THESIS FOR THE DEGREE OF LICENTIATE OF ENGINEERING

# Sustainability of Social Housing in the Urban Tropics

## A Holistic Multi-Perspective Development Process for Bamboo-Based Construction

CORINNA SALZER

Department of Civil and Environmental Engineering

CHALMERS UNIVERSITY OF TECHNOLOGY

Gothenburg, Sweden 2016

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Cover: Two story housing with structural round bamboo in Iloilo, Philippines
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SUSTAINABILITY OF SOCIAL HOUSING IN THE URBAN TROPICS

Thesis for the Degree of Licentiate of Engineering

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ABSTRACT

The Licentiate thesis looks at sustainable building approaches for social housing in emerging economies. It combines theoretical concepts with practical applications of sustainability and underlines the relevance and strength of multi-dimensional development. At the example of the Philippines, the conceptual framework for a multi-perspective development process of a bamboo-based building system is developed. Sustainability Assessment Criteria are defined based on data from three stakeholder clusters: (1) Builders and users of traditional bamboo houses in the Philippines; (2) Stakeholders involved in using forest products for housing in countries around the world; and (3) Stakeholders in the field of social housing of the Philippines. Through a qualitative content analysis, research areas are identified and categorized into five dimensions of holistic sustainability: technology, society, ecology, economy, and governance. The Licentiate names methods leading to measurable, quantitative endpoints for those research areas and presents selected results: from mechanical property and fire resistance testing in the technical pillar, to environmental impact assessment in the ecological dimension as well as pathways towards a legal approval as contribution to the governance pillar. An accompanying implementation project is introduced, producing outputs in economic, social and governance dimension, and a pathway for the course of the PhD is shaped. By the end of the PhD thesis, a holistic sustainability assessment of the building technology will be provided for the given context of social housing in the Philippines.

Keywords: Sustainable Building, Asia-Pacific, Alternative Building Materials and Methods, Holistic Sustainability, Urban Housing, Stakeholder Needs, Bamboo

# PREFACE

The thesis summarizes two years of research at the Chair of Sustainable Building at Chalmers University of Technology in Gothenburg, Sweden. The funding of the research is provided by Hilti Foundation. The research results are materialized in an application project named Base, operating in Singapore and the Philippines.

Thanks are extended to my supervising Professor Holger Wallbaum, the colleagues at the Chair of Sustainable Building, the Chalmers Area of Advance Built Environment profile "Responsible Use of Resources" supporting the research, Base Team Members from the applied project, the Hilti Foundation Management as well as my family. Fruitful exchanges, expert and interdisciplinary reflections have supported to shape the thesis and are highly valued.

Corinna Salzer

Gothenburg, September, 2016

# LIST OF PUBLICATIONS

The thesis is based on the following appended conference and journal papers:

Journal Papers:

I. Salzer, C. (2015). Sustainability of Social Housing in Asia: A Holistic Multi-Perspective Development Process for Bamboo-Based Construction in the Philippines. *Sustainability*. **Status**: published January 2016, **Authors**: Corinna Salzer; Holger Wallbaum, Luis Lopez, Jean-Luc Kouyoumji

II. Salzer, C. (2015). Environmental performance of social housing in emerging economies: Life Cycle Assessment of conventional and alternative construction methods in the Philippines. *International Journal of Life Cycle Assessment*. **Status**: 1st Review - Minor Revisions, **Authors**: Corinna Salzer; Holger Wallbaum, York Ostermeyer, Jun Kono

III. Salzer, C. (2015). Determining material suitability for low-rise housing in the Philippines: Physical and mechanical properties of the bamboo species Bambusa blumeana. *BioResources*. **Status**: Handed-in, awaiting response. **Authors**: Corinna Salzer; Holger Wallbaum, Marina Alipon, Luis Lopez

Conferences:

I. Salzer, C. (2015). Preparing for Scale and Impact: Legal approval of bamboo as structural component in housing of the Philippines. *Proceedings of International Conference on Sustainable Practices in Civil Engineering SPACE*. **Status**: presented April, 2015, Manila, Philippines (not published in international database). **Authors**: Corinna Salzer; Luis Lopez

II. Salzer, C. (2015). Innovation for low-rise construction in the urban tropics. *Proceedings of the International Forum on Urbanism*. **Status**: presented June, 2015, Incheon, Korea. **Authors**: Corinna Salzer; Clara Hernando Camarasa

III. Salzer, C. (2015). Stories that change the paradigm: Bamboo structures for sustainable and resilient communities. *Proceedings of the World Bamboo Congress*. **Status**: presented September, 2015, Damyang, Korea. **Authors**: Corinna Salzer; Sonia Fardigo; Andrea Fitrianto

IV. Salzer, C. (2015). Fire resistance of low-rise housing in the tropics: Test results for bamboo-based construction systems. *Proceedings of the World Timber Conference*. **Status**: Accepted for presentation August, 2016, Vienna, Austria. **Authors**: Corinna Salzer; Holger Wallbaum; Lily Tambunan

All papers are written by the PhD Candidate with method or data assessment support or content reflection by the co-authors.

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# 1 Introduction

The introduction is organized in three subchapters, providing the background of the research field, deriving general and specific research objectives, and describing limitations.

## 1.1 Background

ENVIRONMENTAL IMPACT OF CONSTRUCTION

Building practices around the globe are a major consumer of resources and energy, while producing significant emissions and waste [1]. Climate change and the environmental impact of construction make sustainable buildings an urgent requirement. Acknowledging this fact, the concept of sustainable building has spread widely [2]. In several countries, sustainable construction has already been institutionalized, such as in Switzerland through SIA 112/1 [3]. While the call for sustainable buildings is urgent, this holds true also, but not only, for advanced built environments. In rapidly developing urban centers in Asia-Pacific sustainability as design guideline is still limited to selected, advanced construction projects. Incorporating sustainability concepts for the building stock of low-income groups, has received only little attention so far [2], [4], [5].

URBAN CENTURY, NEED FOR COST EFFICIENT, ADEQUATE HOUSING

Tremendous urban growth rates in Latin America, Africa, and Asia-Pacific make an inclusive and sustainable urban development essential [6], with housing being one key component in such. A majority of the needed housing is required by low income groups. In Asia-Pacific alone, approximately 30 percent of the urban population, which accounts for 570 Million people, live in houses which are defined as inadequate by the United Nations [7]. Adequacy refers to a shelter providing safety and privacy, allowing healthy living as well as access to utilities, public services, and livelihood. The building stock of low-income groups is often characterized by substandard practices or temporary shelters, which can lead to fatal failures during earthquakes, typhoons, or floods [8], [9]. In Picture 1 and 2, an exemplary informal settlement and substandard concrete house are shown. The Philippines, being country of consideration for the PhD, belongs to the most affected countries by Climate Change around the globe [10], [11]. In future, extreme impacts are expected even more frequently, which causes vicious cycles of vulnerability for the urban poor. While adequate housing is a desire of most affected people, conventional building technologies, such as concrete and steel, as well as the systems to finance and obtain them, are mostly not adjusted to affordability of low-income dwellers [12]. With financial means of governments and NGOs not large enough to donate relevant quantities of housing units, the market is mainly served by informal service providers or remains unserved. Collective efforts by governments, private sector, urban poor themselves and further relevant stakeholder groups is needed to provide low-income housing at scale and in a more socially-inclusive and sustainable manner [13].


*Picture 1: informal settlement, Metro Manila, Philippines (left)*

*Picture 2: self-build concrete house, Metro Manila, Philippines (right)*

PhD TOPIC: PHILLIPPINES, POTENTIAL OF BAMBOO, ITS CURRENT USE
Solutions for more economic, disaster resistant and socially-inclusive housing are needed, which further provide more environmentally-friendly pathways for urban development. This PhD addresses therefore the need for more holistic housing solutions for low-income groups. The Philippines are chosen as country of exploration. Rapid urban growth and poverty, high vulnerability of low income groups to frequent disasters and the effects of climate change, can be felt today.

The use of locally available raw materials is a potential to be explored in this regard. With the Philippines being country for research and application, one material with interesting potential is the fast growing, widely spread bamboo. Since centuries, traditional bamboo housing can be found in the rural Philippines [14]. The use of bamboo in rural Philippines is mostly of temporary nature. In urban Philippines, it is limited to informal settlements and non-load-bearing applications. In Picture 3 and 4 typical examples for both rural and urban applications of bamboo in the Philippines are shown. In cities, a common perception is that conventional concrete and steel building methods are more modern, safe, and less maintenance intensive.

*Picture 3: Bamboo use today - left: rural, temporary bamboo house*

*Picture 4: Bamboo use today - right: bamboo in informal settlement*

## 1.2 Objectives of PhD and Licentiate

Traditional bamboo construction has never undergone a holistic review to assess its adaptation potential to an urban and/or disaster prone context. The general objective of the PhD is to look at the raw material bamboo strategically and assesses its potential to be an acceptable, viable solution for permanent, sustainable and resilient housing. For this to be achieved, the PhD names three stages to be conducted in consecutive order:

1. To develop a conceptual framework for bamboo-based housing in social housing sector by identifying sustainability criteria for its assessment in this context and deriving a research and implementation roadmap enabling the assessment according to the identified sustainability criteria.
2. To generate scientific results along the defined research roadmap, hand-in-hand to an implementation project accompanying the PhD. The objectives of this stage are described as specific objectives of the PhD.
3. To use the concept of sustainability as a decision-tool, as suggested in [15], conducting a holistic sustainability assessment based on the results of the roadmap.

***The Licentiate will focus on stage one and selected items of stage two. The PhD will cover stage one and two and conclude with the holistic sustainability assessment of stage three.***

The activities of stage two are clustered into ***five pillars of sustainability: Ecology, Society, Economy, Technology and Governance.*** In line with most common definition of sustainability [16], the pillars society, environment, and economy are denominated. It is noted, that all three pillars will be enforced in this work. Therefore weak sustainability, weighing two dimensions over the third, as commonly applied in sustainability decisions of the last decades, is discouraged. Moreover, the given context requires additional pillars to be considered: When dealing with products or product comparison, such as in [17] or this thesis, the technical performance is a critical dimension and demands inclusion. Further, especially in development cooperation, the relevance of governance has to be highlighted, as done in [18], to enable impact at scale. Both dimensions, technology and governance, are critical to bridge the gap between a theoretic approach and materialization of sustainability decisions. The definition of sustainability applied in this PhD is therefore named ***holistic sustainability***.

***Results are generated through research and through an implementation project, both of which will go hand-in-hand and provide feedback loops to each other.*** The pillars Ecology and Technology contain mainly research activities covered partially at the stage Licentiate and fully through the PhD. The pillars Society, Economy and Governance contain mainly activities of the implementation project. The organizational set-up of the implementation project is an initiative of Hilti Foundation named Base. Through a headquarter in Singapore, Base Builds, and an operational entity in the Philippines, Base Bahay [19], bamboo-based construction projects are implemented which make direct use of the research contributions off the PhD. The need for a holistic interpretation of sustainability in this PhD is enforced through the striking distance of research and application.

Figure 1 summarizes the contribution of the Licentiate thesis according to above mentioned principles.

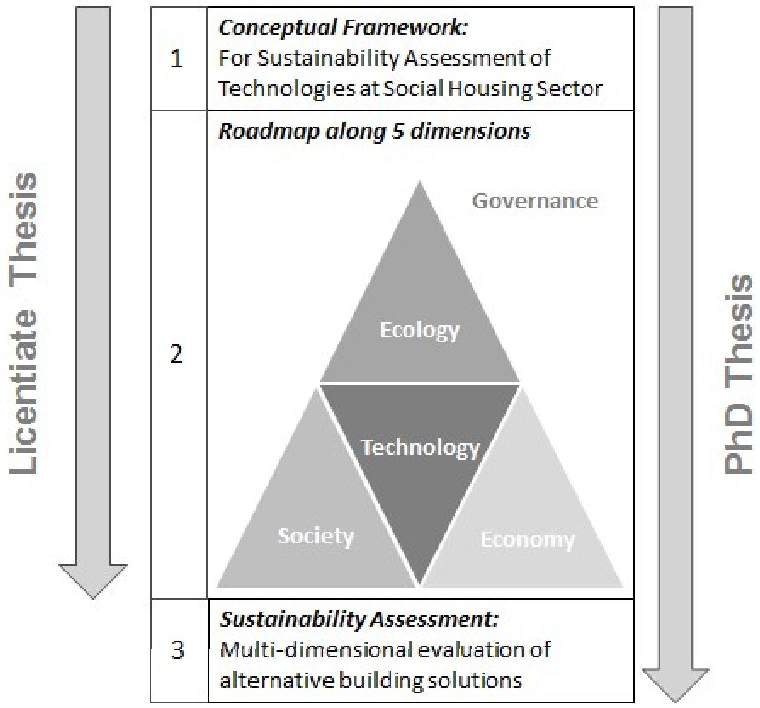



*Figure 1: Licentiate and PhD concept in three stages*

## 1.3 Limitations

The thesis covers a general methodology and selected one-dimensional research results. Further one-dimensional results will be added within the course of the PhD and merged into a holistic technology assessment at the end of the PhD.

# 2 Method

The Method chapter of the Licentiate thesis is differentiated into a general, a specific and a supporting part. The general part, 2.1, is connected to the general objective stage one, in which a conceptual framework is provided through the definition of sustainability criteria based on which a research and implementation roadmap is derived. Consecutive, in 2.2, specific objectives of the roadmap are defined. In 2.2.1, methods of selected research contributions of the roadmap are described. Further, in 2.2.2, methods applied in the supporting implementation project, which go hand-in-hand with the research contributions, are introduced. Latter are however not in the focus of the Licentiate thesis, but mentioned to provide a comprehensive overview.

## 2.1 General Part

To define meaningful, context-specific Sustainability Assessment Criteria for bamboo-based building technologies in social housing of the Philippines, the research question was asked:
*What are requirements, barriers, and opportunities of stakeholders in social housing and for using bamboo as a construction material in this context?*

To ensure a suitable selection of Sustainability Criteria, this research systematically involved stakeholder perspectives. Depending on the respective perspective of stakeholder groups, different rankings are set in weighing Sustainability Criteria, but homogeneous stakeholders` preferences typologies can be identified in stakeholder sub-groups [20]. For the choice of stakeholders to be interviewed or involved, [15], [21], [22] distinguish two general approaches: a top-down or expert-driven approach and a bottom-up or stakeholder-driven approach. A combination of both reflects most recent scientific recommendations and was applied. It ensures the comprehensive capture of barriers and opportunities and enables participation and ownership throughout the layers of society that are affected by a case. The expert and grassroots stakeholders for this research were identified through the context of the case being *social housing in the Philippines* and *bamboo utilization for housing*. Further, both national and international perspectives were captured, leading to the following three stakeholder clusters:

(1) Builders and users of traditional bamboo houses,
(2) Stakeholders involved in using forest products for housing in other parts of the world, and
(3) Stakeholders in the field of social housing in the Philippines.

Stakeholder subgroups of (3) were national and local governments, local and international academia in engineering and architecture, people living in informal settlements, people along the value chain starting with farmers harvesting bamboo up to the construction workers building houses, private sector in the construction field, NGOs and international agencies and finance sector institutions providing loans for housing.

Stakeholder requirements are captured through cognitive interviews for which the interview principles for research and evaluation of [23] were followed. The interviews generated qualitative data on requirements, barriers and opportunities from multiple stakeholder perspectives. Depending on the background and context of the stakeholder group, either a less-formal/-structured *Ethnographic Interview* type, or an *Interview Guide Approach* was chosen. In addition to interview data, *Field Inspections* or *Direct Observations* were carried out over the period of the Licentiate. Barriers and opportunities, expressed by stakeholders or documented in field observations, were transformed in a qualitative *Content Analysis* to elicit most suitable sustainability criteria for the given case.

- As first level sorting, a barrier or opportunity was coded into one or several pillars of sustainability.
- As second level sorting, several sampling strategies, described in [24], were applied to identify common patterns in the qualitative data: (1) *Group characteristic sampling*, identifying patterns for several stakeholders in a group without neglecting their diversity, (2) *Instrumental-use multi-case sampling*, for generating actionable, useful findings, and (3) *Comparison-focused sampling*, for understanding similarities and differences between cases that can be compared to the present case.
- As third level, *Literature review and field observations*, where available, were used to triangulate identified requirement patterns.

The content analysis then derived Sustainability Criteria from the identified patterns. This part can be described as *Analytic Induction,* as it moves from existing concepts to generating a new, case-specific framework. Table 1 below states the identified context specific Sustainability Criteria:

*Table 1: Sustainability Criteria*

| No. | Pillar of Sustainability | | | | | Criteria |
|---|---|---|---|---|---|---|
| | Society | Tech-nology | Economy | Ecology | Gover-nance | |
| 1 | | | | | | Social acceptance & advocacy |
| 2 | | | | | | Participation & identification |
| 3 | | | | | | Capacity building |
| 4 | | | | | | Income at local value chain |
| 5 | | | | | | Maintenance & incremental development |
| 6 | | | | | | Health & comfort |
| 7 | | | | | | Enduring safety & performance |
| 8 | | | | | | Standardization, quality control, pace |
| 9 | | | | | | Continuous innovation |
| 10 | | | | | | Cost advantage of houses |
| 11 | | | | | | Scalable business model |
| 12 | | | | | | Supply accessibility |
| 13 | | | | | | Supply availability & sustainability |
| 14 | | | | | | Environmental impact |
| 15 | | | | | | Compliance to policies & regulations |

Consecutive to the definition of Sustainability Criteria, a Strategic Development Roadmap for the alternative building method is derived, which transforms theoretic criteria into implementable, measurable results. The following research questions are raised for this purpose: *What are general strategies for implementing the theory of sustainable building on the ground? And to which concrete action items lead these strategies guided by the Sustainability Criteria?*

Four strategies were found being ***research*** about and ***implementation*** of building concepts, ***sustainable supply chain development*** as well as ***stakeholder involvement and capacity building***. An explanation is given in the following: The scientific work of the PhD focuses on research about the building technology. At its core, it analyzes the technical potential of the raw material round bamboo and building concepts using it and provides transparency on its environmental performance compared to the conventional construction solutions. In addition, the implementation of the building concept is a critical contribution to this PhD. As shown in [25] for several countries in Asia, it is deemed a crucial strength of sustainability indicator programs, when they are anchored in long-term implementation strategies. A corresponding implementation project targets to develop people-centered, participatory construction pilots, the creation of ownership and identification of the local population with the said technology, a legal framework in the country of application, sustainable supply chains and economic scale-up strategies. The importance of developing a technology people-centered and along of client's needs is named critical by numerous literature references [13], [21], [26] and institutions such as [27]. For the application of a forest product based technology at larger scale, a specific requirement is a sustainably generated, accessible supply of quality graded raw material. In many economies of bamboo growth, a bamboo supply chain has to be built-up first [28].

Guided by the four strategies and 15 Sustainability Criteria, action items across the five pillars of holistic sustainability were derived as shown in Figure 2. Each roadmap item is connected to one or more methods to obtain measurable outputs.

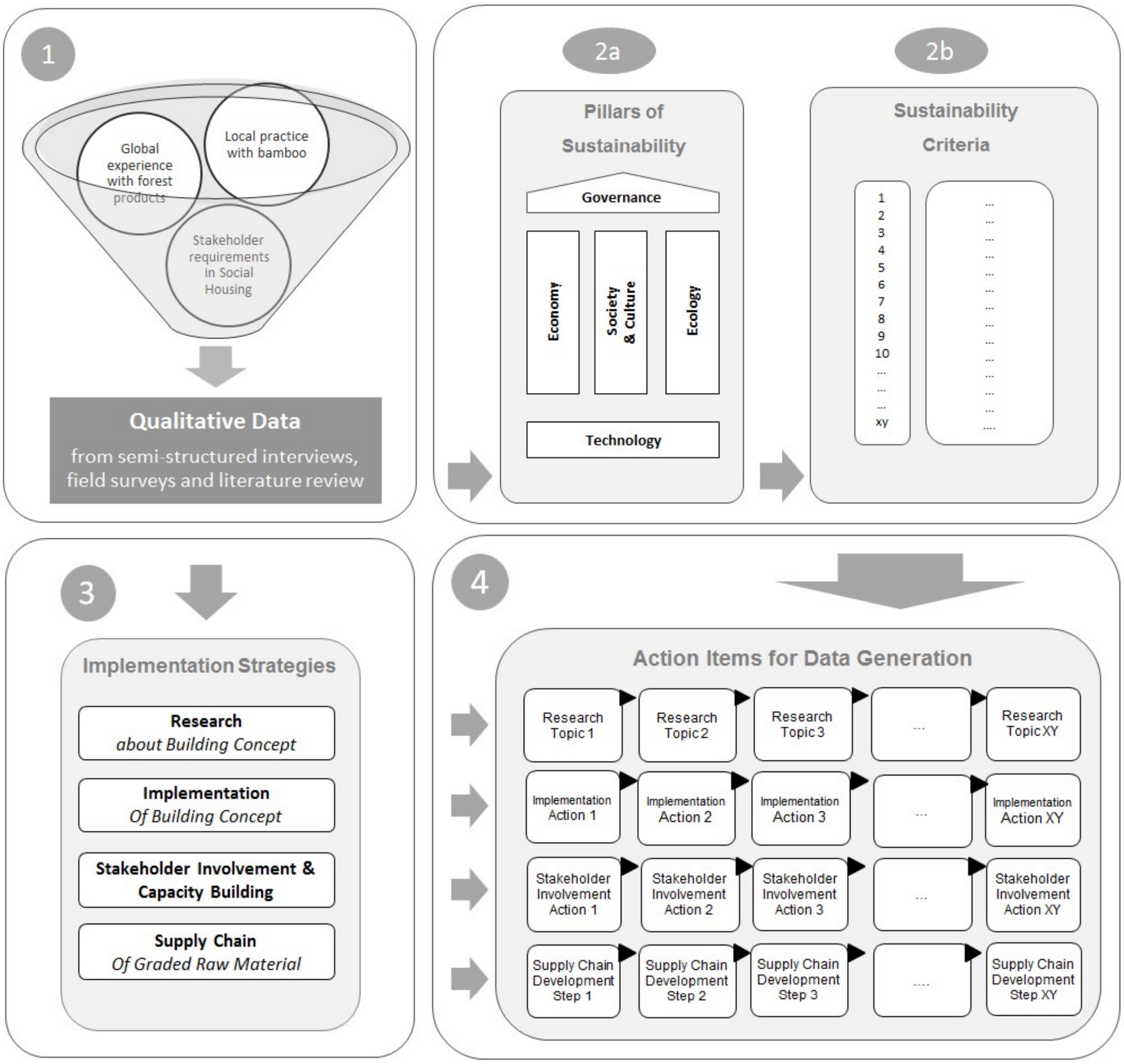



*Figure 2: Systemic approach to identify of roadmap for technology development*

In the following more detail is provided about the PhD relevant research strategy. Through a systematic assessment from micro to macro scale, the PhD analyzes whether a building concept can be developed performing in the five dimensions of holistic sustainability. A comprehensive technical understanding from material- over system- to building-scale, allows evaluating compliance of a previously none-defined forest product with the requirements of an urban built environment. By ensuring that all compared technologies are able to satisfy legal standards and building codes for permanent houses, a direct comparison with existing conventional solutions is enabled. A visualization of the different layers of research can be found in Figure 3.

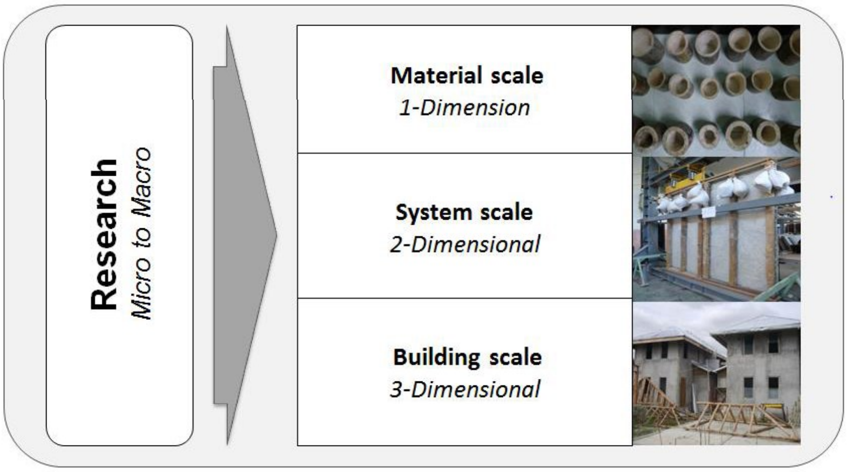



*Figure 3: Systemic research of the PhD from micro to macro angle*

An interpretation of the material, system and building scale within the given context is provided, giving reference to the identified sustainability criteria and methods applied.

**Material-Scale:** Research contains selection and strength grading of bamboo species, which ensures technical performance, cost advantage, and sustainable supply. Through field and literature study potential species is identified. Similar to the field of timber engineering, a strength grading of bamboo culms is carried out to understand the material characteristics and possible methods of utilization. Since no international standard on bamboo strength grading exists, biologic, geometric and mechanical characteristics are defined for it. The results guide engineers in the structural design of houses.

**System-Scale:** In order to maximize the raw material strength as well as to cope with its weaknesses, critical elements for technical performance are structural connections. Connections have to satisfy cost and maintenance criteria, as well as skill demand, modularization, and implementation pace. Further, the resistance of the building system to fire impact and lateral forces is tested on system level to ensure durable performance.

**Building-Scale:** Building-Scale contains testing the building response on three-dimensional model houses. In full scale typhoon tests, the predicted laboratory performance is confirmed under real life conditions. Further, indoor thermal comfort of houses is tested, as mentioned it was mentioned in field surveys to be an important criterion. Transparently evaluating the environmental impact of the structures compared to conventional solutions is captured in Life Cycle Impact Assessment.

All results on material, system, and building scale enable the formulation of a concept for the legal approval of the building method in the Philippines. In Figure 4 the research roadmap is visualized.

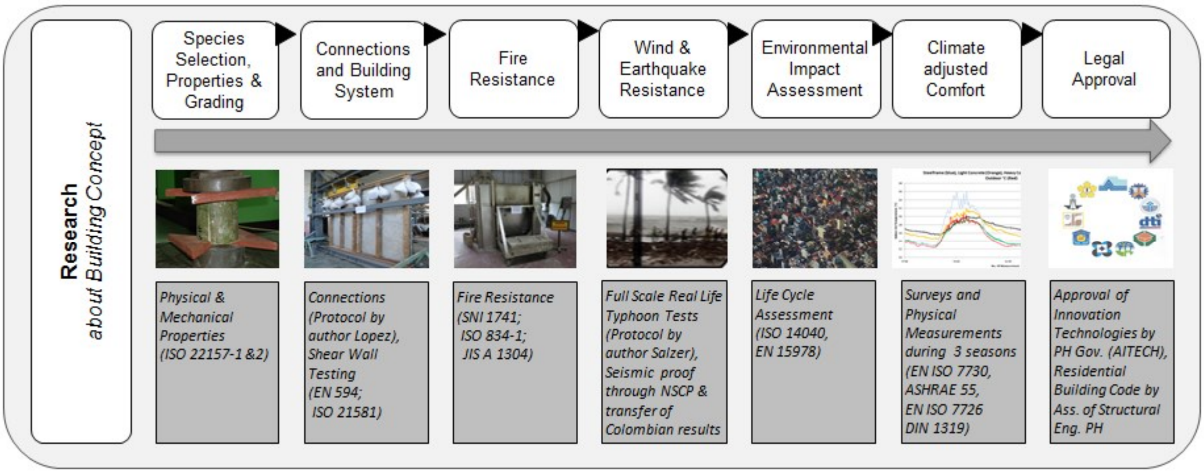



*Figure 4: Systemic approach on PhD research: technical and environmental research fields*

For the Licentiate, selected research results will be presented. These are species selection and properties, fire resistance, Environmental Impact Assessment and legal approval. The graphical visualization of Figure 5 summarizes the contribution of the Licentiate. By the end of the PhD, above research roadmap is targeted to be completed.

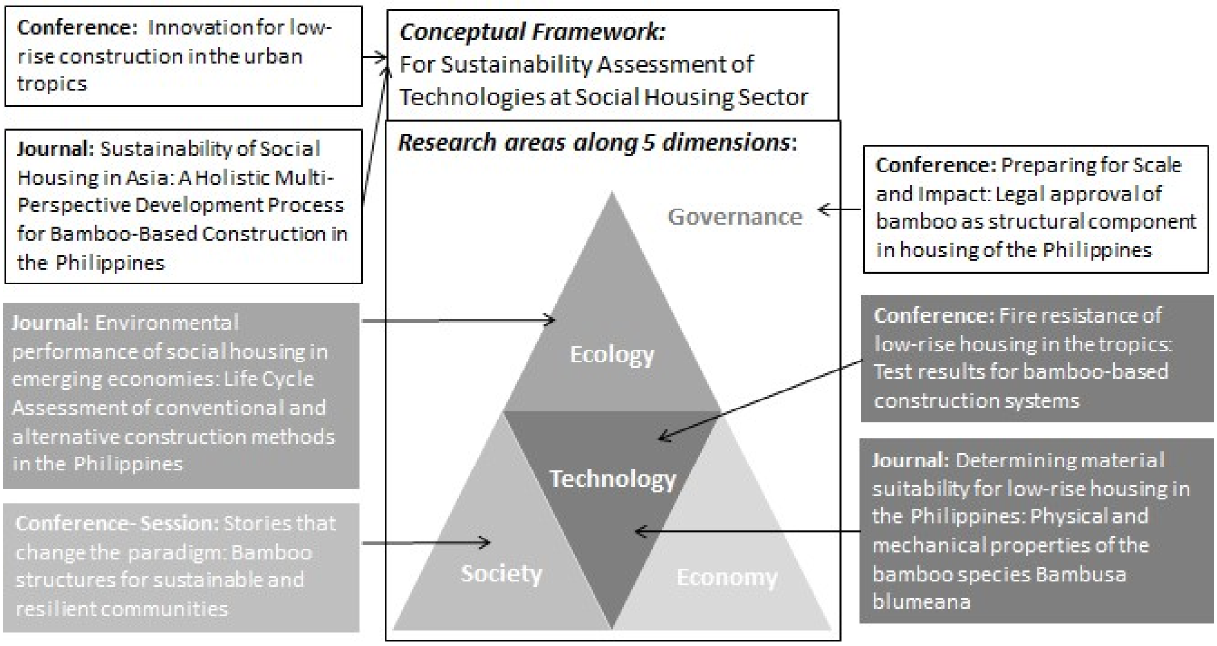



*Figure 5: Overview: Licentiate Contributions*

## 2.2 Specific Part: Methods of selected research contributions

There is a significant potential in using bio resources for the construction of low rise housing in tropical climates. Out of the seven research fields described in the research roadmap to explore this potential, four selected contributions form part of the Licentiate achievements and are described below in more detail. Methods across the specific contributions range from literature study, material testing in laboratory, to calculation with and without simulation software. Material scale testing was conducted with the raw material round bamboo. Fire resistance was tested on system scale. On building scale, environmental impact assessment and the framework for a legal approval as building concepts are introduced. For each of the research topics, specific one-dimensional quantitative testing methods are identified to generate data with scientific validity as well as local and financial applicability for the given context.

### 2.2.1 Species Selection and Properties

This contribution is of technical nature and looks at material scale.

The selection of a suitable bamboo species is a first critical step in assessing the technical suitability for cost-efficient buildings. According to the criteria availability, current utilization and affordability, a bamboo species is selected for further exploration of its technical properties. A comprehensive understanding of the selected organic raw material is needed consecutively, in order to permit an application as load bearing structural member in compliance with urban rules and regulations for construction. Therefore the research looks at the determination of physical and mechanical properties, following ISO 22157 and ISO 22156 on physical and mechanical properties and structural design with bamboo [29]–[31]. The physical properties assessed were shrinkage, relative density and moisture content. The characteristic mechanical strength tested were Compression ($f_{c,o,k}$), Tension ($f_{t,o,k}$), Shear ($f_{v,k}$) and Bending ($f_{m,k}$) as well as a Modulus of Elasticity (MOE). Characteristic strength values are calculated based on the test results. The research concludes with recommended design values, obtained based on the concept of [29], [32]. Testing was conducted at the Forest Products Research and Development Institute in Laguna, Los Banos, Philippines [33] together with local researchers. The identified properties enable a strength grading, based on mechanical, geometric, and biologic criteria, which is subject for introduction on PhD level.

### 2.2.2 Fire Resistance of bamboo-based housing in the tropics

This contribution is of technical nature and looks at system scale.

Similar to timber engineering, a predictable fire resistance is a requirement for the legal approval and application of bamboo-based building concepts at scale. The research assesses fire resistance of a selected construction system, as described in detail in the legal approval document, using structural bamboo as developed in Asia-Pacific and Latin America. Tests were conducted according to the *National Standard of Indonesia SNI 1741: Testing method of fire resistance for structural components in houses and buildings* [34], which is referring to *ISO 834-1 Fire resistance tests - Elements of building construction* [35] and *JIS A 1304: Methods of fire resistance test for structural parts of buildings* [36]. SNI adopted the temperature curve of ISO, as documented in Figure 6.

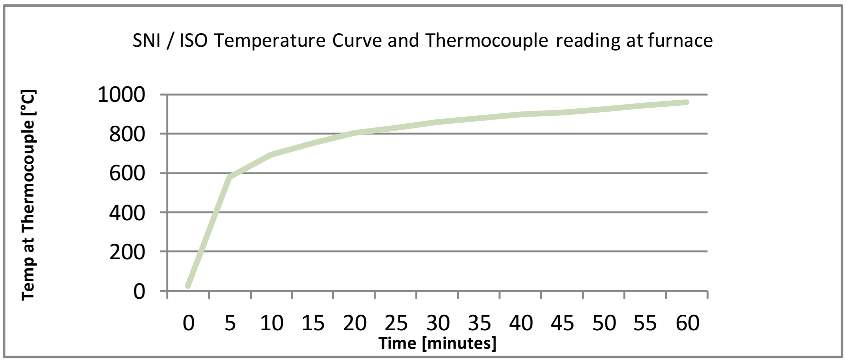



*Figure 6: Temperature Curve for Fire testing of SNI 1741 / ISO 834-1*

Due to the unavailability of a test stand in the Philippines, it was deemed acceptable to test with a different structural bamboo of similar geometric characteristic and chemical composition, since the focus of this testing was to prove performance as system response, not of round bamboo alone. The specimens for testing used the bamboo species *Gigantochloa Apus*, available and common in Java, Indonesia. Java, the island of Indonesia with the largest population of approximately 145 million inhabitants [7] is an attractive housing market too. The bamboo species was chosen because of its structural characteristics, its affordability and availability in Java. *Gigantochloa Apus* has a typical diameter of 80-100mm and a minimum wall thickness of 8-12mm in the structurally deployed part of the bamboo pole, and is therefore comparable to *B. blumeana* in the Philippines.

Bamboo wall cross-sections were tested with specimens of 1050mm by 1050mm and evaluated according to insulation, integrity and mechanical resistance criteria, as required for elements with separating and load-bearing function. In Figure 7 and Picture 5, the specimen specification, a picture of the fabricated specimen as well as the furnace for testing, are shown. Through configuration testing, the following variables and their effect on the performance of the wall system were evaluated: (1) Effect of fire retardant on round bamboo, (2) Anchor options to fix protective cover in bamboo, (3) Type of plaster carrier, (4) Plaster thickness, (5) Plaster composition, (6) Usage of additives in plaster, and (7) Existence of one or two layers of the protective cover. For norm testing only the variables 3 and 7 were varied according to Table 2 below.

*Table 2: Summary of specimen for fire resistance testing*

| No | Plaster carrier | Cover |
|---|---|---|
| 1 | Type A: Organic | One layer |
| 2 | Type B: Metallic | |
| 3 | Type A: Organic | Two layers |
| 4 | Type B: Metallic | |

The other variables were fixed with the following explanation:

- Plaster thickness: The cement plaster acts as fire protection material. Its thickness is critical for the protection time and was designed according to protective function needed to maintain a minimum allowable bamboo cross section after 60 minutes of fire exposure. The failure time of protection is assumed through simplified factor of 1.4 multiplied with the thickness in mm as suggested in [32]. To balance protective function with dead weight of the plaster, a 25mm plaster was applied.

- Given the social housing context, in which a most conservative, affordable and simple specimen configuration is required to reflect the affordability criteria, the following as decided:
- Plaster composition: A standard plaster mixture was chosen without use of additives.
- No fire retardant on round bamboo: The surface treatment of bamboo has indicated positive effects, but requires more in-depth studies including economic effects.
- Standard anchors: To fix the cover in the structural bamboo, common nails were used. Special screws or anchors were excluded.

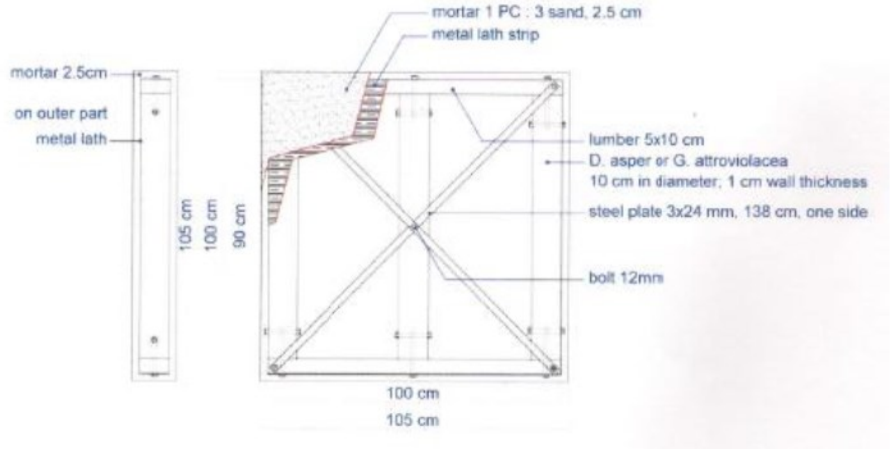



*Figure 7: Constructive Details for specimen with metallic plaster carrier*

Testing was conducted at the *Research and Development Center for Housing and Settlements* in Bandung / Java, Indonesia [37].

*Picture 5: Specimen installation and furnace at* [37]

## 2.2.3 Environmental Impact Assessment

This contribution is of ecologic nature and looks at building scale.

The informal construction sector is a major service provider for the construction of affordable housing. In line with the formal sector, the environmental impact of this building stock is relevant globally, particularly in emerging economies [18]. Life cycle thinking is not yet established, however [38]. The research examines the environmental performance of "as-built" low-cost housing for an example of the Philippines, and the potential to reduce its environmental impact through the use of three alternative construction materials: plastered bamboo, soil-cement blocks, and coconut boards. The additional alternative technologies are captured only for this research, to provide a wider angle towards ecologic potentials in the field of building methods. A Life Cycle perspective on the savings ensures that these benefits are not only measured up to the construction of the houses, but throughout its life cycle on Cradle to Grave perspective.

Through an inventory analysis all mass and energy flows throughout the lifespan of a functional equivalent (FE) are accumulated, with the FE being a typical one-story social housing unit with a 25-m$^2$ floor plan as displayed in Figure 8.

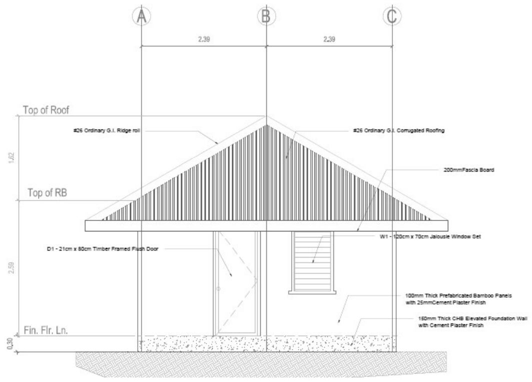



*Figure 8: Visualization of the Building Envelope: 1 story house (FE), 25m$^2$, 25a service life*

Life cycle assessment models are implemented and evaluated with the software SimaPro, using the single-impact indicators global warming potential (GWP), from the International Panel for Climate Change (IPCC), and cumulative energy demand (CED). The latter provides a good general indication of LCA results [39]. The first, is one of the most frequently used single impact indicator and retrieves savings of $CO_2$ equivalents [11]. Both indicators are recommended by [40]. Results are presented according to the Life Cycle Phases defined in EN 15978, stated for Phases A-B-C-D and with boundary conditions defined as Base Case. Figure 9 summarizes for which Phases empirical data or scenarios were applied.

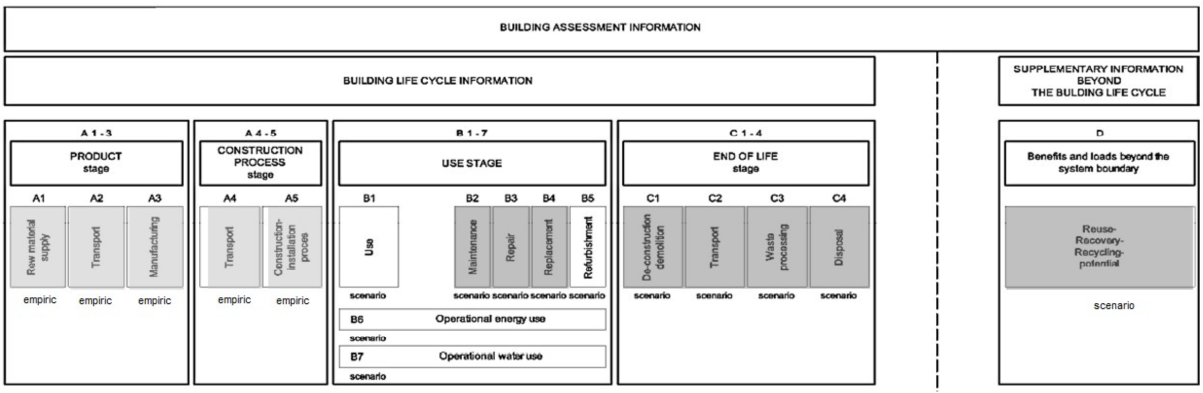



*Figure 9: Life Cycle Phases according to* [40]*: light- empirically validated, dark- scenarios*

The Phases B1 and B5-B7 are excluded from the assessment with reasons being the following: Emissions captured during Phase B1 are neither for well-studied exemplary projects nor for social housing documented and should be studied for future inclusion. Refurbishment (B5) was excluded as unlikely in the informal context. The effect of changes in indoor comfort and associated energy use in Phases B6 and water use in B7 has yet to be quantified and understood in detail, and was therefore omitted at this point in time of the assessment. Theoretical models for Phases A1-A5 are verified with three years of empirical data from construction projects. Phase B, C and D scenarios capture the realities of an emerging economy, through inputs of intensive field research and expert interviews.

### 2.2.4 Legal Approval for bamboo-based construction methods

This contribution is of governance nature and looks at building scale.
To implement a building code for bamboo-based construction in the Philippines and to carry out advocacy on policy level and in professional organizations, are objectives for the Governance dimension. It will enhance nation wide acceptance by academe, governments, communities in need of housing, and the private sector. In the following the method for formulation of the draft building code is described. The drafted code is named: *Philippine Provisions for cement-bamboo frame houses of one and two stories* being discussed as additional chapter to the *National Structural Code of the Philippines (NSCP), Volume 3: Housing* [41]. The design provisions recommended in the draft document are based on the results of the research roadmap and will be reviewed by the Association of Structural Engineers of the Philippines (ASEP) and responsible government institutions. The structure of the document is based on *NSCP*, and Chapter E and G of the *Colombian Code for Seismic Resistant Residential Buildings (NSR-10 2010)* [42]. Author rights of NSR-10 belong to the *Asociación Colombiana de Ingeniería Sísmica (AIS).* Its utilization for the purpose of adaptation to the Philippines was granted for the draft formulation. The document contains further provisions of *Peruvian Technical Norm NSR-1 (E.100)* from the *Ministry of Housing, Construction and Sanitation of Perú (MHCS)* [43].

## 2.3 Supporting Part: Methods of the accompanying implementation project

The housing challenge has multiple dimensions, from technical and environmental covered through the research of the PhD, to social, political, and economic. It was therefore seen essential to cover the latter three dimensions in the accompanying implementation project Base [19]. Although the activities of the implementation project are mentioned in the Method Section, results will only be included on PhD level for a holistic assessment. Below, the objectives and methods of the implementation project are described, differentiated in (1) Supply Chain, (2) Stakeholder Participation and Capacity Building and (3) Implementation of Construction Projects.

### 2.3.1 Supply Chain

Objectives and methods in the Supply Chain activities of the implementation project are described below:

- To create positive social impacts through local value chains from farmers up to construction workers, which create income, skills and jobs. On the other hand, ethical dimensions are also to ensure minimum standards for workers on farms and construction sites (work ergonomics, working hours, salary, safety, social services etc.), and to be specifically careful with the treatment of bamboo against insects in compliance with safety and environmental standards in this field.
- To ensure sustainability of bamboo supply at scale. It is actively advocated, that only harvesting practices are carried out which do not thread biodiversity or cause a land competition with food production. The ecological availability is being assessed to not deplete stands and create scarcity.
- To establish a supply chain producing quality bamboo of structural grade. This includes selection, quality control, pre-processing and treatment and the logistic concept for sourcing and distribution to construction projects.

In summary of Figure 10, the implementation project distinguishes between the following supply related activities:

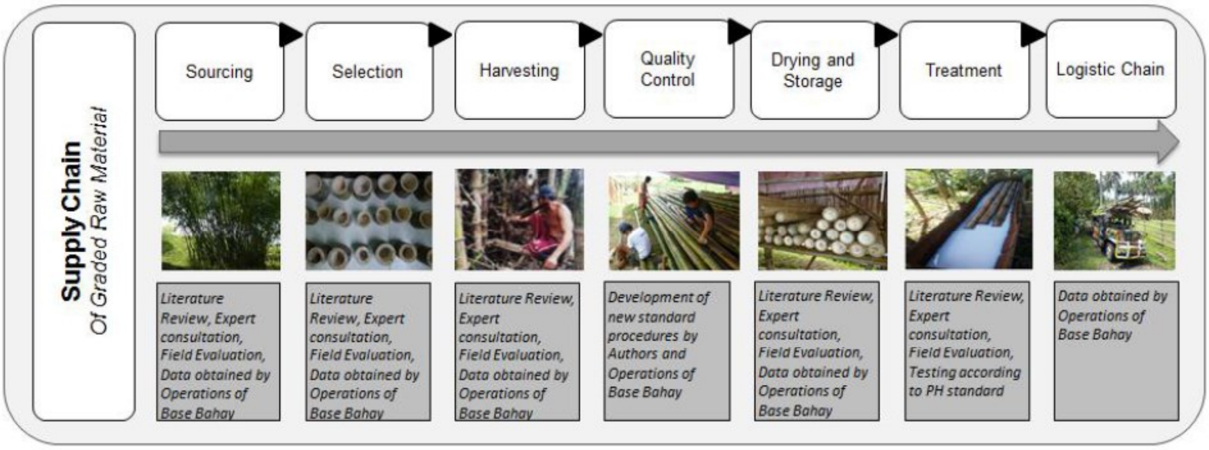



*Figure 10: Systemic approach of implementation project: supply chain development*

### 2.3.2 Stakeholder participation and capacity building

Objectives and methods in the field of people's involvement and skill development of the implementation project are described below:

- To formulate Sustainability Assessment Criteria, for guidance of the technical development, which capture the needs and requirements of stakeholders of urban social housing: from informal settlers themselves, to governments, loan providers, international organizations, professional organizations, academe and further. In addition, to incorporate learnings from current use of the raw material and uses of forest products for housing from around the globe. The concept of putting needs of informal settlers and further relevant stakeholders into the center of the technical development is central to the PhD.
- To develop people-centered houses, ensuring involvement in the development of the product: from participatory design, over skills trainings and demonstration houses to post occupation surveys and customer acceptance tests. Such involvement will create identification with the final product.
- To revive cultural heritage with a traditional material in a modern context of application. The Philippines being a country that has encountered several occupations, foreign status symbols dominate the local market. Working with an ancient, local material and supporting its outperformance, is observed to have positive impact on the local perception. Incorporating, where possible, local practices in bamboo handling, is one component to create ownership.
- To provide a better living standard. Houses are to be more adequate for the well-being of people. Adequacy being defined as more safe, durable, comfortable, and affordable. These aspects will directly or indirectly have a positive influence on the development of the inhabitants' lives.

In summary of Figure 11, the implementation project distinguishes between the following stakeholder related activities:

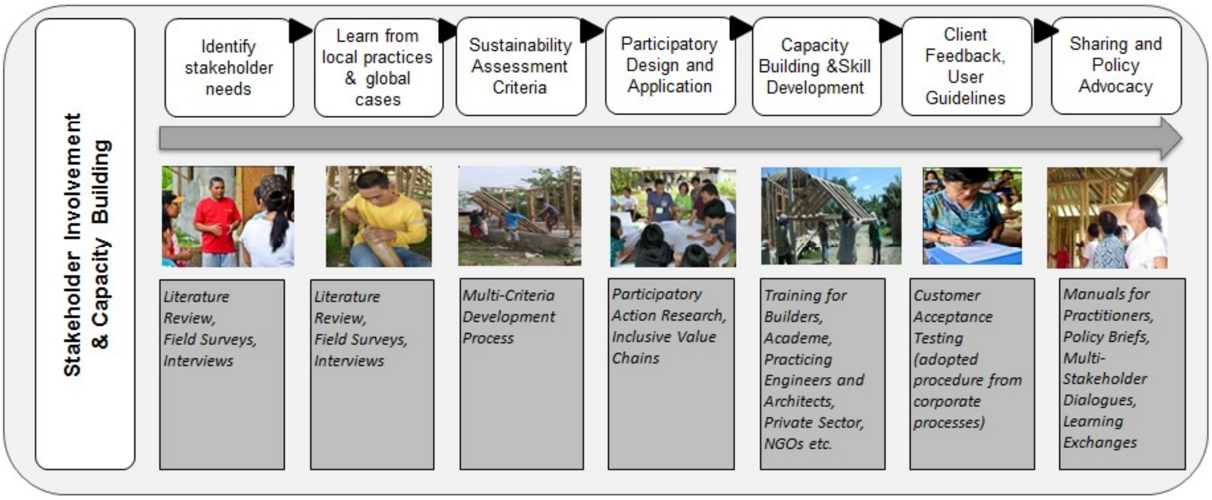



*Figure 11: Systemic approach of implementation project: involvement & capacity building*

### 2.3.3 Implementation of construction projects

Objectives and methods in the field of construction projects of the implementation project are described below:

- To develop social business models which enable more people access to adequate houses due to reduced construction costs and customized loan schemes.
- To maintain an open source and sharing policy ensuring spread of knowledge to all interested people, whether with or without financial means.
- To shape an implementation strategy allowing scale and robust quality: Quality control for robust technical performance, ease of application and skill development, construction speed & scalability through prefabrication as well as continuous innovation are components of such. For the application in the given context, the concept of Prefabrication was chosen. It stands in contrast to the traditional construction practices, where individual skilled community builders guide teams to a performing result. Latter is the dominating method in the bamboo sector, both in the Philippines and around the globe. The ethical explanation behind the need for quality control and prefabrication is that performance needs to be ensured when people take-up once-in-a-life-loans to purchase houses. Given the climatic context of the Philippines, with immense sunshine and strong seasonal rainfalls or winds, it is of value to reduce construction time to a minimum and with that exposure of humans to the elements. Pictures 5-7 provide an example of a pre-fabricated bamboo frame house with the assembled load bearing structure on the left, one prefabricated frame in the middle in two stages of finishing and a fully finished house on the right side. In addition, ease of construction and needed skills have been important elements for the iterative implementation and optimization process. The construction with prefabricated frames reduces the skills needed on construction site and transfers them into the production hall, where capacity can be built for. Expanding skills of bamboo craftsmen contributes to preserving selected traditional skills, while transforming them where needed to a recognized knowhow of today`s industry. Lastly, the technology development stands at the beginning. Continuous innovation, incorporating ideas of all participating stakeholders, is an asset to optimize in iterations over time.
- To provide easily available technical support for post-occupation services. Latter was deemed important to ensure long term durability and with that sustainability.

*Picture 6: Modern bamboo-based housing built in Iloilo, Region IV in 2015 by* [19], [27]

In summary of Figure 12, the implementation project names the following construction project related activities:

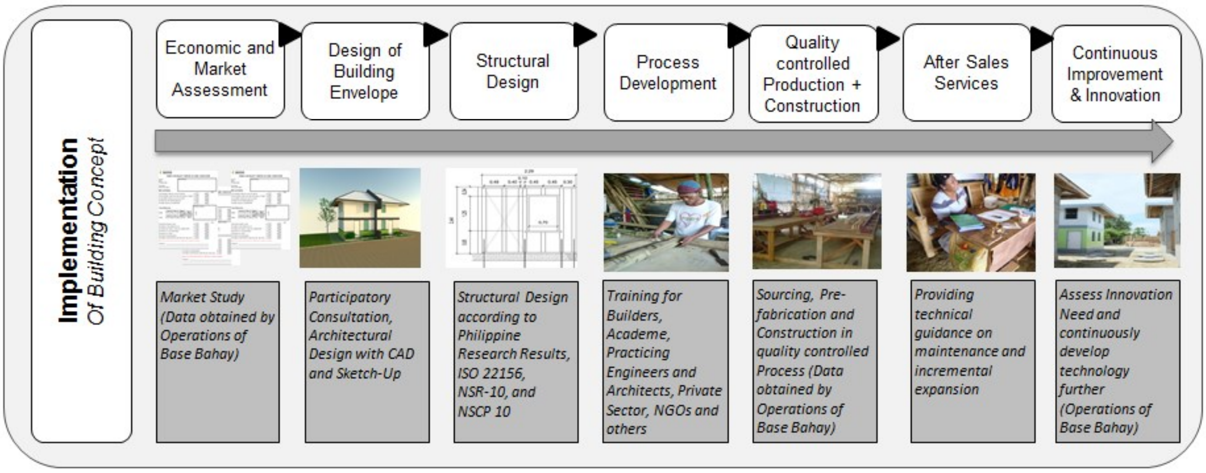



*Figure 12: Systemic approach of implementation project: construction projects*

# 3 Results

This chapter compiles selected research results, being named on the research roadmap and obtained during the Licentiate. The following research items have been selected: Species selection and properties, fire resistance, Environmental Impact Assessment and legal approval for building methods. The contributions to the PhD go along with outputs on actual construction, supply chain and stakeholder involvement of an implementation project. Results of latter will be presented at PhD level and contribute to a five-dimensional holistic impact assessment.

## 3.1 Species Selection and Properties

The chapter summarizes the species selection and the physical and mechanical properties obtained from testing one bamboo species.

SPECIES SELECTION

A crucial step is the selection of a bamboo species for construction. Globally, more than 1200 bamboo species are recorded. On a country level, the Philippines Forestry Sector identifies around 62 different species [44]. A short-list of nine economically relevant species was identified for the Philippines [45], as stated in Table 3.

*Table 3: Economically relevant bamboo species in the Philippines* [45]

| **Latin Name** | **Researcher** | **Local name** |
|---|---|---|
| Bambusa blumeana | J.A. & J.H. Schultes | Kauayan-tinik |
| Bambusa vulgaris | Schrader ex. Wendland | Kauayan-kiling |
| Dendrocalamus asper | (Schultes f.) Backer ex. Heyne | Giant bamboo |
| Bambusa merrilliana or Dendrocalamus merillamus | (Elmer) Rojo & Roxa or (Elmer) Elmer | Bayog |
| Gigantochloa atter | (Hassk.) Kurz | Kayali |
| Gigantochloa levis | (Blanco) Merr. | Bolo |
| Schizostachyum lima | (Blanco) Merr. | Anos |
| Schizostachyum lumampao | (Blanco) Merr. | Buho |
| Bambusa philippinensis or Sphaerobambos philippinensis | (Gamble) McClure (Gamble) Dransfield | Laak |

From the list of economically important species, a highly promising species is *Bambusa blumena (B. blumeana)*. It is the most abundantly available bamboo species in the Philippines, and represents therefore a promising potential for cost-efficient buildings. Its empirical use for traditional houses and its affordability make it a bamboo species of interest to the given context [33]. *B. blumeana* is the species most widely grown throughout all regions of the Philippines. It can be found growing along river banks, hill slopes, and freshwater creeks and tolerates flooding conditions. It is commonly planted in settled areas at low and medium altitudes. Being native to Java, Indonesia, and Eastern Malaysia, it is cultivated in Southern China, Malay Peninsula, Moluccas, Philippines, Sumatra, Borneo, India and Indochina[44]. Previous scientific studies indicated that 3-4 year-old *B. blumeana* has a high relative density, compressive strength and modulus of elasticity in static bending [46]. A modification of the American Standard *ASTM D143-52 Standard Methods of Testing small clear specimens of Timber* [47] has been applied, given the absence of a global bamboo standard at the time of the study. Results from these studies are difficult to compare to other bamboo species due to a lack in uniform test procedure, but provide first insights about the potential suitability of the species. The hypothesis of its technical suitability is further supported through the identified traditional use for vernacular buildings [48]. Although no commercial unit prices exist for bamboo in the Philippines, an evidence of *B. blumeana`s* affordability is that until today a high share of low income groups use it for their temporary housing [19], [49].

PHYSICAL PROPTERTIES

The geometric dimensions of the tested bamboo culms are basis for the physical and mechanical properties and therefore summarized in Table 4.

*Table 4: Geometric Characteristics of Test Specimen*

| **Height** | **Test Specimen – Region IV** | |
|---|---|---|
| | **Diameter [mm]** | **Wall Thickness [mm]** |
| Butt | 78 – 104<br>∅ 94.0 | 19 – 27<br>∅ 24.0 |
| Middle | 81.3 – 109.2<br>∅ 91.2 | 7.6 – 14<br>∅ 10.0 |
| Top | 70.6 – 96.5<br>∅ 80.9 | 6.2 – 7.6<br>∅ 7.0 |

The physical property measurements and an ANOVA assessment have proven a significant trend for *Moisture Content* decrease from the butt to the top. *Relative density* significantly increases from butt to top with an average density of 570 kg/m$^3$. *Shrinkage* of the culm wall thickness from green to oven-dry condition was 6.61, 8.81 and 4.01% at the butt, middle and top, respectively. The shrinkage at wall thickness was higher than of the circumference with 6.33 to 5.13%. Shrinkage longitudinal was minimal, with approximately 0.5% at butt and middle and 0.2% at the top of the test culm. Table 5 summarizes the Physical properties of *B. blumeana*.

*Table 5: Physical properties of B. blumeana*

| **Physical Properties** | **Height** | **Test Specimen – Region IV** | |
|---|---|---|---|
| | | **Mean Value** | **Range of Values** |
| Moisture Content | Butt | 97.55 | 74.17 - 121.47 |
| (%) | Middle | 75.44 | 60.76 - 92.19 |
| | Top | 62.14 | 36.89 - 84.23 |
| | ∅ | *78.38* | |
| Relative Density | Butt | 0.517 | 0.423 - 0.607 |
| | Middle | 0.559 | 0.440 - 0.639 |
| | Top | 0.634 | 0.500 - 0.766 |
| | ∅ | 0.57 | |
| Shrinkage Wall | Butt | 6.16 | 2.52 - 10.29 |
| Thickness (%) | Middle | 8.81 | 3.31 - 19.82 |
| | Top | 4.01 | 0.88 - 8.98 |
| | ∅ | *6.33* | |
| Shrinkage Outside Diameter (mm) | Butt | 3.56 | 2.40 – 4.97 |
| | Middle | 6.59 | 3.78 – 19.82 |
| | Top | 5.24 | 4.25 – 6.32 |
| | ∅ | *5.13* | |
| Shrinkage Length (mm) | Butt | 0.546 | 0.138 -1.737 |
| | Middle | 0.516 | 0.080 - 0.947 |
| | Top | 0.193 | 0.042 - 0.600 |
| | ∅ | *0.418* | |

MECHANICAL PROPERTIES

The *compressive and tension strength* along the grain and *Modulus of Rupture* increases from butt to top of the culm, along with the increase of density towards the top. Latter explains the increase in strength [50], [51]. The characteristic compressive strength is in the range of softwood species. The obtained *bending strength* values are characteristically high and underline bamboos remarkable flexibility. The *shear strength* slightly increases towards the top, while no significant difference between middle and butt were observed. Latter holds true both for specimen with nodes and internodes. The existence of a node does not increase the shear strength, but showed lower results. The internode *tensile strength* significantly increases from butt to top while in the node the increase is not significant. Tensile strength at the node was lower than the internode. The lower values on shear and tensile strength of *B. blumeana*

at the node can be explained with previous scientific research on other bamboo species. According to [52], fibers in a node are interrupted by crossing vessels going into the diaphragm inside the node. In [53] it is explained that the mechanical elasticity is reduced due to the shorter, thicker and forked fibers in the nodal part, thus bamboo culms under tension often break at the node. This has been confirmed in the failure modes of the tension specimen failing in the node itself. *B. blumeana*`s strength in compression along the grain, tension along the grain and bending underline the potential for construction, which was identified earlier for bamboo species from other parts of the world such as [50], [54]. Its weakness in shear strength provides guidance on connection and system design.
Table 6 shows the calculated characteristic strength based on the raw data of *B. blumeana*.

*Table 6: Calculation of Characteristic Strength Values for B. blumeana in [N/mm2]*

| | **Compressive strength parallel to the grain [N/mm$^2$]** | | | | **Tensile strength parallel to the grain [N/mm$^2$]** | | | | **Description** |
|---|---|---|---|---|---|---|---|---|---|
| | Top | Middle | Bottom | All | Top | Middle | Bottom | All | Area of the bamboo pole |
| m | 40.6 | 37.4 | 31.2 | 36.4 | 187.6 | 174.1 | 126.5 | 162.3 | Mean |
| s | 5.4 | 9.0 | 6.9 | 8.0 | 45.7 | 33.1 | 22.1 | 43.2 | Standard deviation |
| $f_{0.05}$ | 34.0 | 24.7 | 22.0 | 22.5 | 128.3 | 127.5 | 101 | 104.7 | 5% percentile |
| n | 10 | 10 | 10 | 30 | 19 | 20 | 20 | 59 | Number of samples tested |
| $f_k$ | 30.1 | 19.6 | 17.8 | 20.0 | 108.9 | 112.9 | 90.3 | 95 | Characteristic strength |

| | **Bending Strength MOR [N/mm$^2$]** | | | | **Modulus of Elasticity (Bending) MOE [N/mm$^2$]** | | | | **Description** |
|---|---|---|---|---|---|---|---|---|---|
| | Top | Middle | Bottom | All | Top | Middle | Bottom | All | Area of the bamboo pole |
| m | 69.0 | 62.5 | 56.7 | 62.8 | 13.5 | 14.1 | 11.7 | 13.1 | Mean |
| s | 14.5 | 19.9 | 16.1 | 17.2 | 3.7 | 4.3 | 2.0 | 3.5 | Standard deviation |
| $f_{0.05}$ | 52.5 | 39.9 | 39.9 | 39.9 | 8.6 | 7.7 | 9.1 | 8.6 | 5% percentile |
| n | 10 | 10 | 10 | 30 | 10 | 10 | 10 | 30 | Number of samples tested |
| $f_k$ | 43.1 | 29.1 | 30.2 | 34.1 | 6.5 | 5.7 | 7.7 | 7.4 | Characteristic strength |

| | **Shear strength parallel to the grain [N/mm$^2$]** | | | | | | | **Description** |
|---|---|---|---|---|---|---|---|---|
| | Top | | Middle | | Bottom | | All | Area of the bamboo pole |
| | node | Inter-node | node | Inter-node | node | Inter-node | | |
| m | 8.8 | 9.4 | 7.4 | 8.1 | 7.1 | 6.9 | 7.9 | Mean |
| s | 1.6 | 1.7 | 1.9 | 1.5 | 0.8 | 1.1 | 1.7 | Standard deviation |
| $f_{0.05}$ | 6.8 | 7.2 | 5.4 | 6.0 | 6.1 | 5.5 | 5.5 | 5% percentile |
| n | 10 | 10 | 10 | 10 | 10 | 10 | 60 | Number of samples tested |
| $f_k$ | 5.8 | 6.1 | 4.2 | 5.1 | 5.4 | 4.7 | 5.1 | Characteristic strength |

In the left column of *Table 7*, the characteristic strength values for B. blumeana bamboo are stated as obtained from the testing, in the right column recommended permissible stresses are written. In line with the limit state design principle, permissible stresses for using B. blumeana bamboo in low-rise construction in the Philippines were derived by dividing with safety factors. Given the natural variability of bamboo, conservative safety factors are recommended. A conservative safety factor of 4.5 is taken into account for permanent loads, which is in line with ISO 22156 [29] and conservative compared to Eurocode 5 [32]. Latter can be reduced for loads of short durations.

*Table 7: Summary Characteristic Strength and Permissible Stresses for B. blumeana*

| **Property** | **Characteristic Strength** | | **Permissible Stress** | |
|---|---|---|---|---|
| | **Symbol** | **Value (MPa)** | **Symbol** | **Value (MPa)** |
| Compression strength parallel to grain | $f_{c,0,k}$ | 20 | $f_{c,0,adm}$ | 8.0 |
| Bending strength | $f_{m,k}$ | 34.6 | $f_{m,adm}$ | 7.7 |
| Shear strength | $f_{v,k}$ | 5 | $f_{v,adm}$ | 1.1 |
| Tension strength parallel to grain | $f_{t,0,k}$ | 95 | $f_{t,0,adm}$ | 21 |
| Modulus of Elasticity – Mean | $E_{mean}$ | 13100 | $E_{mean}$ | 13100 |
| Modulus of Elasticity – 5$^{th}$ percentile | $E_{0,05}$ | 8600 | $E_{min}$ | 8600 |
| Density - Mean | $\rho_{mean}$ | 570kg/m$^3$ | $\rho_{mean}$ | 570kg/m$^3$ |

## 3.2 Fire Resistance of bamboo-based housing in the tropics

The results obtained after one-hour fire impact and documented according to the categories Insulation (I), Integrity (E) and Mechanical Resistance (R).

*Insulation (I):* Figure 13 displays the temperature increase over time on the unexposed side of the construction. All tested specimens received an insulation fire rating of 60 minutes. Maximum reading of a thermocouple at the fire unexposed side was 80°C after 60 minutes, with other thermocouples ranging from 50°C upwards depending on the thermocouple location. 80°C is clearly below maximum allowable temperatures according to norm of 140°C (average) and 180°C (max). Graph x shows the maximum and minimum thermocouple reading for specimen ID1 (organic plaster carrier) and ID2 (metallic plaster carrier). Specimen ID1 had an additional insulating effect compared to ID2 as well as a less rapid temperature rise due to the insulating effect of the organic plaster carrier. Given that both specimens performed sufficient, insulation was not deemed a critical variable for the wall system.

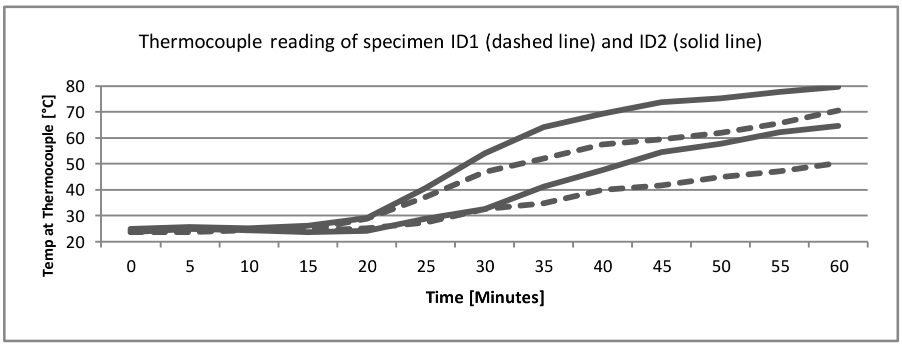



*Figure 13: Min / Max thermocouple reading of specimen with two types of plaster carrier*

Performance of specimens ID3/4 was more conservative in comparison to ID1/2 in regards of their insulation properties. Temperature readings increased more rapid and already after

10 minutes of testing, while ID1/2 specimens only showed temperature rise after 20 minutes. A maximum temperature of 100°C after 60 minutes was obtained. Since the results for ID3/4 specimens remained in allowable temperature range, it was assessed uncritical provided that the specimen with one layer protection is exposed to fire from its protected side. The behaviour of specimen ID1/3 is displayed in Figure 14.

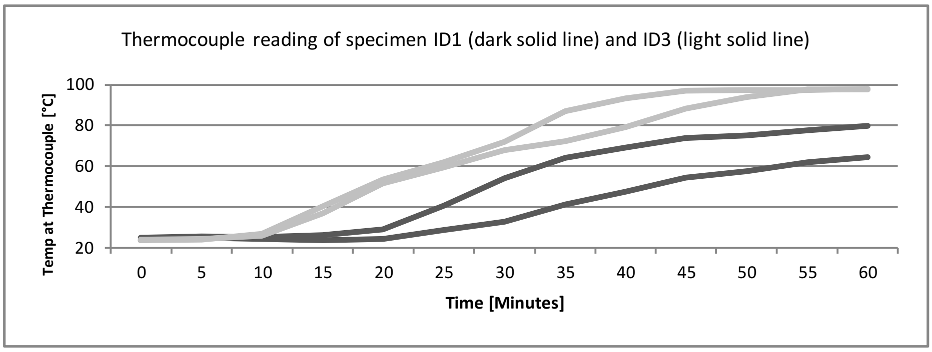
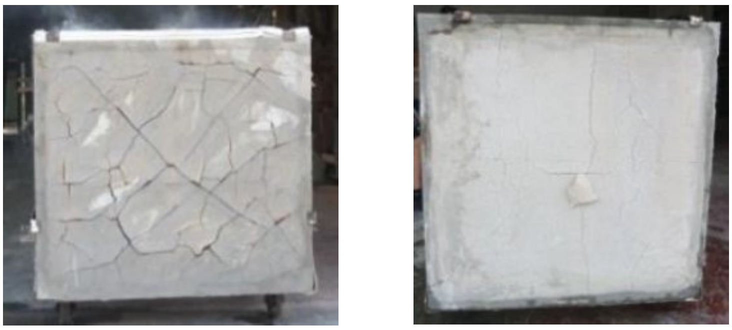



*Figure 14: Test reading of thermocouples of selected specimen during testing*

*Integrity (E):* The integrity of all specimens was maintained during the period of testing. No flame-spread on the fire unexposed side occurred, neither for specimen ID1/2 nor for ID3/4. An assessment of the fire-exposed and unexposed surfaces during and after the testing indicated however a different behaviour between ID1/3 and ID2/4 respectively. Under impact of fire, the specimen ID1/3 encountered strong cracking and partial flaking of plaster portions. The occurrence of wider cracks at the fire exposed surface increased the risk of linear heat peaks. Both effects were significantly reduced with specimens ID2/4. The visual assessment of the crack pattern and crack width indicated less cohesion between the organic plaster carrier and its plaster cover. Picture 7 show left specimen ID1 and right specimen ID2. The appearance of cracks was also observed during the testing from the fire unexposed side of the specimen, as shown in Picture 8.



*Picture 7: Assessment of Surface Integrity after testing, left: organic, middle: metallic*

*Picture 8: ID3 specimen with organic plaster carrier during test (right)*

For the specimen ID3/4, where structural bamboos are unprotected at the unexposed side, the existence of a plaster layer at the unexposed side was an important feature to suppress flame spread and fulfil integrity criterion. In that way, no flame spread occurred during 60 minutes although the structural bamboo partially started to be affected by fire from the exposed side, as visualized in Figure 15.

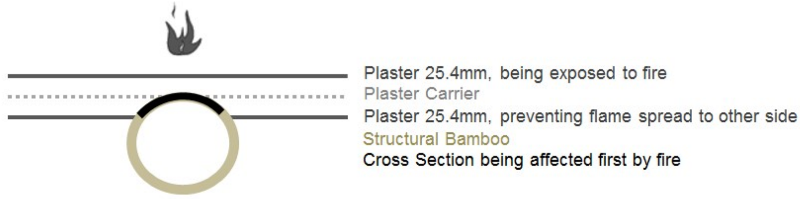



*Figure 15: Scheme showing effect of plaster layer on fire unexposed side of specimen*

Critically, it has to be mentioned that possible effects of reduced penetration depth of anchors holding the cover due to starting charring of the bamboo were less visible when testing without load and only a post testing assessment enabled its evaluation. According to [32], a minimum anchorage penetration of 10mm is required for timber structures. If this requirement is followed for bamboo with a typical bamboo wall thickness of 10mm, any kind of charring would be equal to a failure, although structural capacity would allow for a reduced cross section.

*Mechanical Resistance (R):* Since the test stand at [37] did not provide testing under load, the mechanical resistance was assessed through determination of the effective cross section of bamboo after 60 minutes fire exposure as shown in Picture 9 and Picture 10. Testing under load is recommended as described in the respective standards. Although different levels of charring were identified for specimen ID1/2 from no charring to punctual, linear or regional charring of up to 5mm, the load bearing capacity of bamboo poles after fire impact remained sufficient according to the criterion $E_d < R_d$. Classifications of charring degrees and calculations of the respective effective cross-sections as well as corresponding compression test results are provided.

*Picture 9: Removal of protective cover to assess bamboo cross-section after fire (left)*

*Picture 10: Classification of charring degree on structural bamboo after fire (right)*

To be highlighted are that the increased organic matter of specimen ID1/3 caused longer smoldering periods and enabled higher flame spread across the wall than specimen ID2/4. Both characteristics are a critical risk factor for the mechanical resistance of the wall assembly and favour specimen ID2 over ID1. For specimen ID1/2 a second layer of 25mm plaster enhances the compartmentation, however, since structural bamboo in the wall center starts charring after the failure time of layer one, the second layer acts only for fire protection from both sides of the walls, but does not increase the protective function.

## 3.3 Environmental Impact Assessment

For the base case consideration, the coconut husk-clad house had the greatest impact reduction at 82.6%. The bamboo technology reduced the environmental impact by 74.4% and the interlocking block technology by 35.2%, compared with the conventional concrete house. The latter has served as the reference for 100% impact. In absolute terms this relates to a reduction of 10.3, 9.3, and 4.4t $CO_2$ eq. respectively. Figure 16 shows the result for GWP.

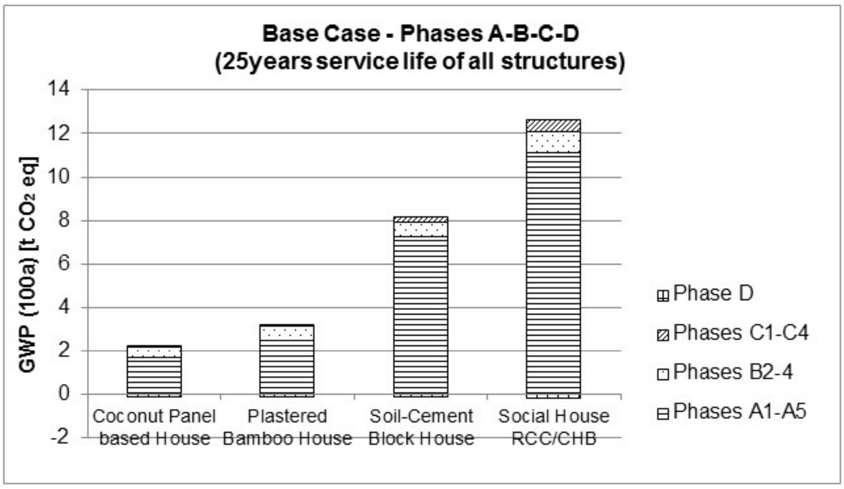



*Figure 16: Comparison of construction technologies in Phases A-B-C-D, GWP (100 years)*

The major impact is caused by Modules A1-A5 with 79%–90% across the technologies. The impact of Phases B2–4 contributed 7%–21% to the overall impact on the houses. The major contributed resulted from maintaining conventional material components, both for alternative and conventional building envelopes (roof sheets and plaster finish). The use phase contribution is considerably smaller than for LCAs in western countries, but excludes Phase B6 which is main contributor of large impacts in advanced construction projects. Given a lack of data for Phases B1, B6 and B7, this topic is subject to further research, as recommended in the future research section, and was not included in the assessment. Research on the demolition and waste scenarios for the formal construction sector states, that its relevance lies at 4–10% of the overall LCA impact [55], [56]. In this assessment the impact share of Phase C was lower with 1.8–4.5%. Module D ranges from -0.5–-1.6% of the overall life cycle impact per technology. The dominance of Phases A can be explained since operational energy use did not contribute and in-country recycling of concrete or steel, biogenic carbon credits, and heat recovery for organic matter was found to be not available in the Philippines. The bamboo base case represents the construction method introduced as Type 3. The results for that type are complemented by the Type 1 and Type 2 bamboo building concepts. Figure 17 shows that all construction methods for the three bamboo house had a similar range of environmental impact reduction compared to conventional concrete houses. A difference of -19%, -21% exists, comparing Type 1 and 2 with base case of Type 3.

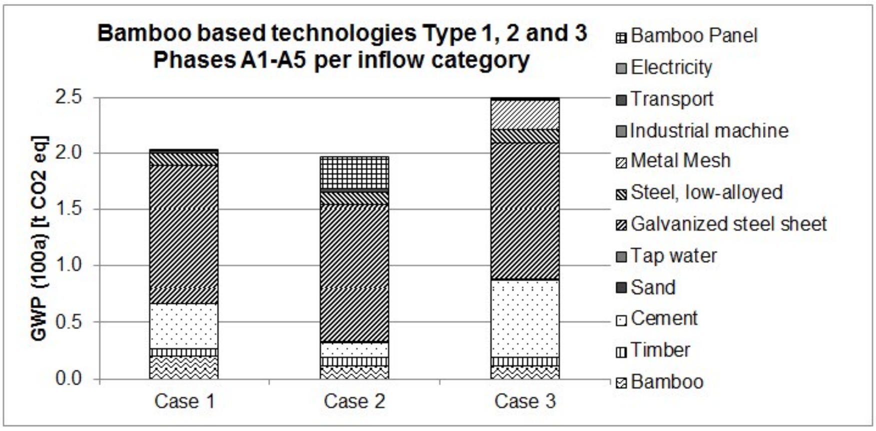



*Figure 17: Bamboo House Types per inflow category, Phases A1-A5, GWP (100 years)*

To verify the general validity of results obtained with use of the single-impact indicator GWP (100-year horizon), two indicators were added, i.e., CED and the multi-impact indicator IMPACT2002+ as shown in Figure 18. The application of these indicators, as shown below, generally validated the magnitude of environmental reduction with maximum variations of below 12% across the indicators. The CED showed slightly stronger impacts for the alternative construction methods coconut panel with a difference of +8.0% from GWP to CED and +6.5% from CED to IMPACT2002+ for the plastered bamboo technology. The soil-cement technology was evaluated -11.2% with CED compared to GWP.

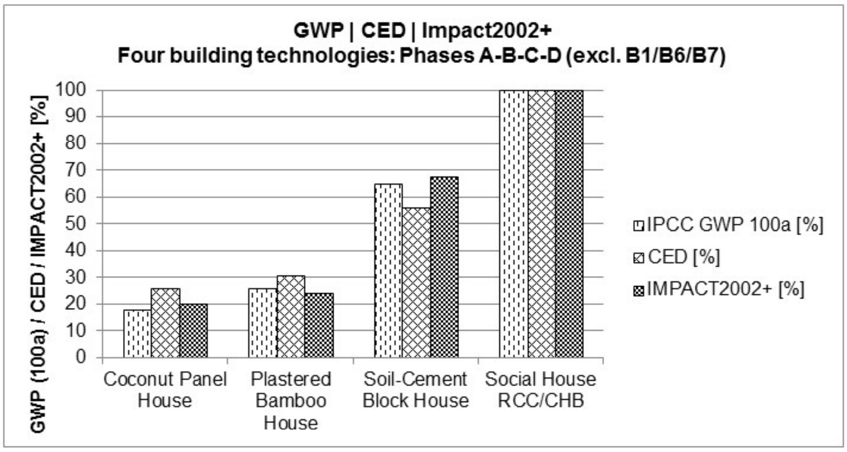



*Figure 18: Comparison Phases A-B-C-D, GWP (100 years) | CED | Impact2002+ in [%]*

To understand the relative contributions of individual inflows, accumulated impacts were broken down into inflow categories. Based on study of the supply, production and construction processes, scenarios A1–A5 were formulated and their influences on overall accumulated impact assessed. *Twenty sensitivity analyses* were performed for the three alternative building technologies at the A1–A5 level. All sensitivities were grouped into scenarios of the minimum and maximum environmental contribution per building technology. Figure 19 presents results of these scenarios compared with the initial base case. The environmental reductions of bamboo houses varied from 73-87%, soil-cement houses from 27-47%, and coir houses from 80-83%. The obtained ranges showed that even in the low performance cases, the alternative technologies remain reducing the environmental impact.

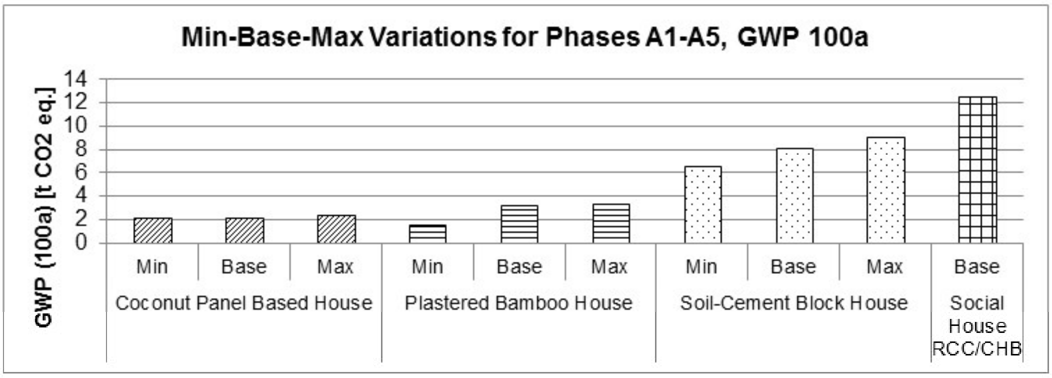



*Figure 19: Comparison Min | Base Case | Max technologies, Phases A1-A5, GWP (100a)*

Based on the above insights, the base case assumptions are believed to have low uncertainty. However, it guides future improvements effectively: For example, the roofing material galvanized iron contributed 41%–46% to bamboo structures. A change to concrete shingles, would reduce the environmental impact as much as 10%, is however not applied in the Philippines.

The effect of the building *lifespan* was studied in two scenarios, keeping the RSP at 25 years. The results are visualized in Figure 20. In scenario one (10 years for all alternatives, 25 years for conventional), environmental impact of the bamboo technology was 55% of a social house made of concrete, while the soil-cement block house was already 53% exceeding the conventional solution. The comparative advantage for plastered bamboo was greatly reduced in scenario two, at only 16.2% (10 years for bio-based structures, 40 years for block-based). The same ecological performance was obtained for bamboo buildings with a life span of 10 years and concrete buildings of 50 years at RSP 25 years.

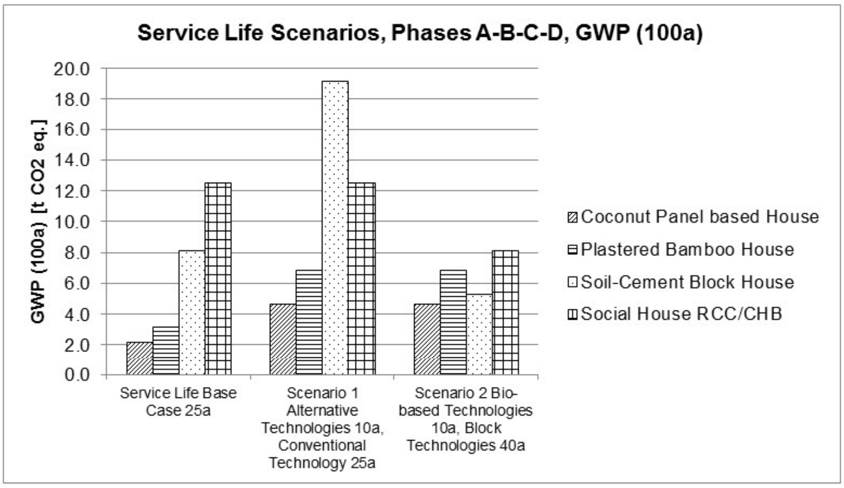



*Figure 20: Scenarios: Service life of houses, Phases A-B-C-D, GWP (100 years)*

## 3.4 Legal Approval for bamboo-based construction methods

The results chapter introduces the table of content for the draft building code, the construction system of the cement-bamboo frame system, and a selected concept of the calculation method, being minimum length of shear walls, is introduced. For more detail it is referred to the draft building code. The table of content is displayed in Table 8 below.

*Table 8: Table of Content- Philippine Provisions for cement-bamboo frame technology*

SECTION 101 GENERAL REQUIREMENTS

101.1 Introduction

101.2 Scope

SECTION 102 DEFINITIONS

102.1 Definitions

SECTION 103 MATERIALS

103.1 Bamboo

103.2 Flattened bamboo

103.3 Wood

103.4 Mortar Plaster

103.5 Masonry

103.6 Concrete

103.7 Reinforcement steel

103.8 Metal mesh

103.9 Metal flat bar

SECTION 104 CONSTRUCTION SYSTEM

104.1 General

104.2 Shear frames

104.3 Exterior and interior wall cover

104.4 Structural System for resistance of lateral loads

SECTION 105 BASIC CRITERIA OF STRUCTURAL DESIGN

105.1 Distribution of structural walls

105.2 Symmetry

105.3 Structural integrity

105.4 Expansion with other building materials

105.5 Seismic gaps for shared walls

105.6 Weight of the structure

SECTION 106 FOUNDATIONS

106.1 General provisions

106.2 Foundation details

SECTION 107 PLASTERED BAMBOO FRAME WALLS

107.1 Components of the walls

107.2 Classification of wall types

107.3 Length of walls in each direction

SECTION 108 BAMBOO COLUMNS

108.1 General provisions

108.2 Location and design of columns

108.3 Allowable loads for bamboo columns

108.4 Assembled columns using multiple bamboo poles

SECTION 109 HORIZONTAL DEAPHRAGMS

109.1 General provisions

109.2 Wooden intermediate floor

109.3 Bamboo intermediate floor

109.4 Balconies and cantilever elements

SECTION 110 ROOF STRUCTURE

110.1 Components of the roof

110.2 Roof loads

110.3 Wooden roof structure

110.4 Bamboo roof structure

SECTION 111 CONNECTIONS

111.1 General provisions

111.2 Types of bamboo cuts for connections

111.3 Types of connections according to the fastener

111.4 Types of connections according to the structural function

SECTION 112 ANNEX A- PROCESS FOR SIMPLIFIED STRUCTURAL DESIGN OF SHEAR WALL HOUSES OF ONE AND TWO STORIES

112.1 Scope

112.2 Method of design

112.3 Minimum design loads

112.5 Wind force

112.6 Seismic force

112.4 Fundamental period of the house

112.6 Force distribution

112.7 Shear strength of the frames

112.8 Symmetry

112.9 Overturning

SECTION 113 ANNEX B- DESIGN EXAMPLE

## *Construction System and Structural Mechanism*

The plastered bamboo frames are a constructive system of two general components: a shear resisting frame and the cover or wall plaster. Both parts are combined to a structural system.

All components of the system can be seen in Figure 21.

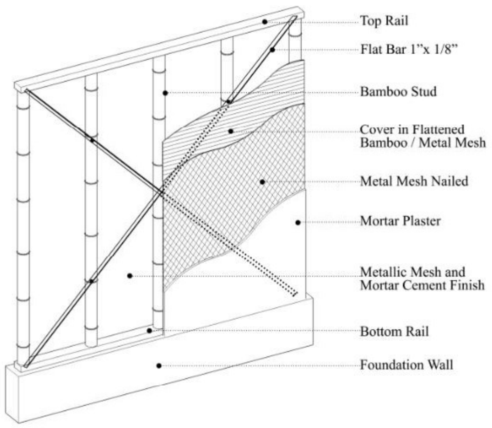



*Figure 21: Plastered cement-bamboo frame system based on* [19], [43]

The frame is made of bamboo, a combination of bamboo and wood or bamboo, wood and metal flat bars. The framework contains two horizontal rails, a bottom rail and a top rail, and studs or vertical elements, connected to the horizontal elements with nails or threaded rods. The outer frame, defined by the bottom and top rails and two external studs, can be built entirely with bamboo or sawn wood. The rest of the frame is generally made from bamboo. The frame has braces to resist to lateral forces.

The cover of the frame is made from two main components: (1) A plaster carrier and (2) the actual plaster. As plaster carrier either a chicken wire nailed to flattened bamboo or on wood sheathing or an expanded metal mesh is used. The plaster carrier must be anchored to the studs. For rib lath mesh nails are sufficient. For flattened bamboo and chicken wire, additional soft iron wire is used braided between the nails.

The individual walls are transferring vertical and lateral loads and provide a combined action through being anchored in diaphragms in their bottom and top. The resistance of the structure is achieved through the following mechanisms:

(a) Sufficient structural walls in both axis of the floor plan to provide resistance against horizontal seismic and wind loads, taking the longitudinal stiffness of each wall into account. Structural walls serve to transfer their own gravity forces, resist the lateral forces parallel to their own plane and vertical forces from the level where forces are generated to the foundation. Structural walls must be designed following the provisions stated.

(b) A diaphragm system (foundation, intermediate floor or roof) that ensures the combined action of the structural walls and a load distribution to each wall. The connection between walls and diaphragms has to be designed according to the specifications given.

(c) A foundation system that transfers all loads from the walls into the ground. The foundation system must have an appropriate stiffness, so that differential settling is prevented. The foundation has to be designed according to the specifications stated.

## LENGTH OF WALLS IN EACH DIRECTION

A minimum length of load bearing walls in both axis of the floor plan is required to ensure the intended system resistance. To provide a uniform distribution of the load transfer to resist forces in the inelastic range, the structural walls in each direction should comply with the conditions below:

The minimum length of walls in each direction must satisfy *Equation 1*:

*Equation 1: Minimum length of walls in each direction*

$$L_i \geq C_B * A_p$$

Where:

$L_i$ = *Minimum length of the sum of all walls w/o openings in direction i*

$C_B$ = *Coefficient for bamboo frames: larger* $C_B$*, depending on the acceleration expected at the location*

$A_p$ = *Floor plan size (in* $m^2$*) of a one story house or for the second floor of a two story house.*

$A_{p2}$ = *Floor plan size (in* $m^2$*), of a ground floor of a two story house. If the floor does not consist of heavy material like cement (the value of* $A_{p,r}$ *relates to the intermediate floor) a reduction of* $0.66*A_p$ *can be applied.*

For the calculation of Equation 1, the bamboo coefficient CB, for seismic and wind, is needed. It can be found in Table 9, calculated for Philippine design loads.

*Table 9: Coefficient CB (seismic and wind) to calculate minimum length of walls* [19], [42]

| **Seismic risk** | **Z** | **$C_{B,seismic}$** | | **Wind Zone** | **Design Wind speed (km/h)** | **$C_{B,wind}$** |
|---|---|---|---|---|---|---|
| Zone 4 | 0.40 | 0.25 | | III | 250 | 0.50 |
| Zone 2 | 0.20 | 0.16 | | II | 200 | 0.31 |
| | | | | I | 150 | 0.18 |

Note: The values of $C_{B,seismic}$ were calculated for each region described in the NSCP. Assumed are walls with plaster cover on both sides for a conservative maximum mass of the walls. The nearest fault line was assumed, being Type A with < 5km distance. The values of $C_{B,wind}$ were calculated for Terrain Roughness Type D, exposure Type D multiplied with the Importance Factor IV according to the NSCP 2010 [57].

# 4 Discussion and conclusion

This chapter develops from a discussion and conclusion about one-dimensional research results to a discussion of the overall conceptual framework developed for the Licentiate. It will end with a conclusion about the overall conceptual framework of the thesis.

## 4.1 Discussion and conclusion: selected research contributions

The specific research contributions will be discussed chapter-wise as introduced in Chapter 2. Conclusions are drawn thereafter.

### 4.1.1 Species Selection and Properties

The results of this paper provide evidence about the structural qualities of *B. blumeana* bamboo sourced from a characteristic bamboo growing region of the Philippines. The test results presented in this report are obtained by following the International Standard ISO 22157 and ISO 22156. In contrast to this, previous tests on *B. blumeana* were based on a modified ASTM standard for timber testing [12]. A direct comparison is therefore difficult. Going forward, it is recommended to apply solely ISO standard for bamboo in order to ensure comparability throughout regions, test dates and species. For the first time, a Philippine bamboo species has been characterized according to the ISO. In comparison to well-known structural bamboo species from Latin American, such as *Gudaua angustifolia Kunth* sourced in Colombia and *Guadua aculeate* sourced in Mexico, *B.blumeana* compares with approximately one third lessened performance in compression, tensile and shear strength parallel to the grain [50], [54], [58], [59]. Irrespective the difference, it classifies to be a structural bamboo for construction. The need for grading of species in their growth region is however underlined. A recommendation for permissible stresses of *B. blumeana* is made, which can serve as design variables for structural design of low-rise houses. It requires, however, that bamboo culms are being quality-controlled, mature and straight from the Philippines.

The following notes can be made in regard of the protocols of ISO22157:

- Bending: Due to the long internode distance of *B. blumeana* culms, the wooden saddle supports transferring the load from Universal Testing Machine to the bamboo when testing bending strength, caused crushing failure in some specimen. Such incorrect failure modes were consequently excluded from the assessment. Further it can be noted, that the saddles were not always located above or below a node as suggested by ISO22157. This discrepancy from the recommendation could not be avoided, given a second, more critical requirement being a symmetric load distribution onto the bamboo.
- Shear: In ISO22157 shear strength is calculated assuming the development of four shear planes. It was noted that the actual failure observed in most specimen was in one of the planes. It is recommended to conduct tests on optimized protocols for shear strength delivering failures in all tested shear planes.
- Tension perpendicular: In addition to the mechanical properties mentioned above, tension perpendicular to the grain is a rarely studied property of bamboo. It is however critical for the performance of a structure. To date, tension perpendicular is not included in the ISO 22157. Further research is recommended to form an evidence base of a testing protocol in order to include it in the standards.

### 4.1.2 Fire Resistance of bamboo-based housing in the tropics

Fire resistance is a critical requirement for building technologies using organic structural members. The research assessed the fire resistance of an alternative construction technology using shear frames made of round bamboo and timber. Due to the hollow shape and thin walls of bamboo members, the fire resistance of bamboo walls has to be obtained through a protective cover. In case of the evaluated building method, this is a cement based cladding fixed to the structure on a plaster carrier. With a target resistance of 60 minutes, the configuration of the cover was a key factor for sufficient protection of the structural members. Through experimental fire testing a recommendable system configuration was derived and relevant criteria determined, such as (1) Usage of favorable plaster composition limiting cracking and crack width on the plaster surface of walls, (2) Usage of a plaster carrier with good cohesion to plaster and minimal flame spread during fire exposure, (3) Application of plaster on fire unexposed side to avoid flame spread in case of interior bamboo exposure and (4) Anchorage system ensuring performance of protective cover in limited wall thickness of bamboo. For all specimens, insulation performance was good. For integrity performance, a metallic plaster carrier performed better than an organic one. Charring of bamboo has to be prevented completely to ensure compliance to minimum penetration depth of anchors holding the protective cover in the bamboo. For the mechanical resistance, a post-impact assessment of the mechanical resistance of bamboo poles showed that initial charring does not immediately set the load bearing capacity of the system at risk and could possibly be considered for the system performance. Given that with the available test stand, mechanical resistance could only be tested after the fire exposure, not during, further testing under load is recommended. Studies to determine necessary safety factors and reduced mechanical properties for structural bamboo are recommended too.

In addition to the active resistance of the building system, a passive protection through risk reduction is recommended for bamboo-based housing projects. Structures using round bamboo for load transfer are to be embedded in a holistic fire safety concept, including set-backs between houses, minimum requirements for safe electrical wiring, behavioural trainings for inhabitants and a general firefighting concept for settlements with a relevant share of houses made from organic matter. Such fire safety concepts have to consider realities in settlements of rapidly growing urban centers in Asia, Latin America and Africa.

### 4.1.3 Environmental Impact Assessment

The validity of Phase A (harvesting to construction) was confirmed by strong correlation between theoretical and empirical models. A range of scenarios portrayed the sensitivities of the inflows. No empirical foreground data was available for Phases B (use), C (end-of-life), and D (beyond life cycle boundaries). The theoretical assumptions in the scenarios for these phases are therefore discussed below.

- The LCA assumed that all houses, irrespective of their building technology, have a *lifespan of 25 years*. The importance of the variable service lifespans was visualized via scenarios with reduced lifespans for the alternative methods of 10, 20 and 40 years, for a fixed reference study period. It was shown that the competitive advantage is strongly reduced or even turned into a disadvantage, when the alternative technologies have a shorter lifespan. The relevance of the results is therefore limited to the advanced building methods introduced herein, not to raw material use in general.

- In EN16485 carbon neutrality is discussed for biogenic products modelled in LCA. It is argued that bamboo has special growth characteristics, which justify the carbon neutrality assumption: In the Philippines, bamboo grows along river banks and sloping land, not attractive for agricultural use or land development. Philippine Government noted this potential and promotes it for erosion control on unfertile or risky lands. Land competition and loss of biodiversity are therefore only scenarios on very large scale. Bamboo clumps have a limited natural size and poles decay after few years to allow reproduction. Therefore, poles can be harvested without reduction of existing stocks, providing farmers annual reoccurring income [60].
- The use of organic raw materials in long-lasting products raises the question of *biogenic carbon storage*, which has become a frequent topic in recent scientific publications [61]–[64]. In essence, credits are addressed for a delayed release of carbon into the atmosphere in Phase D. Although there is common sense about determining short-term and long-term emissions distinctly, there is no consensus on how to weigh such emissions [65]. In a recent scientific investigations, it was reemphasized that no adoption of "optional" carbon storage, as mentioned in [66], is recommended [67]. The IPCC GWP indicator removed consideration of biogenic $CO_2$, given the argument that emissions will re-enter the atmosphere sooner or later [68] and that crediting is not in line with [11] global mass balance and provisions of the [69], based on precaution.
- The assumption of extra carbon sequestration in additional global forest areas, as suggested in [67], is only justified when an increase in product application is likely within a stable industrial setting. Because development of a bamboo-based industry in the Philippines is connected to very uncertain variables, no land-use change assumption was included.
- No local facilities for industrial-scale heat recovery or recycling in the reference year. The LCA models were chosen to be conservative by not considering potential benefits beyond the building life cycle.

As a reflection on overall relevance of the study, IPCC scenarios support that the non-annex countries in Southeast Asia have the greatest predictions of emissions growth in the building sector, followed by Latin America and Africa [11]. In 2015, the Philippines submitted targets for its Intended Nationally Determined Contribution to the United Nations. By the year 2030, a $CO_2$ reduction of 70% is intended. Such ambitious targets can only be achieved by addressing the building sector, having the greatest low-cost GHG mitigation potential, irrespective of world region [70]. Measures to reduce its impact have therefore strong national relevance. The research context suggests considering ecological building concepts for low-rise urban housing development as a target segment. Indications show that the social housing sector constitutes a substantial share of national construction activities in emerging economies. In-depth assessments of the social housing sector, and the segment to which the technologies applies within, are recommended to consider the country-specific building situation and its development.

The present research evaluated the environmental performance of a typical building for low-income groups, compared to selected alternative construction methods. An assessment of large scale system change of building stocks has not been examined in detail. With 40% of the urban population in both the Philippines and the general Asia-Pacific region being low-income groups in need of housing [7], [10], the advocacy of life cycle thinking is important for achieving a more sustainable, inclusive urban development at city, country, and regional scale. Its success will depend on sustainable supply chains, policy advocacy, and multi-stakeholder dialogues such as in [71]. The latter have to be carried out in an inclusive manner, adding stakeholders and decision makers from key sectors in emerging countries, such as governments, academia, the private sector, NGOs, and informal settlers.

These results must be seen in light of technical, economic and social dimensions, because factors such as lifespan are of critical importance to obtained performance. Because durability of buildings is a key consideration in life cycle thinking, validity of the present research is limited to elaborate alternative building methods as the ones selected.

### 4.1.4 Legal Approval for bamboo-based construction methods

*Philippine Provisions for cement bamboo frame houses of one and two stories* have been formulated as a first draft to contribute a chapter to the *National Structural Code Volume (NSCP) 3: Housing.* Technical research results for one Philippine bamboo species, and requirements for designing houses the Philippines as stated in NSCP, have been incorporated in the Colombian Building Code layout. Since norming is a time intensive process with several professional and government institutions involved, there is no guarantee for an inclusion of a bamboo chapter in near future. However, technical requirements are fulfilled and formulations are drafted to showcase the potential path of development. A continuous high level policy dialogue with respective institutions in the Philippines has to follow for social and institutional acceptance.

## 4.2 Discussion and conclusion: conceptual framework and overall methodology

On global scale, there is an intriguing correlation between rapidly growing urban centres and the availability of alternative raw materials such as bamboo. The general objective of the PhD is therefore to assess the potential of bamboo to be used for sustainable, social housing, at the example of the emerging economy, the Philippines. A holistic sustainability assessment is targeted through performance measurement along of five sustainability dimensions: ecology, economy, society, technology and governance. In addition to the classical three dimensions, technical measurements were added due to the assessment of a technical product. Further governance was added due to its relevance for actual implementation in the context of development.

In the focus of the Licentiate was the definition of a roadmap for the development of the technology according to sustainability criteria and the generation of selected technical and ecological research results along this roadmap. Fifteen context-specific Sustainability Assessment Criteria were identified through processing of qualitative stakeholder data in selected sampling strategies. Thereafter, a roadmap was derived, describing a multi-perspective development process, being distinguished into research and implementation activities. Four out of seven strategic fields of research that were named on the roadmap got presented with their methods and results in this Licentiate. The research results presented are a step towards considering round bamboo based building concepts as a reliable and sustainable construction solution. The roadmap guides further research activities for the PhD. In addition, results of an accompanying implementation project will be incorporated for the PhD, which add the economic, social and governance dimensions. Gathering the research and implementation results will enable multi-dimensional, holistic performance assessment of the alternative building technology as suggested by Multi-Criteria Decision Making theory. With that, the PhD provides guidance for decision-makers on whether or not to change current systems from a consumer-, policy-maker, or construction-professional viewpoint. It brings attention to an unexplored, highly relevant research field: sustainable and resilient building for low-income dwellers in rapidly growing urban centers in Asia, Latin America, and Africa.

# 5 Future research

Future research demand is stated to deepen the research findings of the specific part of the Licentiate. In addition, several scientifically relevant fields of activity on the roadmap are highlighted, which will be looked-at in the course of the PhD.

## 5.1 Research to deepen specific Licentiate contributions

In the following, additional research within the specific research fields tackled for the Licentiate are provided.

### 5.1.1 Species Selection and Properties

The Licentiate research covers the testing of one available structural species named *Bambusa Blumeana*. Testing additional bamboo species, similar to the knowledge gathered on different wood species, will support to further strengthen the utilization of bamboo for construction. In addition it will enhance flexibility of sourcing through tapping into additional suppliers.

A strength grading based on the obtained properties, plus geometric and biologic requirements will be added in the course of the PhD.

### 5.1.2 Fire Resistance Testing of bamboo-based housing in the tropics

Since research about the fire resistance of bamboo-based housing is a rarely touched field, the thesis highlights fields for further scientific attention:

- Deepen the assessment of the stability criteria for specimens: Through testing at facilities with ability to test under load or a systematic assessment of bamboo cross sections and load bearing capacities, leading to the formulation of modification factors for mechanical properties and partial safety factors for bamboo in fire.
- Design of anchorage systems for effective fixture of protective cover onto the shear wall frames during fire impact. Further, detailing of connections against fire between wall to roof, wall to intermediate floor, fire walls between housing units etc.
- Material level studies for ignition time and charring rates, as variables for the performance of combined systems.
- Assessment of the smoke spread of bamboo and bamboo based houses.
- Assessing the transferability of research results across bamboo species of structural grade as well as varying growth regions to increase significance of the research findings. Latter includes a comprehensive review of building standards such as Eurocode, ISO, JSP, SNI and others, to understand comparability of test results, where needed.
- Research on more building systems, larger structures and/or settlement level.

### 5.1.3 Environmental Impact Assessment

It is worthwhile to reduce data uncertainty for Phases B, C and D in the social housing sector, with a prominent role for the use phase of houses. Use-phase consumption is likely to rise with an increase of low-income groups in urban areas and a substantial number of people transitioning from the lowest to greater-consuming upper-lower or lower-middle income levels. It is referred to the Chapter Thermal Comfort for more detail on this research demand.

For scale-up scenarios indicating a future change in consumer patterns, in-depth studies on the effects of *biodiversity, scarcity, and land-use changes* are recommended. The ongoing decay of a rich biodiversity in Southeast Asia requires careful consideration of any large-scale system change [72], [73]. Research has shown that the commonly used indicators in LCA that address such topics are not sufficiently comprehensive and systematic [74]–[76]. Although improved integration into LCA is becoming a focus in the field (e.g.,[77], [78], the current shortcomings regarding these aspects and the existence of more elaborate methods outside of LCA [79], [80] are recognized. The lack of such data is not unique to this paper and has been acknowledged as a major gap in LCA today [74]. It is suggested to monitor development in this field and update present LCA once an expert approach is validated and acknowledged. These indicators become more crucial when the analysed alternative technologies replace current practices at a relevant scale. We recommend following the cautious principles toward resource use in large quantities and the guidance of experts in the sector.

## 5.2 Research on additional specific research fields

Future fields of research, which will be covered until the PhD, are introduced below:

### 5.2.1 Connections and Building Systems

Building systems perform only as good as their weakest component. Having tested and understood the technical strength and weaknesses of the raw material round bamboo, it is bamboo connections and building components built with it that follow next in the systemic chain of understanding. For a strategic utilization and entry of bamboo to the low-rise building sector in the Philippines, further studies on performing, cost-efficient bamboo based construction systems and their connections needs to be carried out.

The PhD will present results on connection testing according to testing protocols developed in Colombia for the respective building code. The tests will comprehend the resistance of all typical connections existing in bamboo-based houses. Test results are a critical step towards the structural design for bamboo-based building systems using the Philippine bamboo species. Shear wall racking strength tests according to EN 584 / ISO21581 are assessed in the course of this track of the PhD. For the composition of building components, not only a mere technical consideration applies. Skills for production and installation, economic implications, robustness of the system in addition to the critical lateral strength are evaluated.

### 5.2.2 Wind Resistance

Extreme impacts such as earthquakes and typhoons occur frequently in the Philippines. They cause severe destruction in the build environment and have highest causalities among low income groups living in none-performing, substandard houses. In countries like the

Philippines, typhoons occur around 20 times per year and earthquakes happen every other year. Damage assessments after typhoon Haiyan, which had hit the Philippines in November 2013, highlighted that houses using light materials like bamboo had failed the most often. The PhD targets to show, that the observed failures were directly related to none-engineered construction methods using the raw material. The PhD will conduct research on building houses in a typhoon and seismic resilient manner. As performance benchmark was set to follow the building code requirements while staying in the economic limitations of local affordability.

### 5.2.3 Thermal comfort through climate adjusted materials and designs

In previous LCAs for buildings, it was found that the *use phase of the houses* is vital from a life cycle perspective contributing with 70-90% to the overall balance [81]–[83]. However, LCAs seldom capture ordinary building stock, but rather focus more on “exemplary” buildings with building-integrated technical systems [84]. Through advanced modelling of the use phase of buildings, it was shown that for more energy-efficient buildings, Phases resource extraction to construction, gain importance and the use-phase contribution decreases [85]. Nevertheless, for the industrialized building sector it remains the major contributor to the overall impact. User behaviour of inhabitants at the base of the pyramid, living in naturally ventilated low-cost houses, has never been systematically assessed nor captured in LCA. It is predicted that a building’s use phase will not have the same importance over its life cycle. Factors for consideration are: (1) Service life of structures; (2) impacts of tropical climate [81]; (3) variations of user behavior, unrelated to the design of the building envelope; (4) strongly reduced technical building systems for low-cost houses. Energy use in the tropics is mostly determined by the cooling load. The latter depends on the building material, design of the building envelope, surrounding environment, and exposure to heat intake. Small volumetric houses with metal roofing and without insulation, as analyzed in the PhD, have substantial heat intake during the day. Higher thermal mass of structures causes higher nighttime temperatures within them. Construction costs of conventional solutions offer fewer opportunities for climate-adjusted design of the building envelope. Air conditioning is mostly unaffordable for the studied low-income settlements, albeit socially attractive. Possibly, the user behaviour is not influenced by the type of building envelope or indoor comfort, but rather limited by poverty. The effect of increased indoor comfort has yet to be quantified and understood in detail, and was therefore omitted in the initial Environmental Impact Assessment. Since it is deemed a critical component for ecology, society, and economy, the PhD will cover an assessment of the use-phase energy consumption and thermal comfort in social housing.

## 5.3 Research on accompanying implementation project

The research of this thesis is supported by an accompanying implementation project named Base [19] goes hand-in-hand to the PhD. By the end of the PhD, results produced by Base will be considered for inclusion in the holistic sustainability assessment. These inputs are essential to cover economic, social and governance dimensions. Among others, objectives and methods of Base are introduced in Chapter 2.3. They are differentiated in (1) Supply Chain, (2) Stakeholder Participation and Capacity Building and (3) Implementation of Construction Projects. Although indicators used for measuring the output of Base are still in formation, among others, the indicators could be cost per square meter built up area, life cycle costing, and money spent in building local markets as economic indicators; skills and jobs created, participatory design and customer acceptance test of houses in the society field, and high level policy advocacy for legal approval and climate change mitigation through green building interventions for social housing as milestones in the field of governance.

## 5.4 Research on holistic sustainability assessment

Multi-Criteria Decision Making (MCDM) is recognized and described as one possible *concept for decision making in the field of sustainable development*, which can be applied by the end of the PhD. It is commonly applied to compare technologies of several disciplines, such as natural resource management [86], biofuel [87], farming [88], transportation [89], energy and reviews of energy sector applications [90], [91] solid waste management [17] or public investment [92]. In [93], over 400 MCDM techniques and applications, published within two decades, were compared. Engineering was ranked the most common field of application. In the field of civil engineering, it was applied for building materials [94], housing related choices [95]–[97], or renovation choices [98]. The inclusion of stakeholder perspectives, as implemented in this PhD, was piloted in combination to using MCDM [99].

A majority of the product related studies cited above, compared technologies that are already established on the market [98]. For the PhD, five dimensions of sustainability are named according to which the raw material potential bamboo is developed and assessed as solution for the social housing context in the Philippines. In the Licentiate, selected one-dimensional technical and environmental results were generated. In the course of the PhD, further research results will be generated and outputs of the implementation project on economic, social and governance dimension added. The sum of all five dimensions will enable comparing the alternative building method holistically to current conventional practices.

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# 7 Annex

The Annex contains all papers in the order specified in the List of Publications.