(2), 228-242. https://doi.org/10.2307/2389077

Lu, X.-x., Wang, K., Yi, X., Liou, J., & He, J. (1985). A study on the physic-mechanical properties of culmwood of Phyllostachys Glauca of Shandong. *Journal of Bamboo Research [Zhuzi yanjiu huikan]*, *4*(2), 98-106.

Lucas, R. (2016). *Research methods for architecture*. Laurence King Publishing.

Lugt, P., & Vogtlander, J. (2015). *The Environmental Impact of Industrial Bamboo Products: Life-Cycle Assessment and Carbon Sequestration* (2 ed., Vol. 35). INBAR. https://www.inbar.int/resources/inbar_publications/the-environmental-impact-of-industrial-bamboo-products/

Lugt, P. v. d., Vogtländer, J. G., Vegte, J. H. v. d., & Brezet, J. C. (2015). Environmental Assessment of Industrial Bamboo Products - Life Cycle Assessment and Carbon Sequestration. In *10th World Bamboo Congress*. https://repository.tudelft.nl/islandora/object/uuid%3A4764e44d-1e5e-42bc-8680-4beb83a948ac

Lycken, A., Ziethen, R., Olofsson, D., Fredriksson, M., Brüchert, F., Weidenhiller, A., & Broman, O. (2020). *State of the art summary on industrial strength grading, including standards* (Vol. 2020:92) http://urn.kb.se/resolve?urn=urn:nbn:se:ri:diva-51009

Lynch, K. (1960). *The image of the city*. MIT Press.

Ma, C., Yu, C., Yan, Y. J., & Crolla, K. (2021). Expanding Bending-Active Bamboo Gridshell Structures' Design Solution Space Through Hybrid Assembly Systems. In J. v. A. A. Globa, A. Fingrut, N. Kim, T.T.S. Lo (Ed.), *PROJECTIONS - Proceedings of the 26th CAADRIA Conference - Volume 1, The Chinese University of Hong Kong and Online, Hong Kong, 29 March - 1 April 2021* (pp. 331-340). CAADRIA https://doi.org/10.52842/conf.caadria.2021.1.331

MacDonald, K., Schumann, K., & Hauptman, J. (2019). Digital Fabrication of Standardless Materials. In *ACADIA 19 UBIQUITY AND AUTONOMY: Proceedings of the 39th Annual Conference of the Association for Computer Aided Design in Architecture (ACADIA) The University of Texas at Austin School of Architecture, Austin, Texas 21-26 October, 2019* (pp. 266-275). ACADIA. https://doi.org/10.52842/conf.acadia.2019.266

Maclaine Pont, H. (1922, April 15). *Bijdrage tot de oplossing van de technische moeilijkheden van het volkshuisvestingsvraagstuk, speciaal voor den inlandschen bouw* Volkshuisvestingscongres, Semarang, Indonesia. http://colonialarchitecture.eu/

Madden, J., Gutierrez Gonzalez, M., & Maluk, C. (2018). Structural performance of laminated bamboo columns during fire. In *Australian Structural Engineering Conference: ASEC 2018* (pp. 210-219). Engineers Australia.

Mahdavi, M., Clouston, P. L., & Arwade, S. R. (2011). Development of Laminated Bamboo Lumber: Review of Processing, Performance, and Economical Considerations. *Journal of Materials in Civil Engineering*, *23*(7), 1036-1042. https://doi.org/10.1061/(ASCE)MT.1943-5533.0000253

Manandhar, R., Kim, J.-H., & Kim, J.-T. (2019). Environmental, social and economic sustainability of bamboo and bamboo-based construction materials in buildings. *Journal of Asian Architecture and Building Engineering*, *18*(2), 49-59. https://doi.org/10.1080/13467581.2019.1595629

Manful, K., Batsani-Ncube, I., & Gallagher, J. (2022). Invented Modernisms: Getting to Grips with Modernity in Three African State Buildings. *Curator (N Y)*, *65*(3), 569-589. https://doi.org/10.1111/cura.12505

Mania, P., Majka, J., & Zborowska, M. (2019). The effect of thermo-mechanical treatment of moso bamboo (Phyllostachys Pubescens) on its sorption and physicomechanical properties. *Drvna industrija*, *70*(3), 265-272. https://doi.org/10.5552/drvind.2019.1847

Mardjono, F. (2002). *A bamboo building design decision support tool* [Phd Thesis 1 (Research TU/e / Graduation TU/e), Technische Universiteit Eindhoven]. Eindhoven. https://doi.org/10.6100/IR561720

Martín Domínguez, D. G., & de Esteban Garbayo, D. J. (2018). Interacciones en la periferia de Tokio: La Casa Moriyama de Ryue Nishizawa. *Revista de Arquitectura*, *23*(34), 45-53. https://doi.org/10.5354/0719-5427.2018.47906

Martinez-Meza, E., & Whitford, W. G. (1996). Stemflow, throughfall and channelization of stemflow by roots in three Chihuahuan desert shrubs. *Journal of Arid Environments*, *32*(3), 271-287. https://doi.org/10.1006/jare.1996.0023

Matson, C. W., & Sweet, K. (2016). Simplified for Resilience: A parametric investigation into a bespoke joint system for bamboo. In R. A. M. Iglesias, A. E. Granero, D. C. Pimentel, P. L. Muñoz, D. R. Barros, T. J. Rojas, C. Voto, & M. A. Velazquez (Eds.), *SIGraDi 2016, XX Congreso de la Sociedad Ibero-americana de Gráfica Digital 9-11, November, 2016 - Buenos Aires, Argentina* (pp. 405-411). SIGraDi. https://doi.org/10.5151/despro-sigradi2016-801

Maurina, A., & Prastyatama, B. (2017). Bamboo Architectonic: Experimental Studies using Bundled-Bamboo-Split (BBS). *International Journal on Advanced Science Engineering Information Technology*, *7*(3), 850-857. https://doi.org/10.18517/ijaseit.7.3.2131

Maver, T. (1971). PACE 1: Computer aided building appraisal. *Architects Journal*, *154*(30), 207-214.

Maver, T. (1988). Software Tools for the Technical Evaluation of Design Alternatives. In *CAAD futures '87, Eindhoven, The Netherlands, 20-22 May 1987* (pp. 47-58).

May, J. (2010). *Buildings without architects: A global guide to everyday architecture*. Rizzoli.

Mayer, H. P., & Conrad, R. (1990). Factors influencing the population of methanogenic bacteria and the initiation of methane production upon flooding of paddy soil. *FEMS Microbiology Letters*, *6*(2), 103-111. https://doi.org/10.1111/j.1574-6968.1990.tb03930.x

MCBI. (2007). JG/T 199: Testing Methods for Physical and Mechanical Properties of Bamboo Used in Building. In. Beijing, China: MCBI (Ministry of Construction and Building Industry).

Megraw, S. R., & Knowles, R. (1987). Methane production and consumption in a cultivated humisol. *Biology and Fertility of Soils*, *5*, 56-60. https://doi.org/10.1007/BF00264347

Mena, J., Vera, S., Correal, J. F., & Lopez, M. (2012). Assessment of fire reaction and fire resistance of Guadua angustifolia kunth bamboo. *Construction and Building Materials*, *27*(1), 60-65. https://doi.org/10.1016/j.conbuildmat.2011.08.028

Mendell, M., J., Mirer, A., G., Cheung, K., Tong, M., & Douwes, J. (2011). Respiratory and Allergic Health Effects of Dampness, Mold, and Dampness-Related Agents: A Review of the Epidemiologic Evidence. *Environmental Health Perspectives*, *119*(6), 748-756. https://doi.org/10.1289/ehp.1002410

Menges, A. (2010a). Material systems, computational morphogenesis and performative capacity. In M. Hensel, A. Menges, & M. Weinstock (Eds.), *Emergent Technologies and Design: Towards a Biological Paradigm for Architecture*. Routledge. https://doi.org/10.4324/9781315881294

Menges, A. (2010b). Unkomplizierte Komplexität. In M. Bechthold, J. Bettum, T. Bonwetsch, D. Bosia, B. Cache, M. Carpo, D. Gethmann, F. Gramazio, M. Kohler, H. Hamm, U. Hirschberg, H. Kloft, J. Kokol, A. Lechner, T. Lensing, M. Lins, K. K. Loenhart, J. H. Mayer, A. Menges, F. Scheurer, C. Schindler, J.-

C. Stockebrand, & G. Vrachliotis (Eds.), *GAM Architecture Magazine 06* (pp. 140-151). Springer Vienna. https://doi.org/10.1007/978-3-211-99210-4_11

Menges, A. (2015). The New Cyber-Physical Making in Architecture: Computational Construction. *Architectural Design*, *85*(5), 28-33. https://doi.org/10.1002/ad.1950

Menges, A., & Knippers, J. (2021). *Architecture Research Building*. Birkhäuser. https://doi.org/10.1515/9783035620405

Mera, F., & Xu, C. (2014). Plantation management and bamboo resource economics in China. *Ciencia y Tecnología*, *7*, 1. https://doi.org/10.18779/cyt.v7i1.137

Merkel, J., & Whitaker, C. (2010). Rebuilding from Below the Bottom: Haiti. *Architectural Design*, *80*(5), 128-134. https://doi.org/10.1002/ad.1147

Michiels, T., Lu, L., Archer, R., Adriaenssens, S., & Tresserra, G. (2017). Design of Three Hypar Roofs Made of Guadua Bamboo. *Journal of the International Association for Shell and Spatial Structures*, *58*, 95-104. https://doi.org/10.20898/j.iass.2017.191.844

Midjourney. (2023). *Midjourney*. In [Generative artificial intelligence program]. https://www.midjourney.com/

Mignolo, W. D. (2012). *Local Histories/Global Designs*. Princeton University Press. https://doi.org/10.1515/9781400845064

Miller, S. A., Horvath, A., & Monteiro, P. J. M. (2016). Readily implementable techniques can cut annual CO2 emissions from the production of concrete by over 20%. *Environmental Research Letters*, *11*(7). https://doi.org/10.1088/1748-9326/11/7/074029

Miller, S. A., Horvath, A., & Monteiro, P. J. M. (2018). Impacts of booming concrete production on water resources worldwide. *Nature Sustainability*, *1*(1), 69-76. https://doi.org/10.1038/s41893-017-0009-5

Mimendi, L., Lorenzo, R., & Li, H. (2022). An innovative digital workflow to design, build and manage bamboo structures. *Sustainable Structures*, *2*(1). https://doi.org/10.54113/j.sust.2022.000011

Minke, G. (2012). *Building with bamboo*. Birkhäuser.

Minke, G. (2023). *Building with Bamboo* (3 ed.). Birkhäuser. https://doi.org/10.1515/9783035625738

Miro. (2022). *Miro*. In [Digital (visual) collaboration platform]. www.miro.com

Mitchell, M., & Bevan, A. (1992). *Culture, cash and housing: Community and tradition in low-income building*. VSO/IT.

Moloney, J., & Issa, R. (2003). Materials in Architectural Design Education Software: A Case Study. *International Journal of Architectural Computing*, *1*(1), 46-58. https://doi.org/10.1260/147807703322467423

Mondal, B., Maity, D., & Patra, P. K. (2020). Tensile characterisation of bamboo strips for potential use in reinforced concrete members: experimental and numerical study. *Materials and Structures*, *53*(5), 128. https://doi.org/10.1617/s11527-020-01563-z

Monteiro, P. J. M., Miller, S. A., & Horvath, A. (2017). Towards sustainable concrete. *Nat Mater*, *16*(7), 698-699. https://doi.org/10.1038/nmat4930

Mortice, Z. (2023, June 20). *Vision Setting and Problem Solving: AI in Architecture Is Changing Design*. Autodesk. Retrieved 29/07/2023 from https://redshift.autodesk.com/articles/ai-in-architecture

Morton, P. A. (2000). *Hybrid Modernities: Architecture and Representation at the 1931 Colonial Exposition, Paris*. MIT Press.

Mottram, T. (2017). Fibre Reinforced Polymer Structures: Design Guidance or Guidance for Designers. Advanced Composites in Construction 2017, Sheffield, UK.

Mukhopadhyay, P. (2008). Role of bamboo in seismic architecture. *Indian Architect and Builder*, *22*, 102-106.

Muladi, S. (1996). Quantification and use of Dipterocarp wood residue in East Kalimantan. In A. Schulte & D. Schöne (Eds.), *Dipterocarp Forest Ecosystems: Towards Sustainable Management* (pp. 603-615). German Agency for Technical Cooperation. https://doi.org/10.1142/9789814261043_0026

Müller, D. B., Liu, G., Løvik, A. N., Modaresi, R., Pauliuk, S., Steinhoff, F. S., & Brattebø, H. (2013). Carbon Emissions of Infrastructure Development. *Environmental Science & Technology*, *47*(20), 11739-11746. https://doi.org/10.1021/es402618m

Muthmainnah, K., & Kurniawan, K. R. (2018). Traditionality and Modernity: Post-Colonial Architecture in Indonesia. *E3S Web Conf.*, *65*, 01003. https://doi.org/10.1051/e3sconf/20186501003

Naboni, E., & Havinga, L. (2019). *Regenerative Design In Digital Practice. A Handbook for the Built Environment*. Eurac Research.

Nature. (2018). A once-lush country on the verge of total deforestation. *Nature*, *563*, 159. https://doi.org/10.1038/d41586-018-07230-2

Nature. (2021). Control methane to slow global warming -- fast. *Nature*, *596*, 461. https://doi.org/10.1038/d41586-021-02287-y

Naylor, J. O. (2021). Protection by Generative Design - Designing for full-culm bamboo durability using sunlight-hours modelling in Ladybug. In V. Stojaković & B. Tepavčević (Eds.), *Towards a New, Configurable Architecture - Proceedings of the 39th International Hybrid Conference on Education and Research in Computer Aided Architectural Design in Europe - Volume 1, University of Novi Sad, Novi Sad, Serbia, 8-10 September 2021* (Vol. 1, pp. 315-324). eCAADe (Education and Research in Computer Aided Architectural Design in Europe). https://doi.org/10.52842/conf.ecaade.2021.1.315

Naylor, J. O., Leconte, N., & Vendryes, F. R. M. (2020). Education to practice to ecology: A review and preliminary evaluation of a new architectural design curriculum using computational design tools and bamboo in Haiti. In N. B. Escobar & D. A. Torreblanca-Díaz (Eds.), *SIGraDi 2020 Proceedings of the 24th Conference of the Iberoamerican Society of Digital Graphics, Online Conference 18 - 20 November 2020* (Vol. 8, pp. 643-651). Blucher Design Proceedings. https://doi.org/10.5151/sigradi2020-89

Naylor, J. O., Stamm, J., & Vahanvati, M. (2022). Applying design tools for full-culm bamboo. In *18th International Conference on Non-conventional Materials and Technologies (NOCMAT 2022)*. https://doi.org/10.5281/zenodo.6570449

NBBJ Digital Practice. (2017). *Bifocals*. In [Software plug-in for Grasshopper]. https://www.food4rhino.com/en/app/bifocals

NBS. (2021). *BIM adoption over time*. NBS. Retrieved 19/04/23 from http://www.thenbs.com/digital-construction-report-2021/section-1-BIM/

Neves, A. C. d. O., Nunes, F. P., de Carvalho, F. A., & Fernandes, G. W. (2016). Neglect of ecosystems services by mining, and the worst environmental disaster in Brazil. *Natureza & Conservação*, *14*(1), 24-27. https://doi.org/10.1016/j.ncon.2016.03.002

Newsweek. (2010, July 1). *Stronger Than Steel*. Newsweek. Retrieved 20/06/20 from https://www.newsweek.com/stronger-steel-85533

Ngab, A. S. (2001). Structural Engineering and Concrete Technology in Developing Countries: An Overview. In A. Zingoni (Ed.), *Structural Engineering, Mechanics and Computation* (Vol. 2, pp. 1339-1348). Elsevier Science. https://doi.org/10.1016/B978-008043948-8/50149-1

Nicholas, C., & Oak, A. (2020). Make and break details: The architecture of design-build education. *Design Studies*, *66*, 35-53. https://doi.org/10.1016/j.destud.2019.12.003

NIOSH. (2022, July 27). *Indoor Environmental Quality*. CDC. Retrieved 26/08/2023 from https://www.cdc.gov/niosh/topics/indoorenv/mold.html

NMX-R-079-SCFI. (2015). NMX-R-079-SCFI-2015: Escuelas – Seguridad estructural de la infraestructura física educativa-requisitos [Schools - Structural security of the educational physical infrastructure - requeriments]. In: Dirección General de Normas,.

Norman, F. (2005). Digital to Analog: Exploring Digital Processes of Making. *International Journal of Architectural Computing*, *3*(2), 191-202. https://doi.org/10.1260/1478077054214398

NSR-10. (2010). NSR-10: Título G — Estructuras de Madera y Estructuras de Guadua. In M. d. A. V. y. D. Territorial (Ed.): Ministerio de Ambiente Vivienda y Desarrollo Territorial.

NSR. (1998). NSR-98 Normas Colombianas de Diseño y Construcción Sismo Resistente. In A. C. d. I. Sísmica (Ed.), (pp. 399): Asociación Colombiana de Ingeniería Sísmica.

NTNU, & Nikken Sekkei. (2019). *Reindeer*. In [Plug-in software for timber structural design and fabraction modelling]. NTNU. https://github.com/CSDG-DDL/PTK

O´Brien, M. J. (2010). Hybrids on the way to the Western Platform Frame. In *Preservation Education and Research* (Vol. 3, pp. 37–52). NCPE.

OECD. (2019). *Global Material Resources Outlook to 2060*. OECD. https://doi.org/10.1787/9789264307452-en

OED. (2023a). bamboo, n., sense a. In https://doi.org/10.1093/OED/6763323721

OED. (2023b). greenwash, v. In https://doi.org/10.1093/OED/4891715166

OHCHR. (2014). *The Right to Adequate Housing* [Fact Sheet](21/Rev.1). OHCHR. https://www.ohchr.org/sites/default/files/Documents/Publications/FS21_rev_1_Housing_en.pdf

OHCHR. (2019, June 25). *UN expert condemns failure to address impact of climate change on poverty*. Retrieved 22/10/2021 from https://www.ohchr.org/EN/NewsEvents/Pages/DisplayNews.aspx?NewsID=24735&LangID=E

Ohrnberger, D. (1999a). SUBTRIBE BAMBUSINAE. In D. Ohrnberger (Ed.), *The Bamboos of the World* (pp. 249-317). Elsevier. https://doi.org/10.1016/B978-044450020-5/50007-1

Ohrnberger, D. (1999b). SUBTRIBE GUADUINAE. In D. Ohrnberger (Ed.), *The Bamboos of the World* (pp. 349-360). Elsevier. https://doi.org/10.1016/B978-044450020-5/50010-1

Oliver, P. (2006). *Built to meet needs: Cultural issues in vernacular architecture*. Architectural Press, Elsevier.

Olivier, J. G. J., Janssens-Maenhout, G., Muntean, M., & Peters, J. A. H. W. (2016). *Trends in global CO2 emissions: 2016 Report*. PBL Netherlands Environmental Assessment Agency. https://www.pbl.nl/en/publications/trends-in-global-co2-emissions-2016-report

OMA. (1991). *Yokohama Masterplan*. OMA. Retrieved 29/07/2023 from https://www.oma.com/projects/yokohama-masterplan

Ongugo, P. O., Sigu, G. O., Kariuki, J. G., Luvanda, A. M., & Kigomo, B. N. (2000). *Production-to-Consumption Systems: A Case Study of the Bamboo Sector in Kenya*. INBAR. https://www.inbar.int/resources/inbar_publications/production-to-consumption-systems-a-case-study-of-the-bamboo-sector-in-kenya/

Open CFD. (2022). *OpenFOAM*. In (Version 2112) [CFD software]. OpenCFD. https://www.openfoam.com/

OpenStructures. (2019). *OpenStructures*. OpenStructures. Retrieved 23/09/2021 from https://openstructures.net/

Opoku, D., Ayarkwa, J., & Agyekum, K. (2016). Factors Inhibiting the Use of Bamboo in Building Construction in Ghana: Perceptions of Construction Professionals. *Materials Sciences and Applications*, *7*(2), 83-88. https://doi.org/10.4236/msa.2016.72008

Oxman, R. (2017). Thinking difference: Theories and models of parametric design thinking. *Design Studies*, *52*, 4-39. https://doi.org/10.1016/j.destud.2017.06.001

Oxman, R., & Oxman, R. (2014a). Introduction: Vitruvius digitalis. In R. Oxman & R. Oxman (Eds.), *Theories of the digital in architecture* (pp. 1-9). Routledge.

Oxman, R., & Oxman, R. (2014b). Parametrics. In R. Oxman & R. Oxman (Eds.), *Theories of the digital in architecture* (pp. 137-141). Routledge.

Oxman, R., & Oxman, R. (2014c). Performance/Generation. In R. Oxman & R. Oxman (Eds.), *Theories of the digital in architecture* (pp. 97-102). Routledge.

Oxman, R., & Oxman, R. (2014d). *Theories of the Digital in Architecture*. Routledge.

Padmalal, D., & Maya, K. (2014). Impacts of River Sand Mining. In *Sand Mining* (pp. 31-56). https://doi.org/10.1007/978-94-017-9144-1_4

Pancel, L. (2015). Species Files in Tropical Forestry. In *Tropical Forestry Handbook* (pp. 1-157). https://doi.org/10.1007/978-3-642-41554-8_112-3

Papadopoulos, A. N., & Hill, C. A. S. (2003). The sorption of water vapour by anhydride modified softwood. *Wood Science and Technology*, *37*(3-4), 221-231. https://doi.org/10.1007/s00226-003-0192-6

Paraskeva, T., Pradhan, N. P. N., Stoura, C. D., & Dimitrakopoulos, E. G. (2019). Monotonic loading testing and characterization of new multi-full-culm bamboo to steel connections. *Construction and Building Materials*, *201*, 473-483. https://doi.org/10.1016/j.conbuildmat.2018.12.198

Park, E., Ho, H. L., Tran, D. D., Yang, X., Alcantara, E., Merino, E., & Son, V. H. (2020). Dramatic decrease of flood frequency in the Mekong Delta due to river-bed mining and dyke construction. *Sci Total Environ*, *723*, 138066. https://doi.org/10.1016/j.scitotenv.2020.138066

Parsons, J. J. (1991). Giant American Bamboo in the Vernacular Architecture of Colombia and Ecuador. *Geographical Review*, *81*(2), 131-152. https://doi.org/10.2307/215979

Parvin, A. (2013). Architecture (and the other 99%): Open-Source Architecture and Design Commons. *Architectural Design*, *83*(6), 90-95. https://doi.org/10.1002/ad.1680

Patil, S., & Mutkekar, S. (2014). Bamboo as a Cost Effective Building Material for Rural Construction. *Journal of Civil Engineering and Environmental Technology*, *1*(6), 35-40.

Pauleus, O., & Aide, T. M. (2020). Haiti has more forest than previously reported: land change 2000–2015. *PeerJ*, *8*, e9919. https://doi.org/10.7717/peerj.9919

Pawlyn, M. (2016). *Biomimicry in Architecture* (2 ed.). RIBA Publishing.

Pedrono, M., Smith, L. L., Sarovy, A., Bourou, R., & Tiandray, H. (2001). Reproductive Ecology of the Ploughshare Tortoise (Geochelone yniphora). *Journal of Herpetology*, *35*(1), 151-156. https://doi.org/10.2307/1566041

Pellek, R. R. (1988). Misperceptions of Deforestation in Haiti: Problems of Available Data and Methodology. *Ambio*, *17*(3), 245-246. https://www.jstor.org/stable/4313463

Peng, L., Searchinger, T. D., Zionts, J., & Waite, R. (2023). The carbon costs of global wood harvests. *Nature*, *620*, 110–115. https://doi.org/10.1038/s41586-023-06187-1

Pereira, K. (2020). *Sand Stories: Surprising Truths about the Global Sand Crisis and the Quest for Sustainable Solutions*. Rhetority Media.

Peters, T. F., & Building Arts Forum/New York. (1991). Architectural and Engineering Design: Two Forms of Technological Thought on the Borderline between Empiricism and Science. In *Bridging the gap: Rethinking the relationship of architect and engineer - The proceedings of the Building Arts Forum/New York Symposium, held in April of 1989 at the Guggenheim Museum* (pp. 23-36). Van Nostrand Reinhold. https://www.tib.eu/de/suchen/id/BLCP%3ACN003751521

Pickering, K. L., Efendy, M. G. A., & Le, T. M. (2016). A review of recent developments in natural fibre composites and their mechanical performance. *Composites Part A: Applied Science and Manufacturing*, *83*, 98-112. https://doi.org/10.1016/j.compositesa.2015.08.038

Picon, A. (2014). The seducation of innovative geomatries. In R. Oxman & R. Oxman (Eds.), *Theories of the digital in architecture* (pp. 47-53). Routledge.

Pier, M. (2017, December 31). *Colombian Architect Simon Velez on Culture of Bamboo*. People are Culture. Retrieved 31/07/2020 from https://www.peopleareculture.com/blog/simon-velez-colombian-architect

Piker, D. (2013). Kangaroo: Form Finding with Computational Physics. *Architectural Design*, *83*(2), 136-137. https://doi.org/10.1002/ad.1569

Pilcher, H. R. (2004). Bamboo under extinction threat. *Nature*. https://doi.org/10.1038/news040510-2

Plank, H. K., & Hageman, R. H. (1951). Starch and Other Carbohydrates in Relation to Powder-Post Beetle Infestation in Freshly Harvested Bamboo. *Journal of Economic Entomology*, *44*(1), 73-75. https://doi.org/10.1093/jee/44.1.73

Podgorelec, V., & Zorman, M. (2009). Decision Trees. In R. A. Meyers (Ed.), *Encyclopedia of Complexity and Systems Science* (pp. 1826-1845). Springer New York. https://doi.org/10.1007/978-0-387-30440-3_117

Pomponi, F., Hart, J., Arehart, J. H., & D'Amico, B. (2020). Buildings as a Global Carbon Sink? A Reality Check on Feasibility Limits. *One Earth*, *3*(2), 157-161. https://doi.org/10.1016/j.oneear.2020.07.018

Poppens, R. P., van Dam, J. E. G., & Elbersen, H. W. (2013). *Bamboo: Analyzing the potential of bamboo feedstock for the biobased economy*. NL Agency, Ministry of Economic Affairs. https://edepot.wur.nl/381054

Porada, B. (2013, October 8). *Reconstruction of the Hospital of the State University of Haiti / MASS Design Group*. ArchDaily. Retrieved 29/07/2023 from https://www.archdaily.com/430793/mass-design-group-s-proposal-to-reconstruct-haitian-hospital

Preisinger, C. (2013). Linking Structure and Parametric Geometry. *Architectural Design*, *83*(2), 110-113. https://doi.org/10.1002/ad.1564

Puri, V., Chakrabortty, P., & Majumdar, S. (2015). A Review of Low Cost Housing Technologies in India. In *Advances in Structural Engineering* (pp. 1943-1955). https://doi.org/10.1007/978-81-322-2187-6_150

Qi, Y., Zhong, R., Kaiser, B., Nguyen, L., Wagner, H. J., Verl, A., & Menges, A. (2021). Working with Uncertainties: An Adaptive Fabrication Workflow for Bamboo Structures. In *Proceedings of the 2020 DigitalFUTURES* (pp. 265-279). https://doi.org/10.1007/978-981-33-4400-6_25

Qi, Y., Zhong, R., Kaiser, B., Tahouni, Y. W., Hans-Jakob , Verl, A., & Menges, A. (2021). Augmented Accuracy - A human-machine integrated adaptive fabrication workflow for bamboo construction utilizing computer vision. In V. Stojakovic & B. Tepavcevic (Eds.), *Towards a new, configurable architecture - Proceedings of the 39th eCAADe Conference - Volume 1, University of Novi Sad, Novi Sad, Serbia, 8-10 September 2021* (Vol. 1, pp. 345-354). eCAADe (Education and Research in Computer Aided Architectural Design in Europe). https://doi.org/10.52842/conf.ecaade.2021.1.345

Quinlan, J. R. (1986). Induction of decision trees. *Machine Learning*, *1*(1), 81-106. https://doi.org/10.1007/BF00116251

Rahim, A., & Jamelle, H. (2020). Architectural Impact After the Digital. *Architectural Design*, *90*(5), 6-13. https://doi.org/10.1002/ad.2605

Ramos, M. C. (1989). Some ethical implications of qualitative research. *Research in Nursing & Health*, *12*(1), 57-63. https://doi.org/10.1002/nur.4770120109

Ranasinghe, K. (2014). *Eurocode 5 span tables for solid timber members in floors, ceilings and roofs for dwellings. 4th edition. Contents, list of tables, preface and Part 1 - Introduction. (1 of 7)* (4 ed.). BM TRADA.

Rao, A. N., Rao, V. R., & Williams, J. T. (1998). *Priority species of bamboo and rattan* (A. N. Rao, V. R. Rao, & J. T. Williams, Eds.). IPGRI and INBAR. https://www.inbar.int/resources/inbar_publications/priority-species-of-bamboo-and-rattan/

Rao, F., Li, X., Li, N., Li, L., Liu, Q., Wang, J., Zhu, X., & Chen, Y. (2022). Photodegradation and Photostability of Bamboo: Recent Advances. *ACS Omega*, *7*(28), 24041-24047. https://doi.org/10.1021/acsomega.2c02035

Rao, I. V. R., Motukuri, B., & Karpe, S. (2009). *Breaking Barriers and Creating Capital*. INBAR and CIBART.

Ratti, C., & Claudel, M. (2015). *Open Source Architecture*. Thames and Hudson Ltd.

Reid, K., Flowers, P., & Larkin, M. (2005). Exploring lived Experience. *The Psychologist*, *18*, 18-23.

Restrepo Ochoa, C. (2022). Toward a Critical Tropicalism. *Architecture and Urbanism (a+u) - Feature: Colombia*, *2022*(3). https://au-magazine.com/shop/architecture-and-urbanism/au-202203/

RIBA. (2018). *Digital Transformation in Architecture*. RIBA. https://www.architecture.com/knowledge-and-resources/resources-landing-page/digital-transformation-in-architecture

RIBA/AJ. (1970). News: RIBA - Computers and you. *Architects Journal*, *151*(8), 472.

Ridley-Ellis, D., Gil-Moreno, D., & Harte, A. M. (2022). Strength grading of timber in the UK and Ireland in 2021. *International Wood Products Journal*, *13*(2), 127-136. https://doi.org/10.1080/20426445.2022.2050549

Robbins, E. (1997). *Why Architects Draw* (Paperback ed.). The MIT Press. https://doi.org/10.7551/mitpress/7233.001.0001

Robert McNeel & Associates. (2020). *Grasshopper 3D*. In [Visual programming language]. https://www.grasshopper3d.com/

Robert McNeel & Associates. (2022). *Introducing Rhino.Inside.Revit v1.0*. Retrieved 05/05/2022 from https://www.rhino3d.com/inside/revit/1.0/

Robert McNeel & Associates. (2023). *Rhinoceros 3D*. In (Version 7) [3D computer graphics and computer-aided design application]. https://www.rhino3d.com/

Robson, C. (2002). *Real world research: A resource for social scientists and practitioner-researchers* (2 ed.). Blackwell Publishers.

Rocker, I. M. (2006). When code matters. *Architectural Design*, *76*(4), 16-25. https://doi.org/10.1002/ad.289

Rojas-Sandoval, J., & Acevedo-Rodríguez, P. (2022). Bambusa vulgaris (common bamboo). *CABI Compendium*. https://doi.org/10.1079/cabicompendium.8398

Rosen, H. N. (1978). The Influence of External Resistance on Moisture Adsorption Rates in Wood. *Wood and Fiber Science*(3). https://wfs.swst.org/index.php/wfs/article/view/1228

Runyan, C., & Dodorico, P. (2016a). Introduction: Patterns and Drivers. In *Global Deforestation* (pp. 1-38). https://doi.org/10.1017/cbo9781316471548.002

Runyan, C., & Dodorico, P. (2016b). Irreversibility and Ecosystem Impacts. In *Global Deforestation* (pp. 103-144). https://doi.org/10.1017/cbo9781316471548.005

Runyan, C., & Dodorico, P. (2016c). Synthesis and Future Impacts of Deforestation. In *Global Deforestation* (pp. 173-194). https://doi.org/10.1017/cbo9781316471548.007

Rutten, D. (2013). Galapagos: On the Logic and Limitations of Generic Solvers. *Architectural Design*, *83*(2), 132-135. https://doi.org/10.1002/ad.1568

Sachse, P., Leinert, S., & Hacker, W. (2001). Designing with computer and sketches. *Swiss Journal of Psychology*, *60*(2), 65-72. https://doi.org/10.1024/1421-0185.60.2.65

Sadeghipour Roudsari, M., & Pak, M. (2013). Ladybug: A parametric environmental plugin for grasshopper to help designers create an environmentally-conscious design. In E. Wurtz (Ed.), *Proceedings of Building Simulation 2013: 13th Conference of the International Building Performance Simulation Association (Chambéry, France, August 26-28, 2013)* (pp. 3128-3135). International Building Performance Simulation Association

Sajap, A. S., Amit, S., & Welker, J. (2000). Evaluation of Hexaflumuron for Controlling the Subterranean Termite Coptotermes curvignathus (Isoptera: Rhinotermitidae) in Malaysia. *Journal of Economic Entomology*, *93*(2), 429-433. https://doi.org/10.1603/0022-0493-93.2.429

Schandl, H., & Krausmann, F. (2017, February 19). *The 20th century saw a 23-fold increase in natural resources used for building*. The Conversation Trust (UK) Limited. Retrieved 29/09/2021 from https://theconversation.com/the-20th-century-saw-a-23-fold-increase-in-natural-resources-used-for-building-73057

Scheer, D. (2014). *The Death of Drawing: Architecture in the Age of Simulation* (1 ed.). Routledge. https://doi.org/10.4324/9781315813950

Schilling, A. (2018). *Architecture and Modelbuilding: Concepts, Methods, Materials*. Birkhäuser. https://doi.org/10.1515/9783035614732

Schittich, C. (2019). *Vernacular architecture: Atlas for living throughout the world*. Birkhäuser Verlag GmbH.

Schmidt, O., Wei, D., Tang, H., & Liese, W. (2013). Bamboo and fungi. *Journal Bamboo and Rattan*, *12*(1-4).

Schon, D. A. (1984). *The Reflective Practitioner: How Professionals Think In Action*. Basic Books.

Schoof, J. (2018). Timber Construction Returns to the City. *DETAIL*(1/2), 24-33. https://inspiration.detail.de/essay-timber-construction-returns-to-the-city-114086.html

Schuller, M. (2019). “Haitians Need to Be Patient”: Notes on Policy Advocacy in Washington Following Haiti’s Earthquake. In M. H. Susanna & E. B. Roberto (Eds.), *Disaster Upon Disaster* (pp. 241-264). Berghahn Books. https://doi.org/10.1515/9781789203462-014

Schumacher, P. (2009a). Parametric Patterns. *Architectural Design*, *79*(6), 28-41. https://doi.org/10.1002/ad.976

Schumacher, P. (2009b). Parametricism: A New Global Style for Architecture and Urban Design. *Architectural Design*, *79*(4), 14-23. https://doi.org/10.1002/ad.912

Schumann, K., Hauptman, J., & MacDonald, K. (2019). Addressing Barriers for Bamboo: Techniques for Altering Cultural Perception. In C. Jarrett, P. Plowright, & H. Rashed-Ali (Eds.), *Architectural Research Centers Consortium 2019 - Future Praxis: Applied Research as a Bridge Between Theory and Practice May 29 - June 1, 2019*. https://www.arcc-journal.org/index.php/repository/article/view/664

Sci. Am. (1906). The Advantages and Limitations of Reinforced Concrete. *Scientific American*, *94*(19), 383-387. https://www.jstor.org/stable/24998996 (Scientific American)

SDXL. (2023). *Stable Diffusion XL – SDXL 1.0 Model*. In [AI image generation model]. https://stablediffusionxl.com/

Searchinger, T., Peng, L., Zionts, J., & Waite, R. (2023). The Global Land Squeeze: Managing the Growing Competition for Land. *World Resources Institute*. https://doi.org/10.46830/wrirpt.20.00042

Segura, F. R., Nunes, E. A., Paniz, F. P., Paulelli, A. C. C., Rodrigues, G. B., Braga, G. U. L., Dos Reis Pedreira Filho, W., Barbosa, F., Jr., Cerchiaro, G., Silva, F. F., & Batista, B. L. (2016). Potential risks of the residue from Samarco's mine dam burst (Bento Rodrigues, Brazil). *Environ Pollut*, *218*, 813-825. https://doi.org/10.1016/j.envpol.2016.08.005

Seitz, S. (2016). Pixilated partnerships, overcoming obstacles in qualitative interviews via Skype: a research note. *Qualitative Research*, *16*(2), 229-235. https://doi.org/10.1177/1468794115577011

Sekhar, A., & Rawat, M. (1964). Some studies on the shrinkage of Bambusa nutans. *Indian Forester*, *90*(3), 182-188.

Seksan, N. (2019). *Ng Seksan Open Source Designs*. Seksan Design - Landscape, architecture and planning. Retrieved 01/10/2019 from https://www.seksan.com/open-source-drawings

Senosiain, J. (2007). *Nido de Quetzalcóatl*. Retrieved 29/07/2023 from https://www.arquitecturaorganica.com/

Senske, N. (2017). Evaluation and Impact of a Required Computational Thinking Course for Architecture Students. In *Proceedings of the 2017 ACM SIGCSE Technical Symposium on Computer Science Education* (pp. 525–530). Association for Computing Machinery. https://doi.org/10.1145/3017680.3017750

Seymour, F., & Busch, J. (2016). Tropical Forests and Development Contributions to Water, Energy, Agriculture, Health, Safety, and Adaptation. In *Why Forests? Why Now?* (pp. 59-88). Brookings Institution Press.

Sharma, B., Bauer, H., Schickhofer, G., & Ramage, M. H. (2017). Mechanical characterisation of structural laminated bamboo. *Proceedings of the Institution of Civil Engineers - Structures and Buildings*, *170*(4), 250-264. https://doi.org/10.1680/jstbu.16.00061

Sharma, B., Gatoo, A., Bock, M., Mulligan, H., & Ramage, M. (2015). Engineered bamboo: state of the art. *Proceedings of the Institution of Civil Engineers - Construction Materials*, *168*(2), 57-67. https://doi.org/10.1680/coma.14.00020

Sharma, B., Gatóo, A., Bock, M., & Ramage, M. (2015). Engineered bamboo for structural applications. *Construction and Building Materials*, *81*, 66-73. https://doi.org/10.1016/j.conbuildmat.2015.01.077

Sharma, B., Gatóo, A., & Ramage, M. H. (2015). Effect of processing methods on the mechanical properties of engineered bamboo. *Construction and Building Materials*, *83*, 95-101. https://doi.org/10.1016/j.conbuildmat.2015.02.048

Sharma, B., Mitch, D., Harries, K. A., Ghavami, K., & Kharel, G. (2013). Pushover behaviour of bamboo portal frame structure. *International Wood Products Journal*, *2*(1), 20-28. https://doi.org/10.1179/2042645311y.0000000003

Sharma, S. K., Shukla, S. R., & Sethy, A. K. (2014). Utilization of Bambusa bambos (L.) and Dendrocalamus strictus (Roxb.) as an alternative to wooden dunnage pallets. *Journal of the Indian Academy of Wood Science*, *11*(1), 21-24. https://doi.org/10.1007/s13196-014-0112-4

Shaughnessy, R. J., Haverinen-Shaughnessy, U., Nevalainen, A., & Moschandreas, D. (2006). A preliminary study on the association between ventilation rates in classrooms and student performance. *Indoor Air*, *16*(6), 465-468. https://doi.org/10.1111/j.1600-0668.2006.00440.x

Sheil, B. (2005). Design Through Making: An Introduction. *Architectural Design*, *75*(4), 5-12. https://doi.org/10.1002/ad.97

Sheil, B. (2008). Protoarchitecture: Between the Analogue and the Digital. *Architectural Design*, *78*(4), 6-11. https://doi.org/10.1002/ad.699

Sheil, B. (2012). Distinguishing Between the Drawn and the Made. *Architectural Design*, *82*(2), 136-141. https://doi.org/10.1002/ad.1390

Shinohara, Y., Misumi, Y., Kubota, T., & Nanko, K. (2019). Characteristics of soil erosion in a moso-bamboo forest of western Japan: Comparison with a broadleaved forest and a coniferous forest. *Catena*, *172*, 451-460. https://doi.org/10.1016/j.catena.2018.09.011

Simpson, W. T. (1997). *Effect of Air Velocity on Drying Rate of Single Eastern White Pine Boards [Research Note FPL–RN–266]*. U.S. Department of Agriculture, Forest Service, Forest Products Laboratory.

Sinclair, C. (2010, April 10). *The Role of The Architect in Rebuilding Haiti: To Compete or To Construct?* Huff Post. Retrieved 16/07/2020 from https://www.huffpost.com/entry/the-role-of-the-architect_b_453905

Sinha, A., Way, D., & Mlasko, S. (2014). Structural Performance of Glued Laminated Bamboo Beams. *Journal of Structural Engineering*, *140*(1). https://doi.org/10.1061/(asce)st.1943-541x.0000807

Smil, V. (2013). *Making the Modern World: Materials and Dematerialization*. Wiley.

Smith, J. A. (2011). Evaluating the contribution of interpretative phenomenological analysis. *Health Psychology Review*, *5*(1), 9-27. https://doi.org/10.1080/17437199.2010.510659

Smith, J. A., Jarman, M., & Osborn, M. (1999). Doing Interpretative Phenomenological Analysis. In M. Murray & K. Chamberlain (Eds.), *Qualitative Health Psychology: Theories and Methods* (pp. 218-240). Sage. https://doi.org/10.4135/9781446217870

Sodhi, N. S., Koh, L. P., Brook, B. W., & Ng, P. K. (2004). Southeast Asian biodiversity: an impending disaster. *Trends Ecol Evol*, *19*(12), 654-660. https://doi.org/10.1016/j.tree.2004.09.006

Song, X., Zhou, G., Jiang, H., Yu, S., Fu, J., Li, W., Wang, W., Ma, Z., & Peng, C. (2011). Carbon sequestration by Chinese bamboo forests and their ecological benefits: Assessment of potential, problems, and future challenges [Review]. *Environmental Reviews*, *19*(1), 418-428. https://doi.org/10.1139/a11-015

Souza, E. (2021, November 23). *The Potential of Bamboo and Mass Timber for the Construction Industry: An Interview with Pablo van der Lugt*. Arch Daily. Retrieved 16/07/2023 from https://www.archdaily.com/972254/the-potential-of-bamboo-and-mass-timber-for-the-construction-industry-an-interview-with-pablo-van-der-lugt

Stamm, J. (2001). *Guia para la construccion de puentes en guadua*. Joint project of Pereira Technological University and German Society for Zechnical Cooperation (GTZ).

Stamm, J. (2022). Lightweight bamboo structures [Lecture series - AA Panama Workshop 2022]. In. Isthmus University, Panama City: Architectural Association School of Architecture Visiting School.

State of the Tropics. (2020). *State of the Tropics 2020 Report*. James Cook University. https://www.jcu.edu.au/state-of-the-tropics/publications/2020

Stavric, M., Sidanin, P., & Tepavcevic, B. (2013). *Architectural Scale Models in the Digital Age: design, representation and manufacturing*. Ambra Verlag. https://doi.org/10.1515/9783990435274

Storonov, T. (2017). *The design-build studio: Crafting meaningful work in architecture education*. Routledge.

Studio Libeskind. (2010). *18.36.54, Connecticut, USA*. Studio Libeskind. Retrieved 29/07/2023 from https://libeskind.com/work/18-36-54/

Sun, K. N., Lo, T. T., Guo, X., & Wu, J. (2022). Digital Construction of Bamboo Architecture Based on Multi-Technology Cooperation: Constructing a New Parameterized Digital Construction Workflow of Bamboo Architecture From Traditional Bamboo Construction Technology. In J. v. Ameijde;, N. Gardner;, K. H. Hyun;, D. Luo;, & U. Sheth; (Eds.), *POST-CARBON - Proceedings of the 27th CAADRIA Conference* (pp. 223-232).

Sundberg, J. (2009). Eurocentrism. In R. Kitchin & N. Thrift (Eds.), *International Encyclopedia of Human Geography* (pp. 638-643). Elsevier. https://doi.org/10.1016/B978-008044910-4.00093-6

Sutherland, I. E. (Ed.). (1963/2003). *Sketchpad: A man-machine graphical communication system [Reproduced 2003 as University of Cambridge Technical Report Number 574]*. University of Cambridge. https://doi.org/10.48456/tr-574.

Suzuki, S., & Knippers, J. (2017). ElasticSpace: A computational framework for interactive form-finding of textile hybrid structures through evolving topology networks. *International Journal of Parallel, Emergent and Distributed Systems*, *32*(sup1), S4-S14. https://doi.org/10.1080/17445760.2017.1390101

Suzuki, S., & Knippers, J. (2018). Digital Vernacular Design. Form-finding at the edge of realities. In P. Anzalone, M. Del Signore, & A. J. Wit (Eds.), *ACADIA // 2018: Recalibration. On imprecisionand infidelity - Proceedings of the 38th Annual Conference of the Association for Computer Aided Design in Architecture (ACADIA) Mexico City, Mexico 18-20 October, 2018* (pp. 56-65). ACADIA. https://doi.org/10.52842/conf.acadia.2018.056

Suzuki, S., Slabbinck, E., & Knippers, J. (2020). Computational Bamboo: Digital and Vernacular Design Principles for the Construction of a Temporary Bending-Active Structure. In C. Gengnagel, O. Baverel, J. Burry, M. Ramsgaard Thomsen, & S. Weinzierl (Eds.), *Impact: Design With All Senses. DMSB 2019* (pp. 224-236). Springer, Cham. https://doi.org/10.1007/978-3-030-29829-6_18

Svilans, T. (2021). GluLamb: A toolkit for early-stage modelling of free-form glue-laminated timber structures. In *Proceedings of the 2021 European Conference on Computing in Construction* (Vol. 2, pp. 373-380). European Council on Computing in Construction. https://doi.org/10.35490/EC3.2021.194

Svilans, T., Tamke, M., Thomsen, M. R., Runberger, J., Strehlke, K., & Antemann, M. (2019). New Workflows for Digital Timber. In *Digital Wood Design* (pp. 93-134). https://doi.org/10.1007/978-3-030-03676-8_3

Swann, C. (2002). Action Research and the Practice of Design. *Design Issues*, *18*(1), 49-61. https://doi.org/10.1162/07479360252756287

Swanson, A. (2015, March 24). *How China used more cement in 3 years than the U.S. did in the entire 20th Century*. Washington Post. Retrieved 08/11/2021 from https://www.washingtonpost.com/news/wonk/wp/2015/03/24/how-china-used-more-cement-in-3-years-than-the-u-s-did-in-the-entire-20th-century/

Tang, T. K. H., Schmidt, O., & Liese, W. (2012). Protection of bamboo against mould using environment-friendly chemicals. *Journal of Tropical Forest Science*, *24*(2), 285-290. https://www.jstor.org/stable/23617085

Tardio, G., Mickovski, S. B., Rauch, H. P., Fernandes, J. P., & Acharya, M. S. (2018). The Use of Bamboo for Erosion Control and Slope Stabilization: Soil Bioengineering Works. In H. P. S. A. Khalil (Ed.), *Bamboo: Current and Future Prospects*. https://doi.org/10.5772/intechopen.75626

Taylor, M. J. (2000). Return of the Master Builder [Article]. *Civil Engineering*, *70*(3), 40.

Teacă, C. A., Roşu, D., Bodîrlău, R., & Roşu, L. (2013). Structural Changes in Wood under Artificial UV Light Irradiation Determined by FTIR Spectroscopy and Color Measurements – A Brief Review [Wood; Chemical modification; Coating; UV irradiation; FT-IR spectroscopy; Color changes]. *2013*, *8*(1), 1478-1507. https://bioresources.cnr.ncsu.edu/resources/structural-changes-in-wood-under-artificial-uv-light-irradiation-determined-by-ftir-spectroscopy-and-color-measurements-a-brief-review/

Tedeschi, A. (2014). *AAD Algorithms-Aided Design: Parametric Strategies using Grasshopper* (1 ed.). Le Penseur.

TEEB, ten Brink, P., Kettunen, M., Vakrou, A., & Wittmer, H. (2009). The global biodiversity crisis and related policy challenge. In *The Economics of Ecosystems and Biodiversity for National and International Policy Makers* (Vol. Part 1). TEEB – The Economics of Ecosystems and Biodiversity for National and International Policy Makers.

Teischinger, A., Krug, D., Sandberg, D., & Tobisch, S. (2023). Sawn-Timber Products. In *Springer Handbook of Wood Science and Technology* (pp. 1283-1346). Springer Nature Switzerland. https://doi.org/10.1007/978-3-030-81315-4_25

Tekpetey, S. (2011). *Bamboo Resources in Ghana: Diversity, properties, products and opportunities.* ITTO.

Tekpetey, S., Frimpong-Mensah, K., & Atta-Boateng, A. (2020). Bamboo in Green Construction in Ghana: the Studies of Selected Anatomical Properties. In J. E. Winandy & V. L. Herian (Eds.), *Proceedings of the International Convention of Society of Wood Science and Technology and United Nations Economic Commission for Europe – Timber Committee October 11-14, 2010, Geneva, Switzerland*. UN.

Terzidis, K. (2003). Algorithmic form. In K. Terzidis (Ed.), *Expressive Form: A Conceptual Approach to Computational Design* (pp. 65-73). Spon Press.

Terzidis, K. (2008). Algorithmic complexity: Out of nowhere. In G. Andrea & V. Georg (Eds.), *Complexity* (pp. 75-88). Birkhäuser. https://doi.org/10.1515/9783034609692.75

Thorne, M., & Duran, P. (2016, May 5). *The role that architecture can play in the development agenda*. Devex Impact. Retrieved 23/09/2021 from https://www.devex.com/news/the-role-that-architecture-can-play-in-the-development-agenda-88124

Torres, A., Brandt, J., Lear, K., & Liu, J. (2017). A looming tragedy of the sand commons. *Science*, *357*(6355), 2. https://doi.org/10.1126/science.aao0503

Torres, A., Simoni, M. U., Keiding, J. K., Müller, D. B., zu Ermgassen, S. O. S. E., Liu, J., Jaeger, J. A. G., Winter, M., & Lambin, E. F. (2021). Sustainability of the global sand system in the Anthropocene. *One Earth*, *4*(5), 639-650. https://doi.org/10.1016/j.oneear.2021.04.011

Trost, J. E. (1986). Statistically nonrepresentative stratified sampling: A sampling technique for qualitative studies. *Qualitative Sociology*, *9*(1), 54-57. https://doi.org/10.1007/BF00988249

Trujillo, D. (2020, November 17). *Making bamboo a mainstream structural material [55:05]*. INBAR. Retrieved 06/09/21 from https://youtu.be/_8rHQGndpuE

Trujillo, D. (2021). Behind bahareque. *Bamboo and Rattan Update*, *2*(1), 9-11. https://www.inbar.int/resources/inbar_publications/vernacular-bamboo-architecture-tradition-or-future-bamboo-and-rattan-update-volume-2-issue-1/

Trujillo, D., & López, L. F. (2016). Bamboo material characterisation. In K. A. Harries & B. Sharma (Eds.), *Nonconventional and Vernacular Construction Materials* (pp. 365-392). Woodhead Publishing. https://doi.org/10.1016/B978-0-08-100038-0.00013-5

Turnbull, D. (2016). Bamboo. In H. Selin (Ed.), *Encyclopaedia of the History of Science, Technology, and Medicine in Non-Western Cultures* (pp. 811-812). Springer Netherlands. https://doi.org/10.1007/978-94-007-7747-7_8468

Turner, A., Barlow, J., & Ilbery, B. (2002). Play Hurt, Live Hurt: Living with and Managing Osteoarthritis from the Perspective of Ex-professional Footballers. *Journal of Health Psychology*, *7*(3), 285-301. https://doi.org/10.1177/1359105302007003222

Ubidia, J. M. (2015). *Manual de Construcción con Bambú [Tercera Edición adaptada para Perú]* (3 ed.). Red Internacional de Bambú y Ratán and INBAR. https://www.inbar.int/resources/inbar_publications/construir-con-bambu-spanish/

Uduku, O. (2006). Modernist architecture and 'the tropical' in West Africa: The tropical architecture movement in West Africa, 1948–1970. *Habitat International*, *30*(3), 396-411. https://doi.org/10.1016/j.habitatint.2004.11.001

UN-Habitat. (2003). *The Challenge of Slums: Global Report on Human Settlements 2003*. U. N. H. S. Programme. https://unhabitat.org/the-challenge-of-slums-global-report-on-human-settlements-2003

UN-Habitat. (2011). *Ghana Housing Profile*. UN-Habitat. https://unhabitat.org/ghana-housing-sector-profile

UN-Habitat. (2015). *HABITAT III Issue Papers - 22 – Informal Settlements*. U. N. H. S. Programme. https://unhabitat.org/habitat-iii-issue-papers-22-informal-settlements

UN-Habitat. (2016a). *SDG-Goal 11 Monitoring Framework*. U. N. H. S. Programme. https://unhabitat.org/sdg-goal-11-monitoring-framework

UN-Habitat. (2016b). *Slum Almanac 2015/2016: Tracking Improvement in the Lives of Slum Dwellers*. U. N. H. S. Programme. https://unhabitat.org/slum-almanac-2015-2016-0

UN. (2021a). *Goal 13*. UN. Retrieved 20/10/2021 from https://sdgs.un.org/goals/goal13

UN. (2021b). *Goal 15*. UN. Retrieved 13/10/2021 from https://sdgs.un.org/goals/goal15

UN. (2021c). *UN SDG Report 2021 - Goal 11*. UN. Retrieved 23/07/2023 from https://unstats.un.org/sdgs/report/2021/goal-11/

UN Studio. (1998). *Möbius House*. UN Studio. Retrieved 29/07/2023 from https://www.unstudio.com/en/page/12105/m%C3%B6bius-house

UNCCD. (2006). *Third National Report of the Republic of Haiti - Executive Summary*. https://www.unccd.int/sites/default/files/prais-legacy/Haiti/2006/Haiti%20-%20ACP%20-%202006%20eng%20summary.pdf

UNEP. (2014). *Sand, rarer than one thinks*. U. N. E. P. (UNEP). https://na.unep.net/geas/archive/pdfs/GEAS_Mar2014_Sand_Mining.pdf

UNEP. (2019). *Sand and Sustainability: Finding new solutions for environmental governance of global sand resources*. U. N. E. P. (UNEP). https://wedocs.unep.org/20.500.11822/28163

UNEP. (2022). *2022 Global Status Report for Buildings and Construction: Towards a Zero-emission, Efficient and Resilient Buildings and Construction Sector*. U. N. E. P. (UNEP). https://www.unep.org/resources/publication/2022-global-status-report-buildings-and-construction

UNISDR. (2015). *Sendai Framework for Disaster Risk Reduction 2015 - 2030* (UNISDR/GE/2015 - ICLUX EN5000). UNISDR. https://www.undrr.org/publication/sendai-framework-disaster-risk-reduction-2015-2030

United Nations. (2015). *Transforming Our World: The 2030 Agenda For Sustainable Development* (A/RES/70/1). https://sdgs.un.org/2030agenda

USGS. (2018). *2015 Minerals Yearbook: Cement*. U. S. G. Survey. https://www.usgs.gov/media/files/cement-2015-0

USGS. (2020a). *Mineral Commodity Summaries 2020*. U. S. G. Survey. https://pubs.usgs.gov/periodicals/mcs2020/mcs2020.pdf

USGS. (2020b, August 7). *Shakemap - M 7.0 - 10 km SE of Léogâne, Haiti*. U.S. Geological Survey. Retrieved 07/09/23 from https://earthquake.usgs.gov/earthquakes/eventpage/usp000h60h/shakemap/pga

van der Lugt, P. (2008). *Design interventions for stimulating bamboo commercialization - Dutch design meets bamboo as a replicable model* TU Delft]. https://repository.tudelft.nl//islandora/object/uuid:6ee4497f-9a2c-4d40-ba89-d869e2d75435 van der Lugt, P. (2017). Engineered Bamboo Products - A Sustainable Choice? In D. E. Hebel & F. Heisel (Eds.), *Cultivated Building Materials: Industrialized Natural Resources for Architecture and Construction* (pp. 86-95). Birkhäuser.

van Drunen, N., Cangás, A., Rojas, S., & Kaminski, S. (2016). *Post-earthquake report on bamboo structures and recommendations for reconstruction with bamboo on the Ecuadorian coast*. INBAR. https://www.inbar.int/resources/inbar_publications/post-earthquake-report-on-bamboo-structures-and-recommendations-for-reconstruction-with-bamboo-on-the-ecuadorian-coast/

van Leerdam, B. F. (1995). *Architect Henri Maclaine Pont: Een speurtocht naar bet wezenlijke van de Javaanse architectuur (Architect Henri Maclaine Pont: A quest for the essence of Javanese architecture) - Translated from Dutch to English by the author* TU Delft]. TU Delft. http://resolver.tudelft.nl/uuid:37764eb3-f2bd-4c99-aa63-38f6540a9ea8

van Uffelen, C. (2014). *Bamboo Architecture & Design*. Braun.

Vélez, S., Vegesack, A. v., Kries, M., Vitra Design, M., Foundation, Z., & Kenya Citizens Report, C. (2000). *Grow your own house: Simón Vélez and bamboo architecture*. Vitra Design Museum.

Vergilio, C. D. S., Lacerda, D., Oliveira, B. C. V., Sartori, E., Campos, G. M., Pereira, A. L. S., Aguiar, D. B., Souza, T. D. S., Almeida, M. G., Thompson, F., & Rezende, C. E. (2020). Metal concentrations and biological effects from one of the largest mining disasters in the world (Brumadinho, Minas Gerais, Brazil). *Sci Rep*, *10*(1), 5936. https://doi.org/10.1038/s41598-020-62700-w

Vetaas, O. R. (1992). Micro-site effects of trees and shrubs in dry savannas. *Journal of Vegetation Science*, *3*(3), 337-344. https://doi.org/10.2307/3235758

Vincent, J. F. V. (2001). Stealing Ideas from Nature. In S. Pellegrino (Ed.), *Deployable Structures* (pp. 51-58). Springer Vienna. https://doi.org/10.1007/978-3-7091-2584-7_3

Viollet-le-Duc, E. (1876). *The Habitations of Man in All Ages (B. Bucknall, Trans.)*. Sampson Low, Marston, Searle and Rivington (Original work published 1875).

Viray, E. (2011). Why Material Design?: Foreword. In *Material Design: Informing Architecture by Materiality* (pp. 8-9). Birkhäuser. https://doi.org/10.1515/9783034611664.8

Vishnubhotla, S. R., Biswas, G., Oliff, M. D., Cecchin, T., Ragot, J., Sauter, D., Darouach, M., Ghosh, K., Villeneuve, L., Tai, N. D., Ramaswamy, P. K., Wong, T.-L., Nagai, Y., You, I. C., Chu, C. N., Kashyap, R. L., Cheatham, J. B., Wu, C. K., Chen, Y. C., . . . Osterfeld, D. (1989). Expert Systems. In B. Prasad, S. N. Dwivedi, & K. B. Irani (Eds.), *CAD/CAM Robotics and Factories of the Future (Volume II: Automation of Design, Analysis and Manufacturing)* (Vol. 2, pp. 231-295). Springer. https://doi.org/10.1007/978-3-642-52323-6_4

Vitruvius, P. (30-20 BCE/1999). *Vitruvius: Ten books on architecture* (I. D. Rowland, T. N. Howe, & M. Dewar, Eds.). Cambridge University Press. https://doi.org/10.1017/CBO9780511840951

Vorontsova;, M. S., Clark;, L. G., & Baker;, J. D. R. G. W. J. (2016). *World Checklist of Bamboos and Rattans*. INBAR. https://www.inbar.int/resources/inbar_publications/world-checklist-of-bamboos-and-rattans/

Vrachliotis, G. (2020). Models, Media, and Methods: Frei Otto's Architectural Research [Exhibition catalogue]. https://www.architecture.yale.edu/publications/128-models-media-and-methods-frei-ottos-architectural-research

Vrachliotis, G. (2022). *The New Technological Condition*. Birkhäuser. https://doi.org/doi:10.1515/9783035624816

Vries, G. d., & Segaar-Höweler, D. (2009). *Henri Maclaine Pont (1884-1971)*. BONAS, Rotterdam. http://colonialarchitecture.eu/obj?sq=id%3Auuid%3Ae0ae3239-3273-441d-a7df-4bffce52cac9

Walker, C. (2014, June 8). *Bamboo: A Viable Alternative to Steel Reinforcement?* ArchDaily. Retrieved 01/05/2021 from https://www.archdaily.com/513736/bamboo-a-viable-alternative-to-steel-reinforcement

Wang, F. L., & Bettany, J. R. (1997). Methane emission from Canadian prairie and forest soils under short term flooding conditions. *Nutrient Cycling in Agroecosystems*, *49*(1), 197-202. https://doi.org/10.1023/A:1009758308457

Wang, H., Varma, R. V., & Xu, T. (1998). *Insect Pests of Bamboos in Asia (Part 1)*. INBAR. https://www.inbar.int/resources/inbar_publications/insect-pests-of-bamboos-in-asia-part-1/

Wang, M., Harries, K., Zhao, Y., Xu, Q., Wang, Z., & Leng, Y. (2022). Variation of mechanical properties of P. edulis (Moso) bamboo with moisture content. *Construction and Building Materials*, *324*. https://doi.org/10.1016/j.conbuildmat.2022.126629

Wang, T.-H., Espinosa Trujillo, O., Chang, W.-S., & Deng, B. (2017). Encoding bamboo's nature for freeform structure design. *International Journal of Architectural Computing*, *15*(2), 169-182. https://doi.org/10.1177/1478077117714943

Wang, X., & Ren, H. (2008). Comparative study of the photo-discoloration of moso bamboo (Phyllostachys pubescens Mazel) and two wood species. *Applied Surface Science*, *254*(21), 7029-7034. https://doi.org/10.1016/j.apsusc.2008.05.121

Wargocki, P., & Wyon, D. P. (2007). The Effects of Outdoor Air Supply Rate and Supply Air Filter Condition in Classrooms on the Performance of Schoolwork by Children (RP-1257). *HVAC&R Research*, *13*(2), 165-191. https://doi.org/10.1080/10789669.2007.10390950

Weinstock, M. (2006). Self-organisation and the structural dynamics of plants. *Architectural Design*, *76*(2), 26-33. https://doi.org/10.1002/ad.237

Welland, M. (2009). *Sand: The Never-Ending Story* (1 ed.). University of California Press.

West, M. (2008). Thinking with Matter. *Architectural Design*, *78*(4), 50-55. https://doi.org/10.1002/ad.705

West, P. C., Gibbs, H. K., Monfreda, C., Wagner, J., Barford, C. C., Carpenter, S. R., & Foley, J. A. (2010). Trading carbon for food: Global comparison of carbon stocks vs. crop yields on agricultural land. *Proceedings of the National Academy of Sciences*, *107*(46), 19645. https://doi.org/10.1073/pnas.1011078107

Whitford, W. G., Anderson, J., & Rice, P. M. (1997). Stemflow contribution to the 'fertile island' effect in creosote bush, Larrea tridentata. *Journal of Arid Environments*, *35*(3), 451-457. https://doi.org/10.1006/jare.1996.0164

Whiting, J. (2022, August 16). *Countries Most Likely To Survive Climate Change*. Eco Experts. Retrieved 14/09/23 from https://www.theecoexperts.co.uk/blog/climate-change-map

WHO. (2009). *WHO guidelines for indoor air quality : dampness and mould* (E. Heseltine & J. Rosen, Eds.). WHO. https://www.who.int/publications/i/item/9789289041683

Wibowo, A. S., Alfata, M. N. F., & Kubota, T. (2018). Indonesia: Dutch Colonial Buildings. In *Sustainable Houses and Living in the Hot-Humid Climates of Asia* (pp. 13-23). Springer Nature Singapore Pte Ltd. https://doi.org/10.1007/978-981-10-8465-2_2

Widyowijatnoko, A. (2012). *Traditional and Innovative Joints in Bamboo Construction* [PhD Doctor of Engineering, RWTH Aachen University]. Aachen.

Widyowijatnoko, A., & Harries, K. (2020). Joints in bamboo construction. In *Nonconventional and Vernacular Construction Materials* (pp. 561-596). Elsevier Ltd. https://doi.org/10.1016/b978-0-08-102704-2.00020-2

Williams, G. (2012, January 27). *Bali and the chocolate factory*. Financial Times. Retrieved 14/09/2019 from https://www.ft.com/content/b5c65a5e-4291-11e1-97b1-00144feab49a

Willis, D., & Woodward, T. (2005). Diminishing Dificulty: Mass Customization and the Digital Production of Architecture. *Harvard Design Magazine*(23), 71-83.

Willmann, J., Gramazio, F., Kohler, M., & Langenberg, S. (2013). Digital by Material. In S. Brell-Çokcan & J. Braumann (Eds.), *Rob | Arch 2012* (pp. 12-27). Springer. https://doi.org/10.1007/978-3-7091-1465-0_2

Wilson, J. B., & Agnew, A. D. Q. (1992). Positive-feedback Switches in Plant Communities. In M. Begon & A. H. Fitter (Eds.), *Advances in Ecological Research* (Vol. 23, pp. 263-336). Academic Press. https://doi.org/10.1016/S0065-2504(08)60149-X

Wintour, P. (2018, June 8). *A brief history of computation*. Parametric Monkey. Retrieved 05/02/2022 from https://parametricmonkey.com/2018/06/08/a-brief-history-of-computation/

WIS 4-28. (2019). *Durability by design* (Wood Information Sheet, Issue 4-28). BM TRADA.

Woodbury, R. (2014). How designers use parametrics. In R. Oxman & R. Oxman (Eds.), *Theories of the digital in architecture* (pp. 153-170). Routledge.

Woods, L. (2008). Drawn into Space: Zaha Hadid. *Architectural Design*, *78*(4), 28-35. https://doi.org/10.1002/ad.702

World Bank. (2009). Convenient Solutions for an Inconvenient Truth: Ecosystem-based Approaches to Climate Change. In *Environment and Development*. The World Bank. https://doi.org/10.1596/978-0-8213-8126-7

World Bank. (2023). *Low & middle Income Countries*. https://data.worldbank.org/country/XO

Woroniecki, M. (2021). The Intricate Architecture of Enchantment. *Architectural Design*, *91*(6), 90-97. https://doi.org/10.1002/ad.2757

Wortmann, T. (2017). *Opossum: Introducing and Evaluating a Model-based Optimization Tool for Grasshopper*.

Wortmann, T., & Nannicini, G. (2017). Introduction to Architectural Design Optimization. In (pp. 259-278). https://doi.org/10.1007/978-3-319-65338-9_14

Wu, N. H., Dimopoulou, M., Hsieh, H. H., & Chatzakis, C. (2019). Rawbot - A digital system for AR fabrication of bamboo structures through the discrete digitization of bamboo. In J. Sousa, J. Xavier, & G. Castro Henriques (Eds.), *Architecture in the Age of the 4th Industrial Revolution - Proceedings of the 37th eCAADe and 23rd SIGraDi Conference - Volume 2, University of Porto, Porto, Portugal, 11-13 September 2019* (Vol. 2, pp. 161-170). eCAADe, SIGraDi and FAUP. https://doi.org/10.52842/conf.ecaade.2019.2.161

Xiao, Y. (2016). Engineered Bamboo. In *Nonconventional and Vernacular Construction Materials* (pp. 433-452). Elsevier Ltd. https://doi.org/10.1016/b978-0-08-100038-0.00015-9

Xu, Q.-F., Jiang, P.-K., Wu, J.-S., Zhou, G.-M., Shen, R.-F., & Fuhrmann, J. J. (2014). Bamboo invasion of native broadleaf forest modified soil microbial communities and diversity. *Biological Invasions*, *17*(1), 433-444. https://doi.org/10.1007/s10530-014-0741-y

Xu, Q., Harries, K., Li, X., Liu, Q., & Gottron, J. (2014). Mechanical properties of structural bamboo following immersion in water. *Engineering Structures*, *81*, 230-239. https://doi.org/10.1016/j.engstruct.2014.09.044

Xu, X., Xu, P., Zhu, J., Li, H., & Xiong, Z. (2022). Bamboo construction materials: Carbon storage and potential to reduce associated CO(2) emissions. *Sci Total Environ*, *814*, 152697. https://doi.org/10.1016/j.scitotenv.2021.152697

Yadav, M., & Mathur, A. (2021). Bamboo as a sustainable material in the construction industry: An overview. *Materials Today: Proceedings*, *43*(5), 2872-2876. https://doi.org/10.1016/j.matpr.2021.01.125

Yang, H., Cao, Z., Jiang, X., & Wang, Y. (2022). Experimental Study on the Deformation and Mechanical Properties of Bamboo Forest Slopes. *Applied Sciences*, *13*(1). https://doi.org/10.3390/app13010470

Yang, X., & Xu, W. (2021). A Tool for Searching Active Bending Bamboo Strips in Construction via Deep Learning. In A. Globa, J. van Ameijde, A. Fingrut, N. Kim, & T. T. S. Lo (Eds.), *PROJECTIONS - Proceedings of the 26th CAADRIA Conference* (Vol. 1). CAADRIA. https://doi.org/10.52842/conf.caadria.2021.1.463

Yardley, L. (2017). Demonstrating the validity of qualitative research. *The Journal of Positive Psychology*, *12*(3), 295-296. https://doi.org/10.1080/17439760.2016.1262624

Yashaswi, P. (2019, November 14). *Indian designers dismiss "design-school propaganda" as they decolonise their work*. Dezeen. Retrieved 15/05/2020 from https://www.dezeen.com/2019/11/14/indian-designers-decolonise-feature/

Yates, J. K., & Battersby, L. C. (2003). Master Builder Project Delivery System and Designer Construction Knowledge. *Journal of Construction Engineering and Management*, *129*(6), 635-644. https://doi.org/10.1061/(ASCE)0733-9364(2003)129:6(635)

Yi-Luen Do, E. (2005). Design sketches and sketch design tools. *Knowledge-Based Systems*, *18*(8), 383-405. https://doi.org/10.1016/j.knosys.2005.07.001

YM. (2023). *Wood Building Programme*. Ympäristöministeriö Miljöministeriet. Retrieved 19/08/2023 from https://ym.fi/en/wood-building

Yu, H., He, S., Zhang, W., Zhan, M., Zhuang, X., Wang, J., Yu, W., & Gao, L. (2021). Discoloration and Degradation of Bamboo under Ultraviolet Radiation. *International Journal of Polymer Science*, *2021*, 1-10. https://doi.org/10.1155/2021/6803100

Yu, H. Q., Jiang, Z. H., Hse, C. Y., & Shupe, T. F. (2008). Selected physical and mechanical properties of moso bamboo (Phyllostachys pubescens). *Journal of Tropical Forest Science*, *20*(4), 258-263.

Yuan, P. (2016). Parametric Regionalism. *Architectural Design*, *86*(2), 92-99. https://doi.org/10.1002/ad.2029

Yuan, P. F., & Wang, X. (2018). From Theory to Praxis: Digital Tools and the New Architectural Authorship. *Architectural Design*, *88*(6), 94-101. https://doi.org/10.1002/ad.2371

Yudodibroto, H. (1985). Bamboo Research in Indonesia. In A. N. Rao, G. Dhanarajan, & C. B. Sastry (Eds.), *International Bamboo Workshop [6-14 Oct. 1985, Hangzhon, China]* (pp. 33-44). The Chinese Academy of Forestry, International Development Research Centre.

Yuen, J. Q., Fung, T., & Ziegler, A. D. (2017). Carbon stocks in bamboo ecosystems worldwide: Estimates and uncertainties. *Forest Ecology and Management*, *393*, 113-138. https://doi.org/10.1016/j.foreco.2017.01.017

Zachariah, E. J., Sabulal, B., Nair, D. N. K., Johnson, A. J., & Kumar, C. S. P. (2016). Carbon dioxide emission from bamboo culms. *Plant Biology*, *18*(3), 400-405. https://doi.org/10.1111/plb.12435

Zahar, M. (1931). Batir! Informer! *L'Art vivant*, *7*(151), 384.

Zarzycki, A. (2014). Reflections on Computational Design Through Interactions With Materiality and Physical Mock-Ups. *Journal of Architectural Education*, *68*(1), 94-103. https://doi.org/10.1080/10464883.2013.865480

Zea Escamilla, E. (2015). *Development of simplified life cycle assessment methodology for construction materials and buildings outside of the European context through the use of geographic information systems* (Publication Number 23193) [PhD Thesis, ETH Zurich]. Zurich. https://doi.org/10.3929/ethz-a-010617848

Zea Escamilla, E., & Habert, G. (2014). Environmental impacts of bamboo-based construction materials representing global production diversity. *Journal of Cleaner Production*, *69*, 117-127. https://doi.org/10.1016/j.jclepro.2014.01.067

Zea Escamilla, E., & Habert, G. (2015). Global or local construction materials for post-disaster reconstruction? Sustainability assessment of twenty post-disaster shelter designs. *Building and Environment*, *92*, 692-702. https://doi.org/10.1016/j.buildenv.2015.05.036

Zea Escamilla, E., Habert, G., Correal Daza, J., Archilla, H., Echeverry Fernández, J., & Trujillo, D. (2018). Industrial or Traditional Bamboo Construction? Comparative Life Cycle Assessment (LCA) of Bamboo-Based Buildings. *Sustainability*, *10*(9). https://doi.org/10.3390/su10093096

ZHA. (2006). *BMW Showroom*. Zaha Hadid Architects. Retrieved 29/07/2023 from https://www.zaha-hadid.com/architecture/bmw-showroom/

Zhang, X., Li, J., Yu, Y., & Wang, H. (2018). Investigating the water vapor sorption behavior of bamboo with two sorption models. *Journal of Materials Science*, *53*(11), 8241-8249. https://doi.org/10.1007/s10853-018-2166-y

Zhao, H., Zhao, S., International Network for, B., Rattan, Fei, B., Liu, H., Yang, H., Dai, H., Wang, D., Jin, W., Tang, F., Gao, Q., Xun, H., Wang, Y., Qi, L., Yue, X., Lin, S., Gu, L., Li, L., . . . Jiang, Z. (2017). Announcing the Genome Atlas of Bamboo and Rattan (GABR) project: promoting research in evolution and in economically and ecologically beneficial plants. *Gigascience*, *6*(7), 1-7. https://doi.org/10.1093/gigascience/gix046

Zhou, B.-Z., Fu, M.-Y., Xie, J.-Z., Yang, X.-S., & Li, Z.-C. (2005). Ecological functions of bamboo forest: Research and Application. *Journal of Forestry Research*, *16*(2), 143-147. https://doi.org/10.1007/BF02857909

Zhou, Y., Li, X., Chen, W., Meng, L., Wu, Q., Gong, P., & Seto, K. C. (2022). Satellite mapping of urban built-up heights reveals extreme infrastructure gaps and inequalities in the Global South. *Proc Natl Acad Sci U S A*, *119*(46), e2214813119. https://doi.org/10.1073/pnas.2214813119

Zoom. (2022). *Zoom*. In (Version 5.9.1) [Proprietary videotelephony software program]. https://zoom.us/