

THESIS FOR THE DEGREE OF DOCTOR OF PHILOSOPHY

Sustainability of Social Housing in the Urban Tropics

A Holistic Development Process for Bamboo-Based Construction

CORINNA SALZER

Department of Architecture and Civil Engineering

CHALMERS UNIVERSITY OF TECHNOLOGY

Gothenburg, Sweden 2018

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Thesis / Department of Architecture and Civil Engineering, Chalmers University of Technology
Thesis Series Number 4435
ISSN 0346-718X
ISBN: 978-91-7597-754-6

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Cover: Installation of roof frame on a residential building, Iloilo, the Philippines.
Photo: Corinna Salzer

Printed by
Chalmers Reproservice
Gothenburg, Sweden 2018

SUSTAINABILITY OF SOCIAL HOUSING IN THE URBAN TROPICS

Thesis for the Degree of Doctor of Philosophy

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ABSTRACT

Introduction: This thesis is motivated by a tremendous need for more inclusive, sustainable and disaster-resistant social housing in rapidly developing countries in Asia-Pacific, Latin America, and Africa. Recent policy frameworks, such as the Sustainable Development Goals and the New Urban Agenda, name the use of local raw materials as a key area for action to enable sustainable urban development. Looking at the Philippines, bamboo, an underutilized local raw material, is considered for use as a load bearing component in the social housing sector. As in many emerging economies, this sub-sector of the construction industry has a huge housing backlog, with various shortcomings in addressing needs adequately and at scale. No other sub-sector of construction illustrates social inequalities so harshly, while its economic and environmental relevance is insufficiently considered. Bamboo is an available, culturally rooted material, which is frequently used by rural and urban low-income groups in the Philippines. It is known for its environmental advantages and its affordability. However, its current use in buildings in the Philippines does not meet the regulatory, technical and social requirements of urban spaces. Among others, it is documented as the most vulnerable building material during the typhoons that affect the country annually. Thus, it has become a symbol for social of vulnerability. Based on the above, the general objective of this thesis is to guide the development, implementation, and assessment of a bamboo-based building technology for social housing in the Philippines, according to the multi-dimensional requirements of sustainability.

Methods: The conceptual framework of the thesis is aligned to the standards EN 15643 and ISO 15392 on the sustainability assessment of buildings, and its related sub-standards. An interpretation of the standards for the context of social housing in the Philippines has been achieved through a participatory process, wherein *requirements* and *indicators* were discussed by multiple stakeholder groups ranging from grassroots organizations to government. Beyond stakeholders from within the Philippines, this process included a South-South-North learning exchange between Latin America, Asia-Pacific, and Europe. This thesis then conducted issue-focused research to capture the performances according to indicator sets covering the regulatory, technical, environmental, social and economic dimensions, as specified in Table 1. Moreover, overarching governance concerns were highlighted. The indicators were used for the planning, implementation, and continuous improvement of 500 social houses across the Philippines. These were erected by the Base Foundation, an initiative supported by the Hilti Foundation. In a continuous improvement process, the achievements and learning obtained in the research and implementation were exchanged in feedback loops over a period of 4 years.

Table 1 Research and implementation areas according to the conceptual framework

Dimension	Research and implementation areas
Technical and functional	Mechanical properties of structural bamboo; connection testing; racking strength of wall elements; fire resistance of shear walls; real-life typhoon resistance of full scale houses
Regulatory and governance	Compliance with existing regulations; approval for the construction of eight settlements with 500 houses; suggestion of a section in the local structural code; policy advocacy; overarching aspects of governance
Environmental	Life Cycle Assessment (LCA) covering environmental impacts on the global warming potential, cumulative energy demand, human health, ecosystems, natural resources, and more
Social	Participatory research and implementation agendas; assessment of thermal, visual and spatial comfort; value chain approach on community resilience and disaster risk reduction; skill development schemes linking rural farmers with urban workers; social equity of sites
Economic	Compliance with the cost ceiling for social housing in the Philippines, life cycle cost assessment; economic efficiency of processes in construction and sites, economic impacts through a value chain approach that strengthens local economies

Results and Discussion: The most common bamboo species in the Philippines is of a structural grade that is suitable for low-rise house construction. A robust, flexible, yet strongly anchored medium-weight building method was derived balancing complex, and partially contradictory, multi-dimensional requirements. In combination with quality-selected, treated bamboo culms and climate-adjusted house designs, the construction of reliable and durable buildings was possible, designed to withstand the impacts of their surrounding environment. The walls received a fire resistance rating of 60 minutes through a mixed-materials approach and the protection of structural components. Full-scale test houses withstood the storm impacts of four typhoons with 120–213 km/h wind speeds. While nearby traditional bamboo structures were destroyed, the test houses withstood the winds without any structural damage and only minor maintenance efforts. The technical research results complied with local regulations, leading to legal approval for application by the Base Foundation in 2016. Based on the Colombian Building Code for Bamboo and Philippine material properties and design loads, a draft for inclusion to the National Structural Code of the Philippines was prepared and is currently under discussion by local authorities and professional organizations.

A thorough life cycle assessment showed that the building method had significant environmental advantages. Compared with conventional concrete houses in the same segment, it was predicted that the new method would result in a 74%-reduction in carbon emissions. Surveys and physical measurements confirmed that the climate-adjusted design and materials enabled a higher comfort level inside the houses. This may impact the use-phase energy consumption of the inhabitants, as energy-consuming cooling appliances received less importance in inhabitant's priority setting. Furthermore, it has the potential to influence a family's well-being through enhanced indoor safety, productivity, and recovery. Active participation was applied throughout the research and implementation activities, and despite common perceptions, acceptance barriers were overcome among involved stakeholders.

The value chain approach, wherein informal urban communities benefited from accessing more adequate housing, creates synergies with rural farmers and urban workers who in turn gained new skills and income opportunities. Using the renewable local material further strengthened local economies along the bamboo value chain. The new level of physical resistance provided by the buildings and the availability of human skills and quality raw material has the potential to positively influence the resilience of Philippine communities in the future. This value

proposition was obtained while meeting the cost ceiling for social housing as defined by the Housing and Land Use Regulatory Board of the Philippines. While the direct costs are more expensive than temporary buildings, they are more affordable than conventional buildings of the same quality. From a life cycle cost perspective, the most significant cost savings are visible in terms of an increased life span and the safety and comfort of the houses. However, this perspective is not yet established in the social housing segment and is currently subject to sensitive system barriers. Economic efficiency in construction processes and the development of local value chains show promising potential that goes beyond the housing focus. Because adequate housing is only one of many components required for sustainable cities and resilient communities, this thesis aims to contribute to holistic integrated projects and policy advocacy.

Conclusion: This thesis uses sustainability theory as a tool for decision-making in the development, implementation, and assessment of a building technology. By meeting technical and regulatory requirements, the positive performance in environmental, social, and economic dimensions can be exploited. Sustainability is shown to be a continuous, balancing process that can be used to transparently discuss and evolve a holistic value proposition. The broad concept of sustainable building has been localized to social housing in the Philippines. Learning exchanges with other countries in the urban tropics can have an impact that goes beyond the Philippines and will enable to backward integration of localized results to global frameworks for action.

Keywords: Sustainability assessment of buildings, Life cycle, Social housing, Emerging economies, Philippines, Alternative building materials and methods, Bamboo, Stakeholder participation, Climate change mitigation and adaptation, Disaster Risk Reduction

PREFACE

This thesis summarizes 4 years of research at the Chair of Sustainable Building at Chalmers University of Technology in Gothenburg, Sweden. Many thanks go to my supervising *Professor Holger Wallbaum*, the *co-authors* of the papers, my colleagues at the *Chair of Sustainable Building* and the *Chalmers Area of Advance Building Futures*. The research results were created with and used by the Base Foundation in the Philippines. I wish to convey my appreciation to the *Base Team Members*, who helped to ensure that this thesis is so closely aligned to implementation of social housing projects, allowing my research to address and contribute to the realities on the ground. Through the long-term perspective of the *Hilti Foundation*, which made this research and the operations of the Base Foundation possible through its funding, it was enabled to continuously evolve sustainability over time. For the opportunity to combine science and implementation in my work, I wish to express my highest appreciation to the Hilti Foundation.

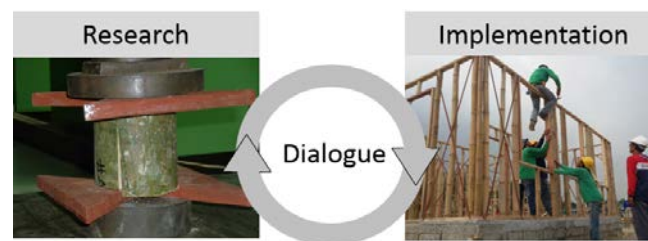


Figure 1 Research, implementation and dialogue

Moreover, this thesis and the work of the Base Foundation embraces the concept of exchange and partnership. Early on, the *United Nations Economic and Social Commission for Asia and the Pacific* shaped the holistic view on the overarching themes, and the grassroots group the *Homeless People's Federation of the Philippines* started using bamboo-based construction following a participatory process. Appreciation is also expressed to the *implementation partners of the Base Foundation*, including *grassroots organizations, farmers groups, universities, NGOs, local government, and international organizations*. They showed progressive thinking with a strong set of values, motivated to jointly begin the journey to sustainability. Beyond the Philippines, the partnership with the *Colombian Association for Earthquake Engineering* and *Bamboo Science and Innovation* helped to accelerate and triangulated processes, as well as narrowing knowledge gaps. Another essential element was the collaboration with various universities over the years, such as that with the *Forest Products Research and Development Institute of the University of the Philippines under the Department of Science and Technology in the Philippines*, the *De la Salle University*, the *Institute of Technology Bandung*, and the *Bern University of Applied Sciences*. To all of the above and further partners, I wish to explicitly convey my thanks. Fruitful exchanges, expert reflections, and interdisciplinary discussions have all shaped this thesis in some way. On a personal note, my warmest thanks go to the people in the Philippines, with their friendly, open minds and a remarkable capacity to bear and continue on among extreme conditions. I have certainly learned a lot from the *Philippine people* and I am thankful for the years spent in this country.

MARAMING SALAMAT PO!

Last, I wish to thank *my husband and son, my parents and siblings, as well as my friends* for their enduring understanding and exchanges about a topic that has been my passion number of years.

Corinna Salzer

Gothenburg, June, 2018

LIST OF PUBLICATIONS

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

Journal Papers:

- I. Salzer, C., Wallbaum, H., Lopez, L., Kouyoumji, J., (2016). Sustainability of social housing in Asia: A holistic multi-perspective development process for bamboo-based construction in the Philippines, *Sustainability*, DOI:10.3390/su8020151
- II. Salzer, C., Wallbaum, H., Ostermeyer, Y., Kono, J., (2017). 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*, DOI:10.1007/s11367-017-1362-3
- III. Salzer, C., Wallbaum, Alipon, M., Lopez, L., (2018). Determining material suitability for low-rise housing in the Philippines: Physical and mechanical properties of the bamboo species *Bambusa blumeana*, *BioResources*, DOI:10.15376/biores.13.1.346-369
- IV. Salzer, C., Wallbaum, H., (2018). From Vulnerable to Resistant- Resistance of Bamboo-based Houses in the Philippines, *Journal of Disaster Risk Reduction*, status: accepted, under peer review
- V. Salzer, C., Wallbaum, H., Goto, Y., (2018). Climate-adjusted building methods and designs for higher thermal comfort in tropical social housing of the Philippines, *Buildings and Environment*, status: submitted

Co-authored Paper:

- I. Boeger, T., Bianchi, S., Salzer, C., Pichelin, F., (2017). Binderless boards made of milled coconut husk: An analysis of the technical feasibility and process restraints, *International Wood Products Journal*, DOI: 10.1080/20426445.2017.1400756

Conferences:

- I. Salzer, C., Lopez, L., (2015). Preparing for Scale and Impact: Legal approval of bamboo as structural component in housing of the Philippines. *International Conference on Sustainable Practices in Civil Engineering SPACE*, Manila
- II. Salzer, C., Camarasa, C., (2015). Innovation for low-rise construction in the urban tropics. *Proceedings of the 8th International Forum on Urbanism on True smart and green cities*, Incheon DOI:10.3390/ifou-e012
- III. Salzer, C., Fadrigio, S., Fitrianto, A., Kim, B., (2015). Stories that change the paradigm: Bamboo structures for sustainable and resilient communities. *Keynote speech and session at the World Bamboo Congress*, Damyang.
- IV. Salzer, C., Tambunan, L., Wallbaum, H., (2016). Fire resistance of low-rise housing in the tropics: Test results for bamboo-based construction systems. *Proceedings of the World Timber Conference*, Vienna
- V. Salzer, C., Jaladoni, M., (2016) Bamboo housing for sustainable and resilient urban development. *Habitat III, co-organized session with the International Network for Bamboo and Rattan*, Quito.
- VI. Salzer, C., Lopez, L., Silisilon, F., (2016) Enhancing the resistance of bamboo houses and communities along a bamboo value chain. *Disaster Risk Preparedness Forum of CSR Asia, Published Interview in News-Letter*, Bangkok
- VII. Salzer, C. (2017). Housing as a catalyst for sustainable growth: a value chain approach, *Asia Pacific Housing Forum, Plenary*, Hong Kong.

VIII. Salzer, C., Jalandoni, M., (2017). Updates from the Ground: Implementing localized projects that contribute to the SDGs, *SDG Week of the United Nations Environmental and Social Commission*, Bangkok.

All papers with the PhD candidate as first author are written by myself with method or data assessment support or content reflection by the co-authors. The proceedings of the conferences II and IV can be found in international databases. The other conferences have local proceedings, or less scientific forms of publications, such as a published keynote speech, published interviews, session protocols, or popular science articles. Exemplary, the releases of the conferences I and III are provided in the Annex. All conferences have contributed to the dissemination of research to relevant audiences. The participation has been in both my roles for the Base Foundation and as PhD candidate.

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ABBREVIATIONS

AITECH	Accreditation of Innovative Technologies for Housing
ASEAN	Association of Southeast Asian Nations
CED	Cumulative Energy Demand
CONT.	Abbreviation for ‘continued’
CO ₂ e	Carbon dioxide equivalent
DENR	Department of Environment and Natural Resources
DOST	Department of Science and Technology
DRR	Disaster Risk Reduction
ECON	Abbreviation for the economic dimension of sustainability
EN	European Standard
ENV	Abbreviation for the environmental dimension of sustainability
ESCAP	Economic and Social Commission for Asia and the Pacific
ESL	Estimated Service Life
FSP	Fiber Saturation Point
FPRDI	Forest Products Research and Development Institute
GABC	Global Alliance for Building and Construction
GDP	Gross Domestic Product
GHGs	Greenhouse gases
GINI	Statistical measure for the income distribution within a nation
GWP	Global Warming Potential
HLURB	Housing and Land Use Regulatory Board
HPFPI	Homeless People's Federation of the Philippines
IEA	International Energy Agency
ISO	International Standards Organization
ITB	Institute of Technology Bandung
JTWC	Joint Typhoon Warning Center
kN	Kilonewton
LCA	Life Cycle Assessment
LOC	Abbreviation for localized sustainability indicators
MJ	Megajoule
MPa	Mega Pascal
NHA	National Housing Authority
NSCP	National Structural Code of the Philippines
NSR AIS	Standard of the Association of Seismic Engineers of Colombia
NUA	New Urban Agenda of UN-Habitat
PAGASA	Philippine Atmospheric, Geophysical, and Astronomical Services Administration
PHP	Philippine Peso
R&D	Research and Development
SDGs	Sustainable Development Goals
SFDRR	Sendai Framework for Disaster Risk Reduction 2015 – 2030
SHFC	Social Housing Finance Corporation
SLCA	Social Life Cycle Assessment
SLP	Service Life Planning
SOC	Abbreviation for the social dimension of sustainability
SSHWS	Saffir-Simpson Hurricane Wind Scale

STI	Science, Technology, and Innovation
UN	United Nations
UNDP	UN Development Programme
UNEP	UN Nations Environment
UNESCAP	UN Economic and Social Commission for Asia and the Pacific
UNFCCC	UN Convention on Climate Change
UN-Habitat	UN Human Settlements Programme
UNISDR	UN International Strategy for Disaster Reduction
USD	United States Dollar
WCED	World Commission on Environment and Development

“In essence, sustainable development is a process of change in which the exploitation of resources, the direction of investments, the orientation of technological development; and institutional change are all in harmony and enhance both current and future potential to meet human needs and aspirations.”

WCED (1987) ‘Our Common Future’, Article I. Paragraph 15, *World Commission on Environment and Development*

1 Sustainability of Social Housing: An Introduction

This thesis is motivated by the tremendous need for more inclusive, sustainable and disaster-resistant social housing in the rapidly developing countries within Asia-Pacific, Latin America, and Africa. Recent policy frameworks, such as the 2030 Agenda with its Sustainable Development Goals (SDGs) (UN 2030 Agenda, 2015) and the New Urban Agenda (NUA) (UN-Habitat III, 2017), name the use of local raw materials as a key area for action to ensure more sustainable urban development. Referring to the Philippines as an example, the raw material bamboo is a local raw material with potential to be applied for load-bearing applications in the social housing sector. As in many emerging economies, this sub-sector of the construction industry has a huge housing backlog, with various shortcomings in adequately addressing needs and at the necessary scale. No other sub-sector of construction visualizes social inequalities harsher, while being left out of consideration in its economic and environmental relevance. Bamboo is an available, culturally rooted material that is frequently used by rural and urban low-income groups in the country (Forest Products Research and Development Institute, 2002). It is known for its environmental advantages and its affordability. However, its current use in buildings in the Philippines does not meet the regulatory, technical and social requirements of urban spaces. In Monteverde et al (2014), it is listed as the building material most vulnerable to typhoon damages, thus, it has become a symbol for social vulnerability.

This thesis raises the research question of whether building methods can be found, that respond more appropriately to the multi-dimensional requirements of sustainability, when using the raw material bamboo as structural elements in social housing.

This introduction provides a brief immersion in the fields of *Sustainability* and *social housing* in an urban century and derives the objectives and limitations of the thesis. It is organized in five sub-sections. Section 1.1 introduces the concept of sustainability and its recent frameworks for actions. Section 1.2 introduces the sector of construction and building use, and relates it to emerging economies and the social housing sub-segment. In Section 1.3, insights about sustainability assessment of buildings are provided. With a geographic focus on the Philippines, Section 1.4 provides a national perspective on sustainability and social housing. Section 1.5 concludes with the general and specific objectives as well as the limitations of this thesis.

1.1 Sustainability

The section expands on the conceptual roots of sustainability and identifies recent policy frameworks related to the concept. Relevant elements and issues of concern are highlighted, which guide the thesis throughout. The section ends with a critical review of the framework agreements and contributes thoughts to the discussion of effective pathways towards a more sustainable and resilient future.

1.1.1 Conceptual Roots

The term ‘sustainable development’ is rooted in the concepts of nature conservation and ecology from the 19th century and the first half of the 20th century (Adams, 2009). The World Conservation Strategy (WCS) was first to mention a development at the confluence of the three pillars - economy, ecology and society - for the present and future generations (IUCN, 1980). The most commonly used definition of sustainable development was formulated in the Brundtland Report ‘Our Common Future’ by the World Commission on Environment and

Development (WCED) in 1987. It described sustainable development as “development that meets the needs of the present without compromising the ability of future generations to meet their own needs” (WCED, 1987). WCED stated that economic practices needed to be reconsidered to address the needs of the poor and the environment. The linkage of economic concerns and the environment was fundamental for the future development of sustainable development. Through a series of historic global conferences and policy frameworks, the term sustainability evolved further. A paradigm that became prominent in the 1990s and remains so today, is people-centered development.

Development, and particularly poverty reduction, is the second important root of sustainable development. This theme was addressed at the 1992 United Nations Convention for Environment and Development (UNCED) Earth Summit in Rio de Janeiro. The major contributions of the UNCED include the Rio Declaration, the Agenda 21, and the establishment of the UN Framework Convention on Climate Change (UNFCCC). UNCED widened the focus on the poor to include both the poor and the rich. As part of the 27 principles of the Rio Declaration, intra-generational equity between poor and rich was included next to inter-generational equity, referring to the current and future generations (UNCED, 1992). It further defined “common but differentiated responsibilities” for these two groups. However, no timeframes or financial commitments were provided. Agenda 21 was described as a comprehensive plan for action, but kept a high-level, aspirational rhetoric. Adams (2009) states that the Earth Summit, in retrospect, is perceived a milestone in “mainstreaming” sustainable development, making it a theme relevant round the globe. As such, Agenda 21 was less radical, finding expressions, values, and terms, that the masses could relate to without discourse and discussions about trade-offs (Adams, 2009). Local Agenda 21 had and has the ambition to provide opportunities at the local level for active participation and decision-making. At its core, Local Agenda 21 aims to identify local needs and strengthen ownership. However, lacking clarity on the link between national and local decisions, it faces questions of power relations and backward integration.

In the 20 years to following the formation of the UNCED, insufficient progress has occurred despite the World Summit on Sustainable Development (WSSD) in 1992 in Johannesburg and the releasing of the Millennium Development Goals (MDGs) under the Millennium Declaration. WSSD was a high-level, large-scale re-affirmation of goals and policy principles. It stressed a long-term perspective and highlighted the concept of participation. It maintained the previously introduced consensus without quantifying historic responsibility and allocating funding (Dresner, 2008). In contrast, the MDGs aimed to be notably concrete, naming quantitative and time-bound targets. However, they can be criticized as insufficiently addressing the interconnectedness of realities in a globalized world.

The UN Convention of Sustainable Development (UNCSD), or Rio+20, in 2012 released the 2030 Agenda and agreed to implement SDGs in continuation of the MDGs (UN 2030 Agenda, 2015). Also called the post-2015 framework, 2030 Agenda declares funding for sustainable development as an important basis for implementation. However, no tangible financial commitments are attached to it. It reconfirmed the relevance of important aspects, such as ending poverty and inequality, tackling climate change, and environmental degradation. The UN describes it as a “detailed operational concept with an expanded scope compared with its predecessors, able to reflect the complexity of today’s challenges holistically” (UN 2030 Agenda, 2015). Common among UNCED, WSSD and UNCSD has been the consensus approach among a global range of participants, which maintained an aspirational yet vague rhetoric.

1.1.2 Recent policy framework

In 2015 and 2016, a number of major global policy frameworks came into force, with the interrelated themes of Disaster Risk Reduction (DRR), sustainable development, climate change mitigation and adaptation, and sustainable cities and settlements. The agreements include the Sendai Framework for Disaster Risk Reduction (SFDRR) (UNISDR, 2015), 2030 Agenda with the SDGs (UN 2030 Agenda, 2015), the Paris Agreement of the UNFCCC (UNFCCC, 2015), and the NUA (UN-Habitat III, 2017). The agreements were developed following a consensus approach via novel global stakeholder processes in terms of magnitude and inclusion. Consequently, they have grown in their complexity and comprehensiveness. Their linkages are acknowledged, yet sometimes debated because of different organizational structures. The key elements that influence this thesis through their relevance in the field of sustainable social housing are highlighted below.

- **2015: Sendai Framework for Disaster Risk Reduction (SFDRR)**

The SFDRR was agreed upon at the 3rd UN World Conference on DRR in Sendai, Japan. The global framework agreement aims to address adaptation to the harmful effects of climate change and disasters. Core elements of relevance in this thesis include those objectives to increase the understanding of disasters risks and awareness of social vulnerability. The latter can be addressed through enhanced disaster risk preparedness and societal resilience. The definition of vulnerability from the Hyogo Framework of Action, its predecessor, is still used, describing it as “the conditions determined by physical, social, economic and environmental factors or processes, which increase the susceptibility of a community to the impact of hazards” (UN International Strategy for Disaster Reduction, 2005). Science and humanitarian practice agrees that vulnerability is a complex, multi-dimensional concept involving numerous variables (Carreño *et al.*, 2017). Because of their interlinkages, these variables are challenging to manage (Kulatunga *et al.*, 2014). Despite its complex nature, Briceno (2015) acknowledges that vulnerability generally can be generally influenced to lower the harmful effects of hazards. Holistic, integrated risk management is recommended for effective DRR (UNISDR, 2015). In SFDRR, resilience is defined as “the ability of a system, community or society exposed to hazards to resist, absorb, accommodate to and recover from the effects of a hazard in a timely and efficient manner, including through the preservation and restoration of its essential basic structures and functions” (UNISDR, 2009). With a human-centered view, the United Nations Development Program (UNDP) formulates it as the “transformative process of strengthening the capacity of people, communities and countries to anticipate, manage, recover and transform from shocks” (UNDP, 2011).

- **2015: 2030 Agenda for Sustainable Development**

The 2030 Agenda and the SDGs were developed between 2012 and 2015 via a large-scale participatory process. 17 goals and 169 targets were released as the core of 2030 Agenda (2015). In 2016, 230 indicators were added, with the need for local, national and regional agendas to specify their approach to the required operationalization (Annex of the 2030 Agenda, 2017). An ongoing debate exists regarding the approach how to fund and implement actions on the ground and to assess, monitor, and report on the SDG progress. The first steps to address these issues are however made (UN SDG, 2017). The SDGs provide relevant guidance in this thesis via their general principles and aspects of concern. Three SDGs have a tangible direct link to social housing: SDG11 on sustainable cities and settlements, SDG12 on responsible production and

consumption, and SDG13 on climate action. Moreover, an indirect linkage exists to many further goals, such as SDG1 on poverty reduction, SDG3 on health and well-being, SDG4 on quality education, SDG5 on gender equality, SDG8 on work and economic growth, SDG9 on industry, innovation and infrastructure, SDG10 on reduced inequality, and SDG17 on partnerships. Regarding settlements, there is SDG6 on water and sanitation and SDG7 on affordable and clean energy, although the access to basic services and infrastructure is formulated as a requirement in this thesis and is not in the scope of the thesis itself.

- **2016: Paris Agreement**

The Paris Agreement was formulated at the Conference of the Parties (COP) 21 in Paris in 2015 by the UNFCCC. It entered into force in 2016, after the threshold of ratifying countries was achieved. The SDG13 on climate action refers to the Paris Agreement as a plan for action to address climate change mitigation. It has legally binding characters, measured through Intended Nationally Determined Contributions (NDCs) of the ratifying countries (UNFCCC, 2015). However, legal enforcement mechanisms do not exist. The Paris Agreement names the construction sector and building use as one of the key areas for action to combat climate change. The assessment of the International Energy Agency (IEA) (2016) that the building sector offers the largest cost-effective GHG mitigation potential, with net cost savings and economic gains possible through implementation of existing technologies, policies and building designs, supports this priority setting.

- **2016: New Urban Agenda (NUA)**

Spearheaded by the United Nations Human Settlements Program, the NUA names 175 statements for action. It contributes to the “implementation and localization of the 2030 Agenda” and is strongly linked to the goals and targets of the SDGs, in particular the SDG11 on sustainable settlements and cities. With its focus on cities, construction and building use are relevant elements of NUA and the most detailed and concrete linkages to this thesis are provided. Among others, it expresses a commitment “to stimulate the supply of a variety of adequate housing options that are safe, affordable and accessible” (UN-Habitat III, 2017). The NUA suggests that environmental concerns are to be related to resilience, which is also a core consideration of this thesis. Furthermore, the use of sustainably sourced local materials is directly highlighted as one entry point for action. The NUA seeks to “Promote the sustainable management and use of natural resources, ensuring reliable supply and value chains that connect urban and rural supply and demand.” Table 2 summarizes the aspects of NUA that influence this thesis.

Table 2 Aspects of NUA relevant to this thesis (UN-Habitat III, 2017)

Aspect	Description
Participation, Inclusiveness	• Need for inclusive and participatory policies and processes, taking into consideration the socio-economic and cultural integration of marginalized and vulnerable groups
Resource Management / Local Materials	• Promote sustainable management and use of natural resources, ensuring reliable supply and value chains that connect urban and rural supply and demand • Prioritizing the use of local, non-toxic materials
Cities / Countries	• Readdressing the way cities and human settlements are planned, designed, financed, developed, governed and managed • Special attention on countries affected by natural disasters

Table 3 Aspects of NUA relevant to this thesis (UN-Habitat III, 2017) cont.

Aspect	Description
Cities / Countries cont.	• Role of small and intermediary cities in providing access to sustainable, affordable, adequate, resilient and safe housing, facilitating effective trade links across the urban-rural continuum.
Housing	• Realization of the right to adequate housing as a component to the right to adequate standard of living • Adequate, affordable, accessible, resource-efficient, safe, resilient, well-connected and well-located housing • Providing high quality buildings, preserving cultural heritage, ensure participation, and avoiding gentrification • Energy efficient buildings and construction modes, and the reduction of greenhouse gas emissions through the sector
Housing Policies	• Commitment to national and local housing policies that support the progressive realization of the right to adequate housing for all. • Housing policies considering social, economic and ecologic requirements • Linkage of housing with education, employment, health, and exclusion
Housing Finance	• Appropriate financing models for affordable, sustainable housing options, including incremental housing and upgrading
Capacity Building / Jobs	• Building of local capacity and creation of decent jobs • Recognizing the informal workforce in the informal / formal sectors
Partnerships and distribution	• Triangular international cooperation, combining North-South and South-South cooperation • Knowledge exchange on science, technology and innovation • Multi-stakeholder partnerships in urban development • Highlight best practices and innovative solutions • Share knowledge through open concepts and platforms

1.1.3 A critical review and pathways forward

The past decades have brought about a series of policy frameworks to address lingering development challenges across the world. The concept of sustainability has developed from a niche to a mainstream concept, and it has arrived at the center of our society. Powerful, aspirational, and high-level policy formulations, and events of an unseen scale, attempt to do justice to this complex, extensive approach to world development. Because there has been relatively little change in the past decades, more effective pathways for implementation must be found. These are, however, contested. In the following, some *barriers to and opportunities for operationalization* are highlighted.

- Concepts and agreements have become more inclusive and comprehensive. This reflects the complex nature of global challenges, but also widens the *gap between aspirations and implementation*. Despite the global effort, policy frameworks remain vague. Dresner (2008) states, that if the world wishes to actually meet its expectations regarding real change, then it must do more than attribute positive effects to theoretical consensus on core issues.
- While the recent agreements included a new variety of stakeholders in their formulation, they do not determine how to handle contradicting concerns and power relations or specify how to concrete actions will be financed. Consensus exists that there is a role and duty for all stakeholder groups; this is irrespective of whether policy makers, grassroots organizations, scientists, or the private sector lead (or are given chance to lead) the change. Financial commitment is needed to implement action on the ground. The institutionalized

participation of low-income groups, such as done by the Community Organizations Development Institute (CODI) (2018) in Thailand, the Orangi Pilot Project in Pakistan (Hasan, 2000), or the Community Mortgage Program in the Philippines (Social Housing Finance Cooperation, 2018), can facilitate processes for funding, decision-making, and localization.

- As time passed, agreements have tended to become less radical. There are requests to return to *stronger definitions of sustainability*. The comprehensiveness of framework agreements bears the risk that subjective agendas can be justified. Thus, it must be questioned to what degree is substitution allowable and practiced, and whether the dimensions are given equal treatment (Barbier and Pearce, 2000).
- Agreements are mostly *voluntary* or lack enforcement mechanisms. This thesis acknowledges that *sustainability is a process*, which requires action, the continuous *balancing* of requirements, and a *dialogue* across stakeholder groups. There are still very few examples in which sustainability is used for active decision-making. Therefore, a pressing task is to increase the *use of sustainability as a tool for decision-making* in implementation at the local level (Waas *et al.*, 2014). Increasing complexity in theory must be accompanied by localized applied initiatives, such as communities of practice, that *transparently share and debate value propositions*, while using new opportunities such as the ones of a digital age (Gregson *et al.*, 2015). Especially the strong definitions of sustainability must prove their grounds for operationalization.
- Effective, open platforms for dialogue are needed for exchange and dissemination. Global and local knowledge needs to meet, and the explicit the tacit. Top-down approaches need to link with bottom-up approaches. Sensitive *backward integration* of local to sub-national, national, regional and global levels is also important.

1.2 Construction and Building Use

The section provides an outline of the construction industry and building use. The focus will be set on the relevance and role of emerging economies and the sub-segment of social housing in those emerging economies. The impact of the sector is reflected along the three dimensions of sustainability.

1.2.1 A global perspective

Construction and building use is at the nexus of urbanization, climate change, disaster risk and sustainability. Urbanization is described as one of the 21st century's most transformative trends, with an expected doubling of the world population by 2050 (UN-Habitat III, 2017). Urban spaces around the world are engines for growth, education and overall progress. The NUA "wishes to realize the historic opportunity to leverage the key role of cities and human settlements as drivers of sustainable development in an increasingly urbanized world" (UN-Habitat III, 2017). Construction and building use, occurring predominantly in and around urban agglomerates, affects all three pillars of sustainability. As a major contributor to gross domestic product (GDP) and an engine for job creation, construction is a measure for *economic development* of countries (GABC/UNEP, 2016).

On the downside, the opportunities are not equally spread among societal groups. The United Nations Department of Economic and Social Affairs (UNESA) (2009) states that, "everyone has the right to a standard of living adequate for the health and well-being of himself and of his family, including food, clothing, housing and medical care and necessary social services."

However, this remains out of reach for many. The lifestyles of the rich and poor in a country are a measure of societal inequality.

Policymakers, scientists, NGOs, and industry have further recognized the construction sector with its global impacts on the environment. Buildings and construction are major consumers of *resources and energy*, while producing significant *emissions and waste*. The IEA predicts that 30 % of the global energy consumption, 40 % of all resource depletion, and 25 % of global greenhouse gases (GHGs) are allocated to construction and building use (IEA, 2016). Numbers are sensitively tied to the boundary conditions of how they are assessed. Huang *et al.* (2018) provide an alternative assessment of carbon emissions in the global construction sector. While numbers depend on the methodology and boundary conditions set, the assessments show that buildings and construction are major contributors to environmental impacts. At the same time, the building sector has the greatest low-cost GHG mitigation potential, irrespective of world region. Therefore, buildings and construction can contribute significantly to achieving climate goals and the common objective of limiting global warming to below 2°C (GABC/UNEP, 2016). Rapid urban development and climate change make environmental friendly buildings an urgent and necessary requirement for the coming decades (IEA, 2013).

Innovation is one entry point to more environmental friendly buildings. As a key means of implementing the Sustainable Development Goals (SDGs), harnessing science, technology, and innovation (STI) for sustainable development plays an important role (UNESCAP, 2016c). The contribution of STI requires geographic and segment specific fit. In Asia-Pacific, for example, UNESCAP expresses that “some of the most dynamic, pioneering and innovative countries [can be found], but at the same time some of the most technologically deprived.” Furthermore, there has not been the required diffusion of innovation irrespective of world region. Rogers (2002) names strategies for diffusion such as peer networks, entertainment-education, champions with large recognition, and a change of perceived attributes and norms. Systemic building, city scale solutions exceeding a product view, and partnerships to address system barriers, are further recommendations to reach a larger scale and impact (Salzer and Camarasa, 2015; GABC/UNEP, 2016).

1.2.2 Emerging economies and the urban tropics

Emerging economies are rapidly developing nations around the world, many of which lie in the tropical and subtropical belt. It is predicted that a large share of global economic contributions will come from these countries, with a nation’s economic development having a strong influence on the magnitude of the construction sector. Measures to classify the degree and pace of development are contested. A World Economic Situation and Prospects report, released by five UN entities, classifies countries as either developed economies, economies in transition, or developing economies (UNDESA, 2018). Various analyst groups apply rating methods to evaluate the economic development of countries, while others apply a broader concept that considers economic and social development. The most common measure to date is the classification of economies based on the gross domestic product (GDP) per capita, broken down into high-income, upper-middle-income, lower-middle-income, and lower-income economies (World Bank, 2018). The World Bank itself highlights however, that “the GDP may be underestimated in lower-income economies that have more informal, subsistence activities. Nor does GDP reflect inequalities in income distribution.” Therefore, the positive evaluation of the GDP in most emerging economies does not provide a statement about poverty, inequality, and vulnerability. This is particularly important in emerging economies where opportunities are often spread unequally and disparities become particularly visible.

The Global Alliance for Buildings and Construction (GABC) describes the coming decades as a critical window of opportunity to address the largest new construction markets and to avoid locking in inefficient buildings for decades (GABC/UNEP, 2016). The IEA predicts, that the global floor plan will double by 2050, with two thirds of the new floor plan area to be built in emerging economies (IEA, 2016). This excludes China, which alone accounts for 16%. The International Panel on Climate Change (IPCC) scenarios support that non-annex countries in Southeast Asia have the greatest predictions for emissions growth in the building sector, followed by Latin America, and Africa (IPCC, 2014). Technology advancement and high-tech solutions in selected capital regions stand in stark contrast to makeshift buildings and informal living on the other hand (UNESCAP, 2016a). Regarding the global risk index, many emerging economies show higher exposure levels than the world average (EM-DAT Disaster Database, 2016). The impacts on buildings are therefore challenging.

Assuming a thermal comfort understanding of and exposure to temperate climates, energy consumption during the use phase of buildings is a significant contributor to the overall life cycle balance. With many emerging economies situated in the tropical and subtropical zones, and with the majority of houses without advanced building-regulation, the definition of indoor comfort requires climate-adjustment. While space cooling today only contributes to 5%, it may increase by a factor of 10 until 2050 (GABC/UNEP, 2016). Energy consumption scenarios of GABC for warm-climate emerging economies highlight that energy consumption for building end-use is experiencing the fastest growth with areas of priority being space cooling, water heating, and lighting.

1.2.3 Informal and social housing in the urban tropics

In general, the world lacks the statistics to quantify the magnitude of the informal sector in emerging and developing economies. As inherently expressed with the word ‘informal,’ people living in informal settlements are often not recognized or mapped in city plans. While not all people living in informal settlements are poor, “housing remains a valid and useful proxy for income poverty, as it is linked to several other dimensions of urban poverty” (UN Population Division, 2014). The contributions of the informal sector to a country’s formal and informal economic development remains unacknowledged and their need for products and services (such as adequate housing) mostly unaddressed. The UN (2015) states that, as long as the “urban poor and their assets are not formally recognized, they are deprived of the rights of urban citizenship, secure land tenure and access to basic services, despite their often significant contributions to urban social and economic life.” In 2014, Asia and the Pacific was the region with the world’s largest urban slum populations and the largest concentration of people living below the poverty line. Approximately 30 % of the urban population, which accounts for 570 million people, lived in informal settlements (UN-Habitat and UNESCAP, 2015).

Social housing is the segment at the intersection between informal and formal. It is the lowest formal segment in proximity to the informal segment. Both the informal and the social housing segments have shortcomings in fulfilling all existing requirements. However, system barriers of informal housing, such as a lack of land tenure and housing finance, are usually overcome. Such systemic barriers are among the various reasons why social housing remains limited in its reach. To date, no government, private sector, non-government organization (NGO), or grassroots initiative has managed to obtain a scale anywhere near to the need. The market is mainly served by informal service providers, or remains unserved. In Rizvi (2010), it is the collective efforts of stakeholders, such as governments, most importantly the urban poor

themselves, but also the private sector, and NGOs, that enable the scale-up of pro-poor housing in a socially-inclusive manner.

Residents in informal settlements are often more vulnerable to the impacts of disasters. The term social vulnerability, expressing this correlation, has gained recognition in the past decade (de Loyola Hummell, Cutter and Emrich, 2016). With extreme impacts expected to become more frequent, vicious cycles in the vulnerability of the urban poor exist. One of many reasons for increased social vulnerability is the lacking structural capacity of buildings to resist environmental loads. The building stock of low-income groups is often characterized by substandard practices and temporary solutions, which can lead to fatal failures during earthquakes, typhoons, or floods (Mahmood, 2009). The condition of the building stock in the informal and the social housing segment is often described by the term ‘adequacy,’ which is found and used in NUA (UN Habitat, 2016). Adequacy refers to shelter that provides safety and privacy, enabling healthy living as well as access to utilities, public services, and livelihood. Many houses in the informal and social housing sectors are evaluated as being not adequate. Adequate housing, however, is defined as a basic human right (UN-Habitat III, 2017). While adequate housing and its provision is a desire of most governments and the affected people, and various strategies have been tested in the past, conventional building technologies, such as concrete and steel as well as the systems to finance and obtain them, are mostly unable to meet economic limitations of low-income dwellers (Buckley and Kalarickal, 2006). Innovation for and investment into research on social housing is much needed and generally practiced rarely in the past decades.

1.3 Sustainability of Buildings

Following the global dissemination of the sustainability concept, introduced in Section 1.1, and the influence of construction and building use on all three dimensions of sustainability as introduced in Section 1.2, the field of sustainable building has gained relevance around the globe. Since 1995, the International Council for Research and Innovation in Building and Construction (CIB) has provided a platform for exchange on research and innovation around sustainable building through the World Sustainable Building Conferences (WSBC). In several countries including Switzerland, sustainable construction has been institutionalized (SNBS V2.0, 2004). However, in absolute numbers, the change is unable to meet its potential and need. The GABC, the collaborative efforts of the United Nations, governments, the private sector, and scientists, coordinates the contribution of the construction sector to the Paris Agreement. On their global roadmap towards low GHG emissions and resilient buildings, it is highlighted that the NDCs to the Paris Agreement can only be met by a more clear address of the building sector (GABC/UNEP, 2016). On global scale, strategies are being developed. In 2016, CIB launched a global research roadmap to promote research and innovation that is of benefit to society (CIB, 2016). The IEA identifies various opportunities for sustainable building transitions in relation to the geographic and climatic world regions. Global priorities are, among others, advanced building envelopes, reduced cooling loads, heat pumps, solar, and biomass use, as well as a range of supporting and incentivizing policy interventions (IEA, 2013). One basis for the definition of global roadmaps and decisions on building level is the sustainability assessment of buildings. The approach involves the documentation of building performance and enables a comparison between options. The methods to do so are widely contested and discussed. In the Section 1.3.1, the diverse options for sustainability assessment of buildings are introduced. Thereafter, Section 1.3.2 discusses how social housing is influenced by the sustainability concept and how requirements change in this segment of construction.

1.3.1 Introduction to the sustainability assessment of buildings

The sustainability assessment of buildings is a requirement to steer activities that effectively and appropriately enhance sustainability for buildings and cities on both local and global scales.

The International Standards Organization (ISO) describes the *objectives of assessing the sustainability of buildings* in the following points (ISO 15392, 2008):

- The improvement of the construction sector and the built environment;
- The reduction of adverse impacts while improving value, where impacts as well as value may be judged against any combination of the three dimensions of sustainability;
- The stimulation of a pro-active approach;
- The stimulation of innovation;
- The decoupling of economic growth from increasing adverse impacts on the environment and/or society; and
- The reconciliation of contradictory interests or requirements arising from short-term and long-term planning or decision-making

To assess the sustainability of a building, a conceptual framework is required “to determine the impacts and aspects of the building and its site and to enable the stakeholders to make decisions and choices that will help to address the need for sustainability of buildings” (EN 15643-1, 2010). A global discourse, however, exists on the methods for such an assessment.

Generally, three steps are distinguished in the sustainability assessments of buildings:

1. A conceptual method is applied, including a set of sustainability indicators;
2. Performance benchmarks and data generation methods to assess these indicators; and
3. A valuation of results to describe the performance of a building or to compare options

A wide range of conceptual methods exists in the field of sustainability assessments for buildings. Figure 2 summarizes the different types according to their characteristics, which are differentiated from one another with regards to their comprehensiveness, legal status, geographic validity, sector-relevance, flexibility, transparency, and evaluation type. The characteristics can be combined in numerous ways, such as issue-focused international guidelines for businesses or comprehensive proprietary schemes, which do not disclose their calculation methods.

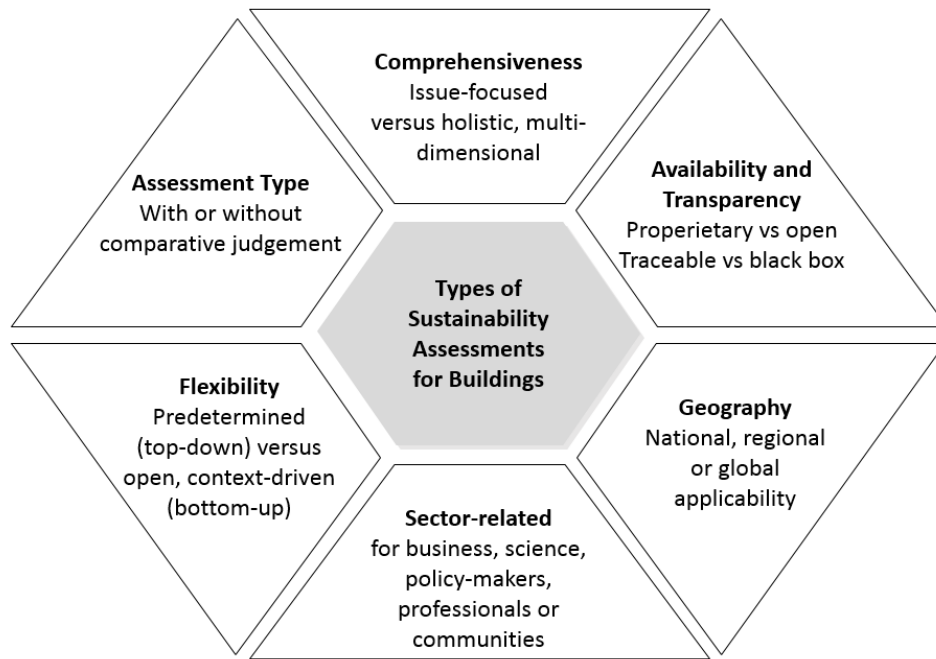


Figure 2 Types of Sustainability Assessments for Buildings

Most methods adopt the *life cycle principle*, wherein material, energy, and emission flows are considered throughout the life cycle of a building (see Section 2.2.1). With its roots in ecology, the most acknowledged method for environmental impact assessments is the Life Cycle Assessment (LCA) (Finkbeiner *et al.*, 2014). Its processes are transparently captured and standardized in regulations in both Europe and internationally (ISO 14040, 2006; EN 15978, 2011; EN 15804, 2013). In recent years, research has been conducted to open the LCA concept to a social impact dimension. Thus, the Social Life Cycle Assessment (SLCA) evolved. It is a young field that has developed quickly but ongoing debate remains regarding its rigor, robustness, and the pathways forward (Di Cesare *et al.*, 2016; Grubert, 2016; Macombe, Loeillet and Gillet, 2016). In future, it may be a meaningful approach to more holistic LCAs. Beyond LCAs, a range of assessment schemes exist that considers the three dimensions of sustainability. In many of these, the LCA is used to cover the environmental dimension (UN-Habitat, 2017). The quantity of available schemes is, however, not a measure of its uptake success. The monitoring and use of sustainability indicator systems falls far behind the number of schemes that actually exist (Krank, Wallbaum and Grêt-Regamey, 2010). In the following, a non-exhaustive overview of three-dimensional assessment guidelines or methods is provided. Differences are highlighted with a specific focus on their applicability for the social housing context in the urban tropics.

In recent years, large-scale open multi-stakeholder processes have taken place to define policy frameworks on sustainability, as introduced in Section 1.1. Stakeholder contributions across societal levels and geographies have contributed in a bottom-up approach and were integrated backward to derive a global vision. While these policy frameworks are not building-specific and many uncertainties regarding sustainability assessments remain, they do provide relevant guidance in the themes they include. Sector-related standards, such as the sustainability reporting schemes for businesses (GRI) by the Global Sustainability Standards Board (GSSB) (Global Sustainability Standards Board, 2016) have been largely developed via expert approaches. They have reached a relatively high level of comprehensiveness in the three

dimensions of sustainability. In the building sector, predetermined proprietor assessment methods for professional use dominate, and indicators have been composed in a top-down manner. These methods range from issue-focused to more holistic, multi-stakeholder assessment schemes (BREEAM, 2018; Deutsche Gesellschaft fuer Nachhaltiges Bauen, 2018; Minergie Association, 2018; Passivhaus, 2018; USGBC, 2018). There is no comparability across schemes because of varying indicators, aggregations, and weighting schemes. The actual market reach of proprietor schemes is often limited as they usually require assessment fees and a licensed assessor. Most schemes are developed for the Western context, with limited applicability for emerging and developing markets (UN-Habitat, 2017). Because they do not meet the open development objective of the thesis, which intends to produce knowledge that can be shared for maximum impact and outreach, they are not considered here.

A few open schemes have been developed for the low-end segment, mostly meant to guide humanitarian practitioners and disaster-aid in decision-making, such as by the International Federation of Red Cross and Red Crescent Societies (IFRC) (2018). Used by both professionals and scientists, there are clear differences in their approaches to sustainability assessment. Post-disaster reconstruction is a field where decisions must be made in urgency, with little to no advance planning or the opportunity to generate comprehensive data. More common than in-depth tools are practical guidelines and quick assessment methods, such as by the Swiss Center for Appropriate Technology (SKAT) (2012) or UN Environment (UNEP) (2015).

Bottom-up approaches in urban development are not limited to housing but cover a broad range of urban concerns within communities. They heavily build on the involvement of local stakeholder groups and are flexible and open in their structure. Furthermore, they usually invite to an emergent, participatory but realistic approach, as described in (Lennie and Tacchi, 2013). Community-driven processes to housing, such as that advocated by the Asian Coalition for Housing Rights (ACHR), deliver an important contribution to sustainable urban development (Asian Coalition for Housing Rights, 2005; Satterthwaite, Mitlin and Patel, 2011). As the ambition of these processes is not one of a sustainability assessment, criteria are not formalized and data are usually of an informal nature. In contrast, scientific sustainability assessments often provide detailed aspects and indicators, using expert knowhow, advanced tools, and comprehensive data. In turn, science delivers traceable results with high reliability, which can be used to shape policy frameworks or guide standards.

Significant efforts have been made at both international and regional levels to standardize sustainability assessment in building and construction (Krigsvoll, Fumo and Morbiducci, 2010). The objective of the standardization is to provide *comparable, geography-spanning, and open standards* for sustainability assessments of buildings. This thesis specifically refers to the International Standards Organization (ISO), and the European Standards Organization (EN). ISO standards aim to remain sufficiently flexible to adjust to local needs while also enabling global applicability. They also guide assessments to obtain a higher degree of harmonization. In contrast, EN standards are customized for the European context. They have achieved a remarkable depth for the environmental impact assessment of buildings. More information on sustainability assessments according to ISO and EN is provided in Section 2.2. Beyond the global and regional standards, multiple countries have developed national standards that provide localized guidance specifically adjusted to the specific needs of that particular country and in harmony with national rules and regulations for buildings and building use. For the Philippines, no national standard on sustainability assessment exists.

The localization of global guidelines through context-specific multi-stakeholder assessment is described in Section 2.2.6. The various influencers that have contributed to this thesis are shown in Figure 3.

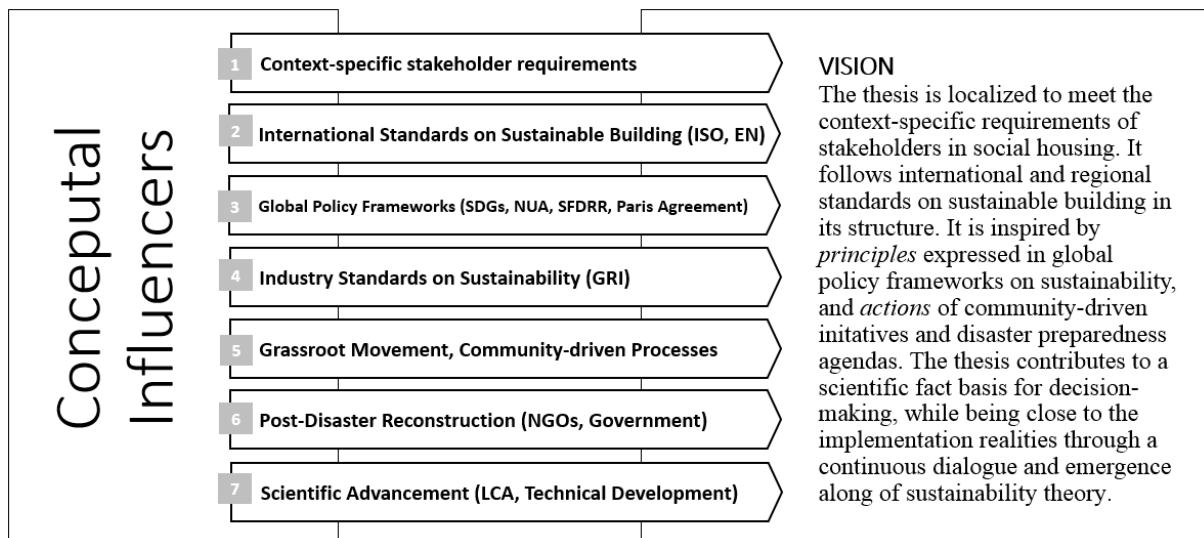


Figure 3 Conceptual influences and the vision of this thesis

1.3.2 Sustainability of social housing in the urban tropics

Tremendous urban growth rates in Latin America, Africa, and Asia-Pacific make an inclusive and sustainable urban development in those regions essential (UN-Habitat, 2013). As highlighted in Section 1.3, construction and building use are important components for such. Policymakers, scientists, and practitioners agree that the concept of sustainability inherently requires a local definition of what is sustainable in a specific context. The IEA, which focuses on energy related transitions in sustainable building, clusters its recommendations on climatic and geographic regions. For the Association of Southeast Asian Nations (ASEAN), key actions include reducing the cooling load and addressing building codes and governmental incentives for green building (IEA, 2013). In contrast, advanced building envelopes, on the other side, are not a priority in warm-climate economies. The building stock in the urban tropics is, however, far from being homogeneous. Not only the climatic region but also the economic limitations define which interventions are applicable. As introduced in Section 1.2.3, informal and social housing represents a large share of the building stock in the urban tropics, with its relevance further increasing. Interventions used in this area look very different to technology-regulated buildings. Addressing the sustainability of buildings in the naturally ventilated, affordable segment is of great importance: first, because of its size and rapid growth, and second, because of the transition of people from this segment to the next higher segment in which technology-regulated buildings are common.

The field of sustainable social housing in warm-climate emerging and developing economies has generally received little attention given its level of relevance (UNEP and UN-Habitat, 2015). Looking at the entry point of energy consumption during the use-phase of buildings, this relevance is underlined in the following. LCAs are more often used in exemplary projects with building-integrated technical systems rather than for ordinary building stock (Cabeza *et al.*, 2014). Multiple studies for exemplary houses state that energy consumption during the use phase, Phase B6 according to EN15643-1 (2010), of a house contributes 70%–90% to the overall life cycle balance (Ortiz, Castells and Sonnemann, 2009; Cabeza *et al.*, 2014; Abd Rashid and Yusoff, 2015). This holds true for the industrialized building sector, but little is

known about the use phase of naturally ventilated, low-cost houses. Many may assume, that a building's use phase will not have the same importance over its life cycle because of the limited consumption options of its inhabitants. However, it would be short-sighted to conclude that the use phase in social housing does not matter. The use phase can be looked at in terms of direct relevance, which requires further study of the user behavior in the social housing segment, and indirect relevance, which is expressed through the social aspiration to obtain energy-consuming air cooling devices or devices that societal development allows for. Today, many emerging economies are far behind the average per capita energy consumption in of Western countries. However, rapid development and the transitioning of societal groups into higher income levels will change this in the coming decades. The UN expresses that "A rapidly growing middle class will result in changing consumption patterns and brings risks and opportunities for sustainable urban development" (UN-Habitat and UNESCAP, 2015). With energy use in the tropics being mostly determined by the cooling load, the performance of buildings in use will depend on the building material, design of the building envelope, the surrounding environment, and the exposure to heat intake. Small volumetric houses with metal roofing and no insulation, as analyzed in this thesis, have substantial heat intake during the day. Structures with a higher thermal mass experience higher nighttime temperatures. The construction costs of conventional solutions offer fewer opportunities for the climate-adjusted design of the building envelope. Air conditioning is mostly unaffordable for the studied low-income settlements, albeit socially attractive. The question of locally adjusted, natural thermal comfort is therefore raised as well as how it can be promoted for emerging and developing warm-climate economies. The tropical climate, the local comfort sensation, and related user behavior are relevant to consider in passive methods for enhanced comfort at no user cost.

Green building interventions do, however, face a number of challenges stemming from the economic limitations and system barriers to addressing the large need for social housing. The factor scale is particularly relevant to this sector, as pilot stage interventions can be found around the globe but hardly exceeding the latter (UN-Habitat, 2012), which requires holistic address of system barriers. The use of local raw materials and value chains has potential for social housing. When it comes to building methods for green social housing, such as described by (UNEP and UN-Habitat, 2015) or (UN-Habitat, 2012), these are mostly outside of the national building regulations. Housing policies and building codes are considered regulatory instruments. UN Environment (2015) names regulatory instruments as one of the four instruments to promote sustainable social housing next to: market-based or economic instruments, fiscal instruments; and voluntary support. Often, informal houses are outside of the regulated building stock. Pro-poor regulations can support to formalize the informal. Furthermore, formal providers of social housing should be required to comply with technical minimum standards. The exemption from safety standards in social housing bears the risk to accelerate vulnerability loops for low-income groups. Market-based instruments need to be adjusted for the segment. While labeling may not be effective, given that clients do strive to fulfill their basic needs instead of ecological ambitions, subsidies for green building could be considered by national governments. Awareness raising, technical training and policy advocacy are mentioned as key concepts for diffusion of sustainability in social housing (UNEP and UN-Habitat, 2015). Many countries in the tropics can already feel the effects of climate change (Kelman, 2015). The naturally increased awareness among those populations in affected countries is a good entry point for action.

1.4 The Philippine Perspective and the case for bamboo

As this thesis focuses on the geographic context of the Philippines, a national perspective on the concept of sustainability and its construction sector is provided. The Philippines are home to more than 100'000 million people (Philippine Statistics Authority, 2018). The Philippines is considered a lower-middle-income country (World Bank, 2017a) or a secondary emerging economy (FTSE, 2017). Approximately 45% of the country's population resides in cities, with predicted growth rates of around 2% annually for the coming decade (UN-Habitat and UNESCAP, 2015). With 6.9% economic growth in 2017, the Philippines is one of the 10 fastest growing economies in the world (World Bank, 2018), as shown in Figure 4. A flourishing construction industry provides a relevant contribution to job creation (World Bank, 2017a). However, there are formidable challenges to ensure inclusive growth that benefits all income-groups (UNESCAP, 2016b).

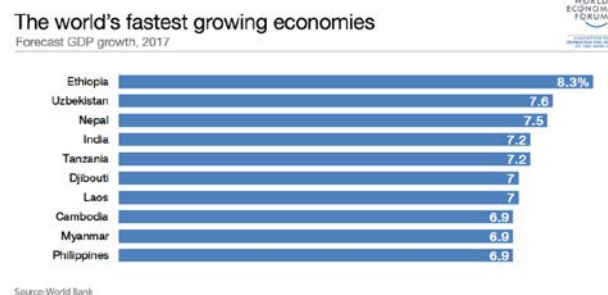


Figure 4 The world's fastest growing economies according to the World Bank

The Philippines are extremely exposed to disasters and the effects of climate change. According to Global Risk Exposure Reports (EM-DAT Disaster Database, 2016), the country is one of the most disaster-prone nations in the world. A map of tropical cyclones over the past 50 years and the ring of fire in relation to global seismic activities, seen in Figure 5, underline its exposed position. In IPCC rankings, the country is one of the most affected by climate change, evident through more frequent and stronger impacts (IPCC, 2014). The population of the Philippines has become more conscious of disaster risks and there are a number of programs to mobilize local governments and communities to preparedness (Crawford, 2012).

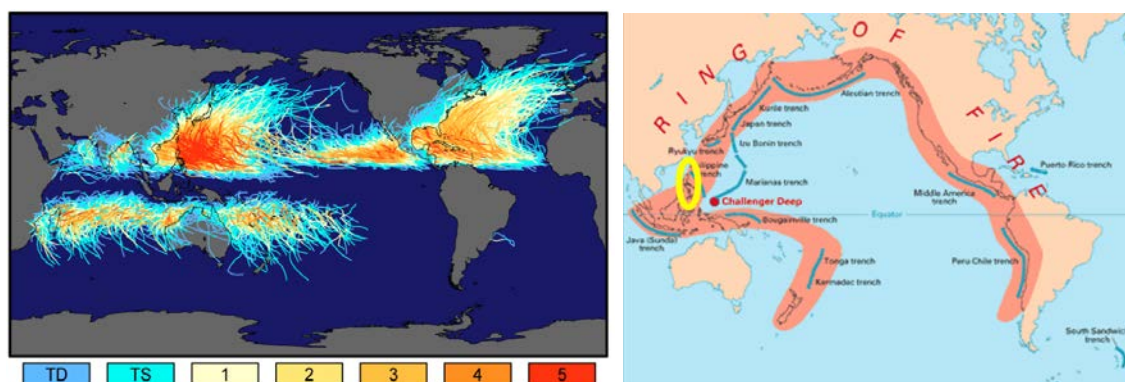


Figure 5 Cyclone Map (NASA Earth Observatory, 2006), Ring of Fire (USGS, 2017)

While the economy in the Philippines is growing rapidly, societal disparity is huge. An increasing number of people reside below the poverty line of USD 1.90 per day (World Bank, 2017b). The GINI index for the country, as a measure for social inequality, lies with 0.45 among

the lowest in Asia-Pacific (Philippine Statistics Authority, 2017). While the relative share of people living informally in the country is decreasing, the absolute number is increasing. It is estimated that one in four settlers resides in an informal settlement (Asian Development Bank, 2011). Furthermore, there is a national housing backlog (referring to the units to be built) of six million (World Bank, 2016).



Figure 6 Dwellings in informal settlements in Quezon City, the Philippines

The need for affordable and adequate housing in the country is increasing, not only because of urbanization and societal disparity, but also because of the significant damage to the building stock from disasters. National statistics show that 15% of the building stock can be destroyed along the track of a strong typhoon, several of which hit the country every year (National Disaster Risk Reduction and Management Council, 2016). Because of its geographically exposed position, and the size of the need, the Philippines has appointed itself a forerunner in localizing global policy frameworks on sustainability.

Already for the Post-2015 Development Agenda, the Philippines has played an active role in assessing the effectiveness of the MDGs in a nationwide stakeholder process. Regarding the SDGs, it co-chairs the Inter-Agency and Expert Group on SDG Indicators (IAEG-SDGs) and The National Economic and Development Authority is proactively rolling out a roadmap, which is linked to its national strategy the *Philippine Development Plan* (National Economic and Development Authority of the Philippines, 2017). The Philippine government released a resolution to gather data to measure progress on the SDGs (Philippine Statistics Authority, 2016) and it has submitted ambitious NDCs to the Paris Agreement (Republic of the Philippines, 2015). According to the latter, a CO₂ reduction of 70% is intended by the year 2030. Considering the impact of construction on the CO₂ balance, besides its use of resources and energy, and its production of waste, the sector is included in the local framework for action (National Economic and Development Authority of the Philippines, 2017). The increasing use of low-carbon building materials and energy-efficient buildings are therefore objectives much aligned to national goals of the Philippine government.

Bamboo is an available and culturally rooted resource that is frequently used by rural and urban low-income groups in the country. It can be found in traditional construction, songs, myths, or games (Tan, 2012).

In 1900, the total land area of the Philippines was 70% covered with forest, with this value declining to 21.8% by 2002 (Environmental Science for Social Progress, 2002). Policy makers in the Philippines have started to react since 2000. Through a series of policies, the extraction of timber from the natural forests was restricted with only a few exceptions for plantation timber. Since 2011, a national log ban on natural and residual forest has been active. Pathways to lessen the resource pressure and contribute to sustainable supply chains had to be developed, with a large potential in the utilization of bamboo. The fast growth and regeneration cycles of bamboo as well as its broad availability in the tropics make it an ecological alternative to conventional construction materials used for low-rise housing such as timber, concrete, and steel (Villegas, 2003; van der Lugt, van den Dobbelssteen and Janssen, 2006; Liese and Koehl, 2015). In the Philippines, the utilization of bamboo for construction has a long tradition in rural areas (Barile *et al.* 2007). Bamboo has been used in the Philippines since centuries, and refined traditional decorative details exist. It is known for its climate-adjusted comfort, environmental advantages and affordability. Figure 7 shows historic houses made from bamboo in the Philippines (Perez, Encarnacion and Dacanay, 1989).

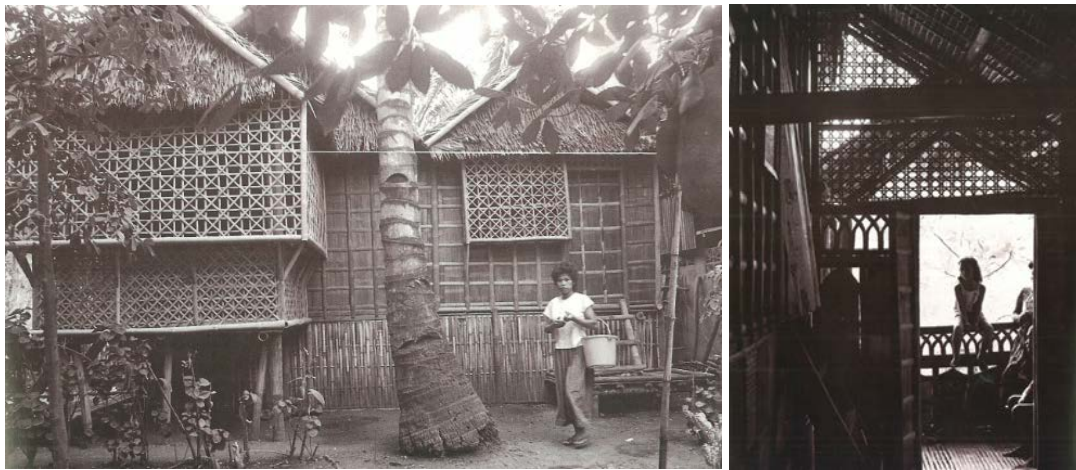


Figure 7 Historic Philippine bamboo housing (Perez, Encarnacion and Dacanay, 1989)

However, these rural structures are often considered temporary and not disaster-resistant, as manifested in the vulnerability curves of (Monteverde *et al.* 2014), which relate the intensity of typhoon damage events to the mean damage ratio of bamboo-based houses. Overtime, traditional skills declined, and skill-intensive maintenance of the rural houses is no more wanted. Ordinary rural residences have become simpler, with less refined details. In ‘rest houses’ that are used to host groups of guests in restaurants, the traditional skills are still visible today. In the urban Philippines, bamboo is limited to informal settlements and non-load-bearing applications. Its current use in construction does not meet most regulatory, technical, and social requirements of urban spaces. Among others, it is listed in local statistics as the most vulnerable building material under typhoon impact. Thus, it has become a symbol for social vulnerability. Figure 8 shows examples of typical rural and urban bamboo use in housing in the Philippines, as it can be seen today. There is a common perception in cities that conventional concrete and steel building methods are more modern, safe, and less maintenance intensive.



Figure 8 Today's bamboo use for housing in the rural and urban areas in the Philippines

Globally, more than 1,200 bamboo species have been recorded, and the Philippines Forestry Sector has identified approximately 62 different species (Philippine Council for Agriculture Forestry and Natural Resources Research and Development, 1991). A shortlist of nine economically relevant species was identified for the Philippines according to the criteria distribution and current utilization. Among the nine economically relevant species, five have been documented for empirical use in construction (Rojo *et al.*, 2000). Endeavors have been made to map the geographical distribution and quantify the availability of bamboo in the Philippines by the national and regional offices of the Department of Natural Resources in the Philippines (2012). However, it was not possible to develop an updated, consistent, country-wide map of bamboo availabilities. One of the reasons for the knowledge gap in distribution and quantification might be that the bamboo market is highly fluctuating, with uncertain price points and clear cutting of existing stands in favor of one-time income opportunities for temporary utilization. The training and implementation of sustainable harvesting practices is therefore crucial for bamboo (Virtucio and Roxas, 2003).

In this thesis, the use of bamboo for the urban housing sector is explored. A global trend, equally valid for the Philippines, is 'rural-urban convergence'. It refers to "blurring interfaces between countryside and urban spaces. Urban lifestyles and economic characteristics and social norms are increasingly penetrating rural areas" (UN-Habitat and UNESCAP, 2015). The reference to the urban tropics, and in particular the urban Philippines are the stricter regulatory, technical, and social requirements of urban spaces. However, the application of bamboo-based housing is equally interesting for the countryside, where it originates from.

All research results presented in this thesis were obtained through research conducted in the Philippines and in collaboration with local research entities. Furthermore, the implementation of research findings received high relevance. People-centered, participatory implementation projects using bamboo-based construction were planned and steered by the Base Foundation (2018). The approach used by the Base Foundation is characterized by its open development, and its long-term perspective on value chain development. This, and the transparent value proposition of the building technology, has attracted various implementing partners such as grassroots groups, large and small NGOs, local and national government, and international organizations. In total, sustainability theory was used to guide research, planning, implementation, and the continuous improvement of 500 social houses across more than 10 projects in the Philippines. A map of the various implementation projects of the Base Foundation and its partners is documented in Figure 9. Exceeding the year 2018, the Base Foundation will provide continuous support as knowledge hub for the construction of quality-controlled bamboo-based social housing in the Philippines and beyond.



Figure 9 Projects implemented by the Base Foundation and its partners (2014-2017)

1.5 Objectives and limitations of the thesis

Traditional bamboo construction in the Philippines has never undergone a holistic review to assess its adaptation potential to an urban and/or disaster-prone context of building. Thus, the general objective of the thesis is provided below:

To guide the development, implementation, and assessment of a bamboo-based building technology for social housing in the Philippines, based on the multi-dimensional requirements of sustainability

For this to be achieved, there are four *specific objectives*:

1. To develop a *conceptual framework* for sustainability assessment in the social housing segment of the Philippines. This includes the localization of global sustainability aspects and indicators through a geography- and segment-specific multi-stakeholder process.
2. To generate *issue-focused scientific research results*, measuring performance in the dimensions of technology and function, society and culture, environment, economy, and governance.
3. To conduct *research in iteration and interaction with implementation projects* to ensure that the scientific contribution closely matches reality.
4. To *evaluate the results on an ongoing basis and continuous stakeholder dialogue*, discussing the value proposition of social housing in the Philippines and to guide an overall sustainability assessment on a transparent, tangible basis.

Given the broad objective of this thesis, it is important to transparently document the *limitations*. This thesis does not intend, suggest, or claim:

- To replace all current building practices in social housing with the building technology discussed in this thesis. It wishes to show one alternative practice under the principle of embracing diversity. System barriers for large-scale applications apply and need to be considered.
- To neglect the negative implications connected to urban sprawl. This building technology is limited to low-rise housing, which is similar to the majority of current social housing. The UN expresses that “only little over 10 percent of the Asia and Pacific region’s urban population actually lives in megacities. The region’s urban population is predominantly found in medium- sized and small cities, and it is in these cities where the region’s urban transition is largely unfolding” (UN-Habitat and UNESCAP, 2015). The building technology is therefore predominantly suited for building in such cities. This thesis acknowledges, however, the risks of urban sprawl, which needs address in complementation to more adequate low-rise housing. Ideally, a mixed methods approach would be found on the city level to address various existing needs.
- To solve the social housing issue in the Philippines through technical development in the building industry. Social housing is a highly complex issue, not a technology problem. Critical system barriers exist including societal inequality, disaster risk, poverty, land tenure, housing finance, and policies. The complexity of the matter requires a holistic response and multi-stakeholder partnerships. This building technology, and particularly the value chain of building with local materials, is one entry point to the nexus. Results are intended to be embedded in holistic settlements and cities, which address further components.
- To suggest that the Philippine approach is a one-size-fits-all solution to the global urban tropics. Local adaptation is always of critical importance. Potential is seen following the principle of “global thinking, local action.” The thesis considers knowledge, like sustainability, as a process that requires stakeholder participation and dialogue. It cannot be collected, stored and exchanged without consideration of people and culture (Hislop, Bosua and Helms, 2018).
- To provide a fixed, one-time valuation at the end of this thesis. While the thesis suggests one value set based on the concept of strong sustainability, this may be adjusted to meet specific stakeholder needs in the future.

2 Methods

The conceptual framework, described in Section 2.1, connects the general objective of the thesis with the general principles that shape the sustainability assessments of buildings. In Section 2.2 the global standards on sustainable building are transformed into a localized segment-specific framework for action. Furthermore, the general boundary conditions for the assessment are documented. Last, Sections 2.3 through to 2.7 describe the issue-specific research methodologies used for the technical, social, economic, and environmental dimensions, respectively.

2.1 Conceptual Framework and General Principles

The conceptual framework of this thesis is guided by the nine general principles of sustainability related to construction works described in ISO15392, which are named in Table 4. These principles are explained below, interpreted in the context of this thesis.

Table 4 General principles of sustainability related to construction work (ISO/TS12720)

General Principles of Sustainability related to Construction Work	
1	Holistic approach
2	Continual improvement
3	Global thinking and local action
4	Involvement of interested parties
5	Equity
6	Long-term consideration
7	Responsibility
8	Precaution and Risk Management
9	Transparency

- **Holistic approach**

Sustainable social housing is a complex field. To address its complexity, a holistic approach is needed. In line with the most common definition of sustainability (WCED, 1987), the primary aspects of society, environment, and economy guide this thesis. For sustainability optimizations along these dimensions, the technical and functional requirements of a building need to be fulfilled (ISO 15392, 2008; EN 15643-1, 2010). These technical and functional requirements are outside the scope of the standards on sustainability assessment, but are considered “by reference to the functional equivalent” (EN 15643-1, 2010). In this thesis, the technical development forms an integral part of the assessment. The starting point of this thesis is the potential of a raw material and a need for housing. The current use of the raw material bamboo for housing in the Philippines does not meet these needs. Therefore, a building technology needs to be developed that meets the technical and functional requirements. Furthermore, client and regulatory requirements must be clear and documented. In the context of this thesis, the broader term ‘stakeholder requirement’ is adopted instead of client requirement, as several forms of clients exist including community organizations, NGOs, contractors, and government; and they all have very different requirements. With the given building segment and geography, this was interpreted as listening to and documenting existing multi-stakeholder requirements. Moreover, the relevance of governance for sustainability at scale is highlighted (UNESCAP, 2017). It comprises tangible themes like compliance to regulations and the legal approval of alternative building systems. Exceeding regulatory aspects, a long-term approach is needed in countries to address system barriers and enable institutional sustainability (UN-Habitat, 2012). Finally, the thesis adopts the concept outlined in ISO 15392 (2008), wherein social aspects are described as being closely related to cultural heritage. The cultural dimension, which is sometimes assessed separately, is captured as part of the social dimension in this thesis. The technical, regulatory, and cultural requirements are critical to bridge the gap between a theoretic approaches and realistic applications. In Figure 10, the multi-dimensional requirements and performance

assessment dimensions of this thesis are illustrated, as are their informing, iterative function over a 4-years period.

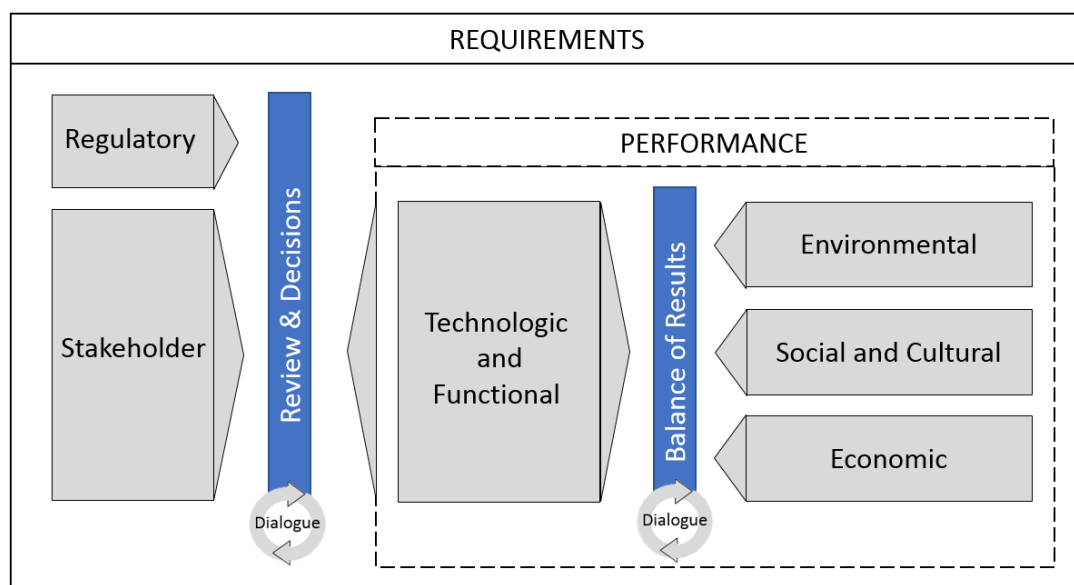


Figure 10 Holistic approach to technology development and assessment in this thesis

- **Continual improvement**

This thesis understands sustainability as a process of continual improvement and as a tool for decision-making. The ISO standard states that sustainability demands continual improvement, wherein all aspects of sustainability will improve over time (ISO 15392, 2008). The EN standards recommends an assessment at the “earliest opportunity during the conceptual stages. As a construction project evolves, periodical reviews are recommended to support decision-making. A final assessment, as-built, should be carried out to obtain final assessment results for communication” (EN 15643-1, 2010). This thesis adopts this approach and applies sustainability assessments during project design, for a continuous review during implementation, and at the completion of a project. The concept of ‘continuous improvement’ of this thesis goes beyond the building life cycle. It analyzes the potential of the raw material ‘round bamboo’ during research ahead of design and implementation. Furthermore, building technology is continuously optimized through a series of projects, using sustainability theory for decision-making throughout. Krank and Wallbaum (2011) studied several Asian countries and found that long-term implementation strategies improve the strength of sustainability indicator programs. The iterative improvement cycle between research, application and stakeholder review is at the center of this thesis. The continuous development cycle is shown in Figure 11.

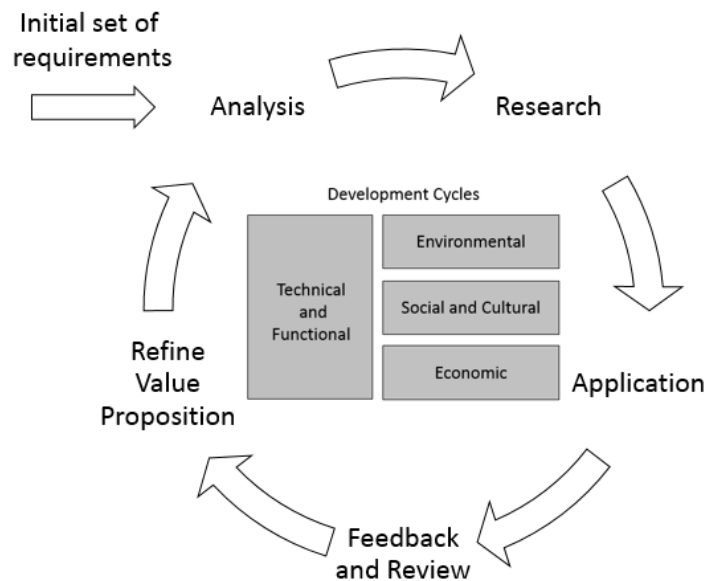


Figure 11 Continuous use of sustainability theory for decision-making

- **Global thinking, local action**

All guiding policy frameworks of today, such as the SDGs, NUA, or the Paris Agreement, acknowledge the interconnectedness of challenges in a globalized world. The localization of theoretic framework agreements is essential to provide meaningful guidance on the ground. This thesis highlights localization and, moreover, the backward integration of the local to the global as essential processes. EN and ISO standards explicitly mention a context-specific adjustment: “The application of sustainability to building construction needs to reflect the context in terms of goals, priorities, preconditions, possibilities and constraints.” (ISO15392). Furthermore, “the choice [of indicators] depends on requirements of interested parties, decision-making bodies, the local context and the availability of information” (ISO21929-1).

Social housing is a specific market segment with characteristics deferred from the general construction market, as outlined in Section 1.2.3. When taking the Philippine context into account (i.e., an emerging economy in the tropics), the international standards must be interpreted to meet the national context and local needs and regulations, as described in the Sections 1.2.2 and 1.4. However, similarities within the social housing segment in tropical areas around the globe can be found. The thesis acknowledges that South-South learning exchanges between Latin America and Asia-Pacific are of high value in this context. Furthermore, segment-specific South-North learning exchanges about the development of a suitable bamboo-based building method enable global thinking with local action. Regarding the definition of tangible, context-adjusted sustainability assessment indicators, a global set of sustainability indicators suggested in ISO and EN standards was localized through a multi-stakeholder process identifying local and segment requirements. For this process, the following stakeholder clusters were considered:

- Builders and users of traditional bamboo houses,
- Stakeholders involved in using forest products for housing around the world, and
- Stakeholders in the field of social housing in the Philippines

Throughout this thesis, the concept of boundary spanning groups was applied, in which “groups of various backgrounds and knowledge boundaries are brought together”, as described in Carlile (2004). Furthermore, the principle described by the International Fund for Agricultural Development (IFAD) was applied, where “local knowledge is blended with scientific results” (IFAD, 2010).

- **Stakeholder Participation**

The importance of developing a technology in a people-centered manner, ensuring that client’s needs are met, is highlighted in numerous studies (Thabrew, Wiek and Ries, 2009; Rizvi, 2010; Bal *et al.*, 2013). Participation is practiced by grassroots groups such as the Homeless People’s Federation of the Philippines (HPFPI) (2017) and NGOs in the social housing sector. The conceptual root of participation is that knowledge and ownership are socially constructed (Berger and Luckmann, 1967). Participation describes a process in which opinions are shared and created. Ideally, such sharing leads to a contribution in decision-making. It should be noted, that power-relations exist between stakeholder groups. Furthermore, they are affected in different ways by social housing. The participation of a stakeholder group may therefore be justified because of their decision-making competence or their legitimacy to be involved based on the level to which they are affected. It needs careful consideration and reflexivity on who’s knowledge and requirements (equally) need consideration (Chambers, 1997). Table 5 shows a comparison of the main stakeholder groups in the context of the thesis compared with the general groups mentioned in ISO12720.

Table 5 Stakeholder groups in this thesis and main ISO stakeholder groups

Main stakeholder groups for the thesis context	Main stakeholder groups mentioned in ISO
• National and local government • Housing Finance Institutions	• Regulatory body
• Local and international academia • Local and international professionals in engineering, architecture, urban planning	• Designer
• Private sector, NGOs and international organizations in social housing related fields • People living in informal settlements	• Contractor / Client / Users • Community
• People along the value chain of bamboo-based building (farmers, consolidators, pre-processors, local entrepreneurs, carpenters, construction workers)	• Suppliers / Manufacturers
	• Facility Managers

- **Equity**

This thesis carefully considers power relations in decision-making and inclusion along the life cycle phases with regard to sourcing, planning, production, and construction, as well as the buildings’ use and use-related services. While there was no standard formula or method for inclusion, all partners were committed to strive for active inclusion. Urbanization and the building sector are drivers for societal and economic development. However, opportunities are not equally spread to all income, gender, age, and minority groups. The equity principle in ISO standards refers to “intergenerational, interregional and intra-societal” ethics, including environmental protection, economic efficiency, and social needs (ISO 15392, 2008).

- **Long term considerations**

The thesis fully embraces the long-term objective of ISO standards, which is noticeable at multiple points throughout the thesis. On a building-level, durability, disaster risk reduction, and life cycle thinking are given high priority. Moreover, the thesis goes beyond a one-time building project. Exceeding the building level, aspects of replicability, and relevant system barriers become important. This is particularly noticeable in the social and economic indicators discussed in this thesis (e.g., income at local value chain, quality control, standardization, and scale), which go beyond the definition of ISO and EN. Regarding the application of a forest product-based technology at a larger scale, a specific requirement is a sustainably generated, accessible supply of quality-graded raw material. In many economies in which bamboo grows, a bamboo supply chain has to be built-up first (Paudel and Lobovikov, 2003). Thus, this aspect was fully considered here.

- **Responsibility**

Via a systematic assessment of micro through to macro scale, the thesis analyzes whether a building concept can meet local requirements. All processes throughout the value chain and along the life cycle are assessed of robustness. Examples include responsible processes with regards to treatment chemicals, the capacity building of the local workforce, and the quality of jobs created.

- **Transparency**

The thesis transparently documents and argues decisions and adjustments with regards to applied indicators. “When some aspects are not considered or are excluded from consideration, the reasons for such omission or exclusion shall be clearly explained and justified” (ISO/TS 21929-2, 2015). Indicators that were not applied are reported as Indicator Not Assessed (INA) (EN 15643-1, 2010). In cases, where the context-specific stakeholder assessment highlighted aspects that were not captured by the standards, these were recommended for inclusion. Regarding reporting, the concept of information groups is adopted from EN standards, “to ensure that the results of the assessment can be understood and interpreted in a transparent and systematic way” (EN 15643-1, 2010). For the verification of the results, (EN 16309, 2014) was adopted to justify the completeness, consistency, and traceability of the data. For the thesis, a more compact version of reporting was included.

2.2 Sustainability Assessment of Buildings According to EN and ISO Standards

This Section provides more details on the structure of EN15643 and ISO15392 and their related sub-standards on sustainability assessments of buildings (ISO 15392, 2008; EN 15643-1, 2010). In the Sections 2.2.1 to 2.2.4, the boundary conditions for the assessment are described using life cycle phases, the functional equivalent, its service life, and system boundaries. In Section 2.2.5, the sustainability aspects and indicators of the global and the European standard are summarized. These are localized in Section 2.2.6 through a segment- and geography-specific stakeholder assessment. They are summarized in Table 13 and provide the basis for the further assessment in this thesis.

The EN and ISO family of standards on sustainability assessments of buildings and construction were developed independent of but parallel to each other. Both institutions agreed through the Vienna Agreement to exchange and align on major principles and concepts (ISO/CEN, 2001).

Therefore, ISO and EN standards follow a matrix concept, in which axis one distinguishes the *social, ecological, and economical dimension* and axis two the *framework, building and product level*. However, the actual allocation of content to sub-standards differentiates on a framework level between the two institutions. Common to both is that a higher level of depth has been achieved for the environmental dimension, while gaps on building and product level exists in the social and economic dimensions. Despite this, EN 15643-1 recommends that “the sustainability assessment will be made concurrently and on an equal footing” across all dimensions. Future releases are expected to provide more guidance for the economic and social dimensions. In the following, the structure of both are described per level:

- On the *framework level*, the general standard of EN 15463-1, is complemented by parts -2, -3, and -4 for environmental, social, and economic dimensions, respectively. In ISO, the general framework standard, ISO15932, is complemented by technical specifications, a standard for indicators across all dimensions, one on terminology, and a sub-set of standards on Service Life Planning. Interrelations are highlighted through the ISO model.
- On the *building level*, EN released one standard per dimension, with 15978, 16309, and 16627 focusing on environment, social and economic dimensions, respectively. ISO released 21931-1 for the environmental dimension and refers to the framework level standard 15868-5 on life cycle costs for the economic dimension and the indicators 21929-1 for all three dimensions.

On the product level, both institutions focus on environmental product declarations, with EN having three standards (i.e., product categories, communication formats, and the selection and use of data) and ISO having released its first standard in 2017. As yet, ISO has introduced no standards regarding social and economic product level. EN refers to some portions of EN 15804, which contain selected interrelated social and economic aspects. The EN and ISO standards on the sustainability assessment of buildings and construction works are summarized in Table 6.

Table 6 EN and ISO standards on sustainability assessment of buildings and construction

Level	Aspect	EN	ISO
Framework or Methodology	General	15643-1 (2010)	15392 (2008)
	Environmental	15643-2 (2011)	
	Social	15643-3 (2012)	
	Economic	15643-4 (2012)	
	Tech. Specifications		12720 (2014)
	Indicators		21929-1 (2006, 2011) 21929-2 (2015)
	Terminology		21932 (2013)
	Service Life Planning		15686-1 to 10 (2014 to 2017)
Building	Environmental	15978 (2011)	21931-1 (2010)
	Social	16309 (2014)	
	Economic	16627 (2015)	15686-5 (2017)
Product	Environmental	15804 (2013)	21930 (2017)
		15942 (2011)	
		15941 (2012)	
	Social	See 15804	
	Economic	See 15804	

2.2.1 Life cycle phases of buildings

The sustainability of buildings is generally assessed using the life cycle approach. Buildings are assessed looking at their resource flows, emissions, and waste flows over their entire life cycle, that is, from cradle-to-grave. EN 15643 and ISO 15392 are aligned in naming the four stages of a building life cycle: (1) Product, (2) Construction, (3) Building Use, and (4) End-of-Life Stages. In addition, EN includes (0) Pre-construction and (5) Supplementary Information beyond the building life cycle. Supplementary information is to be documented separately from stages (0) to (4). In both standards, the four stages have clearly defined sub-stages, which are mostly aligned. Figure 12 illustrates the sub-stages of EN. There are sub-stages that do differ between ISO and EN. Table 33 of the Annex documents shows which standard was followed with respect to the sub-stages.

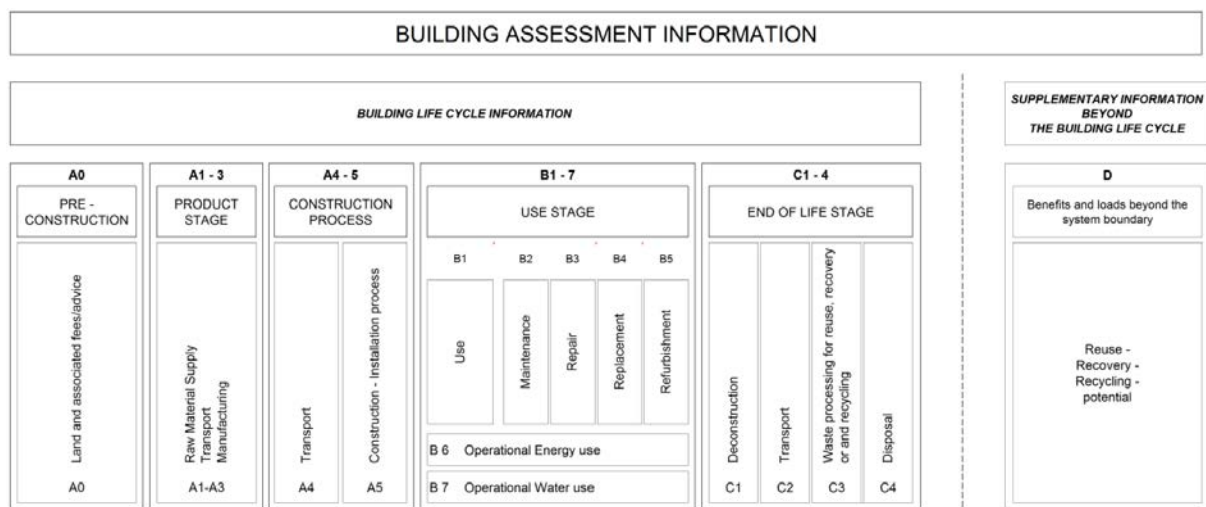


Figure 12: Life cycle phases according to EN 15643

According to EN standards, all impacts and aspects related to the building material and site are to be differentiated from those required for the building operation. ISO relates impacts and aspects also to processes and the location, providing a wider spatial context. This thesis adopts the broader ISO approach, although site- and location-specific aspects and indicators are set as a requirement because this thesis assessed various building projects. In addition to this definition on life cycle phases, the thesis adds a research and project review to the life cycle and expands the definition of planning. The expanded scope is named the Life Cycle of Technology Development for Buildings. For some life cycle phases, no empirically measured or quantitative data were available. These stages were covered using scenario analysis. In Table 7, the inflow data type is documented per the life cycle phase. As described in EN 15978 (2011), the data type has varied over the stages of research, planning, construction, and use, transitioning from scenarios to empirical data, where possible. A distinction is made for quantitative and/or, qualitative methods, a performance-based assessment versus a benchmarking compared with current social housing practices, and whether the input data were either empirical or measured, or scenario based. As no studied building has reached its end-of-life, scenario-based data were used at this stage. More insights are provided in Table 36 in the Annex, where each individual indicator is assessed.

Table 7 Input Data per Life Cycle Stages at the closure of the thesis

Legend L- Qualitative N- Quantitative A- Assessment C- Comparative E- Empiric data S- Scenario	Life Cycle Phase								
	Research*	Planning**	Sourcing	Production	Construction	Review and Local Economy Building*	Use	End of Life	Beyond Life Cycle
Dimension	E	A0	A1	A2-A3	A4-A5	B0	B1-B7	C1-C4	D
Environmental			NACE	NACE	NACE	NACE	NACS	NACS	NACS
Social	L/NAE	L/NAE	L/NAE	L/NAE	L/NAE	L/NAE	L/NAE		
Economic		NACS	NAE	NAE	NAE	NACE	NACE	NAS	
Technical	NAE	NAE					NACE		
Governance	LAE	LAE	LAE	LAE	LAE	LAE	LAE	LAS	

2.2.2 Functional equivalent

Sustainability assessments of buildings according to EN and ISO standards require a reference unit for documenting the sustainability performance of a building and, where aimed, for the transparent comparison with other buildings.

- EN15643-1 “For sustainability assessment the same functional equivalent shall be used for each of the individual dimensions of sustainability,” and the assessment shall be made “on the basis of the same technical characteristics and functionality of the object of assessment.”
- ISO 21929-1 “Sustainability indicators are often used for the comparison of design options or buildings. The user of indicators shall always ensure that the basis for comparison is consistent, appropriate and adequately defined.”

In the EN standards, this reference unit is called a functional equivalent (FE). All indicators used in this thesis for the assessment of technical, environmental, social and economic dimensions are compared with regards to this FE.

The standards distinguish between *building-specific* aspects and *site-specific* aspects. In contrast to the EN and ISO standard assumption, this thesis does not assess one specific building project. As introduced in Section 1.4, sustainability assessments are used throughout several implementation projects in various locations. Thus, the description of the FE focuses on building-specific aspects. The site-specific aspects are, however, rated as highly relevant requirements for sustainable building projects and are mentioned in the localized sustainability indicators in Section 0.

To transparently capture the FE, the *building technology* and the *design of the buildings* are described in the following. The building method is a shear wall system, wherein walls have a load bearing function. The shear walls are called Cement-Bamboo-Frames (CBF). Strength graded, treated full culm bamboo in its natural round shape is used for vertical studs. The roots of this building method lie in Latin America, where the system is called *bahareque*. Through a learning exchange with Colombia (Association of Earthquake Engineers Colombia, 2009), the characteristics of the frame system have been exchanged and interpreted for the Asian context. The design of CBFs consists of two general components: a shear resisting frame and the cover or wall cladding. The system is shown in Figure 13.

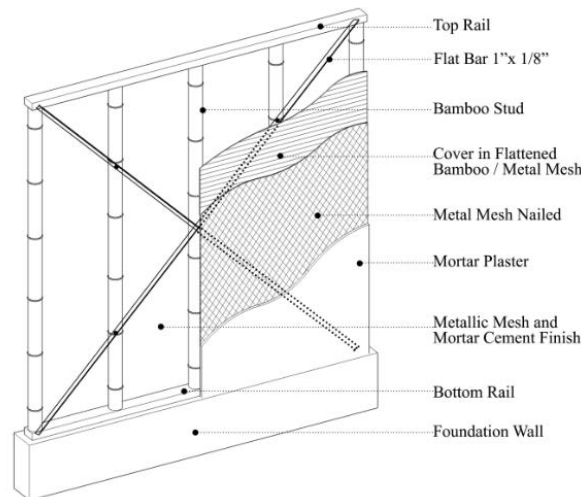


Figure 13 Cement-bamboo frames (Ministry of Housing Construction and Sanitation Peru and Inbar Latin America, 2009; Base Foundation, 2018)

The frame contains two horizontal timber rails (a bottom rail and a top rail) and bamboo studs or vertical elements, which are connected to the horizontal elements with threaded rods. The frame has metal braces to resist to lateral forces. Round bamboo braces have also been tested and used. The cover of the frame is made of a plaster carrier and the cement-based plaster. An expanded metal mesh is used in the plaster carrier. The traditional Latin American version using wire nailed to flattened bamboo as an organic plaster carrier has also been tested and used. The plaster carrier is anchored to the studs with nails. For flattened bamboo and chicken wire, additional soft iron wire is used braided between the nails. The individual walls transfer vertical and lateral loads and provide a combined action through the following mechanisms:

- Sufficient structural walls in both axes 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 gravitational 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.
- 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 must be designed according to the given specifications.
- 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 must be designed according to the stated specifications.

With regards to the building design, the thesis adopts the view of science and humanitarian practice; that is, there no one-size-fits-all solution for social housing. However, a standard design is used for the specific purpose of the FE. Customizations can be made to meet client-, regulatory- and site-specific requirements. The FE is a single detached house with a rectangular floor plan. It is a one-story social housing unit with a 25-m² floor area, as displayed in Figure

14. It is similar in appearance to standard houses found across the Philippines; this was a strongly expressed community preference in the participatory design stage. It is intended for residential use with natural ventilation. Furthermore, sufficient natural lighting was considered alongside artificial lighting. The unit has a conventional concrete foundation with a plain concrete finish of the floor slab. Although floor plan layouts change with each project, the general layout includes two full rooms and one shared area, with a bathroom and kitchen. In several projects, outside kitchens were preferred in exchange for larger rooms inside the house. The kitchen is a shelf with a cooking hob and sink. Sanitary facilities contain a toilet bowl and a water outlet for 'bucket showering.' Each room is separated by internal walls with a load bearing function. The ceilings are 2.44 m high, which is above the minimum standard (2.00 m) for social housing. The roof shape is either a hip or a gable roof, depending on the wind impact zone of the respective site. For this assessment, a hip roof was chosen at an angle of 32° for reduced wind turbulence, with a medium roof overhang for day-to-day sun protection, which can withstand uplift forces in extreme storms. The standard unit comes without ceiling cover. Normal doors and windows are used, which may vary from project to project as per client wishes. The doors and windows are arranged in a symmetric way, where possible, but feng shui requirements are also taken into consideration. For houses in wind zone 1, typhoon shutters are included. The waste water conveyance is a septic tank, being widespread practice in the country. The latter could be changed flexibly to more innovative components. Rainwater harvesting is applied in selected projects.

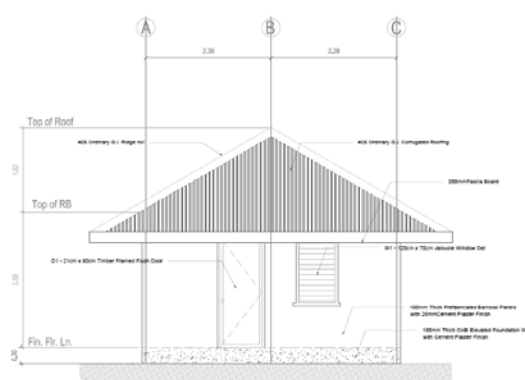


Figure 14 Illustration of the Functional Equivalent: one-story house of 25m²

2.2.3 Service life

Service life is an important variable in the technical, environmental, social and economic performance dimensions. In this thesis, the service life is determined according to ISO 15686-1 through 10 on Service Life Planning (ISO 15686-1, 2011). ISO describes the assumption of service life as a service life prediction (SLP). This is termed estimated service life (ESL) in EN standards. SLP for social housing in emerging economies involves higher levels of risk and uncertainty. The service life is closely connected to the technical and functional requirements, also named agents in ISO. Safety, risk, resilience, maintenance, and adaptation are among the directly related aspects. ISO 15686-1 states that, “To predict service life, one needs to know the microclimate, the performance of components under the intended condition, and the construction and maintenance regime.” According to ISO15686-2, a systematic methodology for the SLP of building components and buildings contains the following features: definition of requirements, impacts and technology characteristics, preparation of mechanisms and

performance characteristics, experimental buildings, in-use exposure and inspection of buildings and evaluation, analysis and interpretation and review and reporting. ISO describes those agents affecting the service life of building components as being of a mechanical, electromagnetic, thermal, chemical, and biological nature. The agents and respective requirements that enable service life are detailed in Table 8.

Table 8 Context-specific agents affecting the service life of building components

Agent Category	Specific agents (ISO15686) Technical Requirements (EN15643)	Action
Mechanical	Typhoons, Earthquakes, Rainfall, Vandalism and bullets	Design, Testing
Electromagnetic	Solar radiation	Design of UV protection (roof, cladding)
Thermal	Fire resistance Heat exposure	Testing Testing, Design, Surveys
Chemical	Water from soil and runoff	Design of Water Barriers
Biological	Molds, fungi, rodents, termites	Development and testing of anti-insect treatment

The SLP of the FE is 25 years, with a 25-years reference study period (RSP). The following methods for SLP according to ISO15686-2 (2012), were applied:

- Interpolation using data from a similar service environment**
 Most LCAs state that a service life of a building is assumed with 50 years (Ortiz, Castells and Sonnemann, 2009; Cabeza *et al.*, 2014; Abd Rashid and Yusoff, 2015). These LCAs focus mostly on houses with advanced technical building systems in the formal building sector. The 50-year assumption is supported by empirical evidence of existing building stock. In this thesis, the life span definition was not a pure technical consideration but reflected the characteristics of the building stock in the informal and social building sectors. These characteristics include rapid transitions in societal status for low-income populations in Asian cities, hot-humid climates, the existence of substandard building quality at the affordable housing level, and a high frequency of extreme impacts, which can cause the earlier failure of substandard structures. A service life of 25 years was therefore considered appropriate for structures in the informal sector, not only limited to bamboo-based building methods.
- Interpolation using data of comparable building methods in Latin America**
 Bamboo is often used following traditional methods in the Philippines (i.e., as a temporary material), with a service life of less than 5 years. In this thesis, a building technology with comprehensive technical testing suited to the urban housing context was considered. In other parts of the world, such advanced technologies with bamboo have a proven track record, reaching life spans of more than 100 years (Cleuren and Henkemans, 2003). Thus, a life span of 25 years for the alternative construction technologies was again considered appropriate.
- Extrapolation in the time dimension: 4-years in-use exposure in the Philippines**
 The studied structures were built and observed in the Philippines, with selected structures being 4 years old. As the service life relates to the main structural component, other components may require maintenance before the SLP. ISO 15686-2 states that “it can be uneconomic or impossible or not functionally desirable, to require all

components to retain acceptable performance without maintenance. Exceptions are structural elements, which do not require maintenance if other components remain in appropriate shape.” (2012). In ISO15686-1, a building’s 25-years design life requires replaceable components that must also last 25 years. It is argued, that “for temporary buildings, it is generally desirable to match the design lives of components to the one of the whole building.” (2011). Looking at the context of social housing in the Philippines, a different approach is suggested. Components may be allowed to last for shorter periods of time, such as 5 and 10 years. To prevent the degradation of the building through components with a shorter life span than the SLP of the building, maintenance is needed. A maintenance plan and manual are provided by the Base Foundation (2018). Maintenance has, however, also a social component (with acceptance and the priority setting of interventions) and an economic component (with the affordability of interventions). Non-compliance to a maintenance plan may result in unexpected degradation. Therefore, these agents need to be addressed to meet performance requirements. ISO 15686-1 provides a categorization of consequences of failures due to degradation, which is shown in Table 9.

Table 9 Hierarchy of safety concerns in ISO15686-1

Category	
1	Danger to life
2	Risk of injury
3	Danger to health
4	Costly repair
5	Costly because repeated
6	Interruption of building use
7	Security compromised
8	No exceptional problems

The Philippines is classified as belonging to a hot, very humid global climate classification of the tropics. Furthermore, the country is surrounded by sea. In line with ISO 15686-7, regular inspections are recommended, every 1 to 2 years for weak points such as galvanized iron roofing sheets, and every 5 years for structural components. A sample inspection of 2-year-old houses (i.e., 2 years of in-use exposure) is documented below. Aging exposure after 4 years confirmed no critical signs of deterioration, but regular maintenance was required for the corrugated metal roofing sheets. The results of the factor categories are shown in Table 10. Overall, the reference and site-specific grading were similar. The structural performance requirements were met despite the extreme indoor and outdoor environments. In some houses, indoor usage was more demanding than referenced, with six to 10 inhabitants. Several components were detected as of critical importance, such as the need for high quality treatment for the bamboo and several layers of moisture protection. This information led to a focus on quality control during treatment and construction in following projects and enabled a stable quality. Therefore, the main bamboo-based building method showed no signs of aging after 4 years. Work execution levels were found to be in line or higher than normal. Maintenance levels varied widely from low to high. A performance degree of 8 was provided for the metal roof sheets, showing initial symptoms of deterioration due to a lack of maintenance and possibly the use of a lower-quality material. It was

documented that the “accepted” quality standards for conventional components in social housing are still sub-standard and need improvement. Prescribed higher quality, pre-painted metal sheets were used for future projects.

Table 10 Typical performance evaluation of service life using the factor method

Factor Category	Designation	Reference in-use condition	Object-specific in-use condition Grading at Inspection	Factor value
A	Quality of Components	High	Normal to high	1.1/1.0= 1.1
B	Design Level	Very high	Very high	1.2/1.2=1.0
C	Work Execution Level	Normal	Normal to high	1.0/0.9=1.11
D	Indoor Environment	Normal	Normal to severe	1.0/1.1=0.9
E	Outdoor Environment	Severe	Severe	0.8/0.8=1.0
F	Usage conditions	Severe	Severe	0.8/0.8=1.0
G	Maintenance Level	Normal	Low / Normal / High	1.0/1.2=0.83, 1.0/0.8=1.25

According to the factor method of ISO 15686-8 (2008), equation 1, a life span of 22 to 34 years was obtained. The factor method shows that there is a risk of a slightly shortened life span, however the houses are likely to fulfil their function for longer. As described in the standard, the factor method is not an assurance and merely gives an empirically supported estimate based on available information. It reflects the “best effort,” but it cannot be expected to be truly accurate or precise. This method is to be used with care, as high uncertainties exist because of interlinkages and equal weighting. The calculation technique used in the factor method was found to introduce high uncertainty; therefore, it is only deemed appropriate in combination with the other SLP methods. For the assessment of in-use buildings and real life exposure, however, the method was considered very informative and a helpful approach for continuous improvement.

Thus, the 25-year assumption is considered sufficiently conservative and suitable for the given context. Critical functional properties such as conformity to the building regulations, comfort, and aesthetics, or critical economic properties such as acceptable maintenance and running cost, are further aspects that may impact the service life.

2.2.4 System boundaries

In the following, the system boundaries are described. This section is more specific to the assessment and should not to be confused with the limitations of the thesis. The following boundaries were set:

- Non-building-fabric related elements were excluded from the assessment. These elements, such as the finishing, can be flexibly adjusted to client specifications. In comparative portions of the thesis, the actual difference to conventional buildings is therefore important, as the relative difference may change due to non-building-fabric related components.
- The assessment was made for the geographic boundaries of the Philippines. There is the potential for knowledge exchange with other tropical emerging economies but this requires a local adaptation process. This thesis acknowledges knowledge is socially constructed and that there is a wide range of knowledge types (e.g., technical, cultural, and empirical).

- The focus on an urban setting was established to include the more comprehensive policies of urban spaces. The technology can be applied in rural settings in equal terms.
- Performance benchmarks for the individual indicators are defined through the sources referred to in Figure 16.
- Where possible, the assessment is based on quantitative indicators. For selected aspects, qualitative measures were defined.
- The depth of study in each dimension may not be homogeneous and reflect the state of the art knowledge in each dimension. In the EN and ISO standards, the environmental dimension has a higher depth than the social and economic assessments. The similar applies to this thesis. The technical dimension was guided by clear methodological approaches and allowed a similarly deep approach.

2.2.5 Sustainability assessment indicators according to EN and ISO

In this section, the sustainability assessment indicators defined in the global ISO and EN standards are described. Sustainability assessment indicators measure the performance of a sustainability aspect in relation to its requirement, to make an assessment about its impact. The relations among the term's aspect, indicator, requirement, performance, and impact are shown in Figure 15.

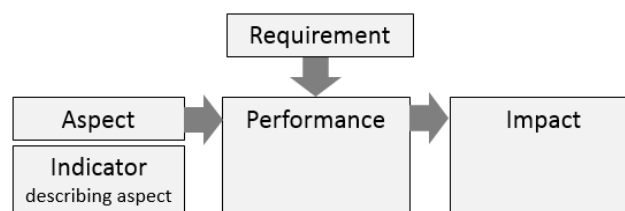


Figure 15 Terms used in ISO and EN sustainability assessments

ISO/TS 21929 names the general requirements and rules for establishing indicator systems. It states that indicators shall be “relevant, simple, valid, informative, sensitive, responsive, and reliable” (ISO/TS 21929-2, 2015). The standard does not define performance benchmarks or valuation methods that describe how to weigh or aggregate the results of indicators to draw a conclusion. Benchmarking and valuation are to be defined specific to the context.

The *ISO family of standards* names four conceptual levels, upon which sustainability indicators are organized. The general principles of sustainability are placed at the highest level, and guide this thesis, as documented in Section 2.1. Thereafter, seven areas of protection relevant to buildings are derived. ISO continues to describe the 14 main aspects of a building that influence the areas of protection; there are 15 indicators connected to these aspects. In ISO21919-1, the aspects and indicators are not allocated to one or more of the primary aspects of sustainability, environment (ENV), society (SOC), and economy (ECON). The latest ISO release, ISO/TS 21929-2 on indicators for the sustainability assessment of civil engineering works, states that, “ideally a sustainability indicator shall be linked to the three dimensions of sustainability”. It also highlights that “the division of [primary aspects and] protection areas along the dimensions is not explicit, thereby indicating the importance of integration.” The thesis incorporates the ISO/TS 21929-2 perspective by relating the indicators found in ISO 21929-1 to one or more of the primary aspects.

The EN family of standards allocates the indicators directly to the primary aspects of sustainability. Because of the division of separate standards, any interrelations among indicators are less visible and may be mentioned only in a comment. In the highly disaggregated environmental dimension, the main aspects (e.g., resources) provide an organizational heading for the actual indicators. These headings are comparable to the level of the areas of protection in ISO. In Table 12, all EN and ISO indicators are shown. In total, EN contains 29 indicators, 21 are allocated to the environment, six to social aspects, and two to the economic dimension. Moreover, its Annex includes an additional eight indicators for the environmental dimension and two each for the social and economic dimensions. While their relevance is acknowledged by their mention, their measure or measurability is contested. Adopting the classification of the Inter-Agency and Expert Group on SDG Indicators, displayed in Table 11, the indicators included in the main body are mostly Tier 2 indicators. Annex indicators belong to Tier 3.

Table 11 Tier classification of sustainability indicators by IAEG SDGs (UN, 2017b)

Tier Classification	Definition
Tier 1	Indicator conceptually clear with internationally established methodology and standards. Data is regularly produced by at least 50% of the countries where it is applies
Tier 2	Indicator conceptually clear. Data is not regularly produced
Tier 3	No internationally established methodology and standard, but will be developed or tested

The number of indicators in the environmental dimension of EN indicates the scientific depth that has been achieved for environmental declarations in Europe. ISO contains a total of 15 indicators. No classification in one of the dimensions exist, instead direct influences (indicated by ‘xx’) and indirect influences (indicated by ‘x’) on the three dimensions are described. For directly environmental indicators, these have a higher aggregation level than in EN. A further 15 further indicators are mentioned in the Annex of ISO. Moreover, ISO/TS 21929-2 contains several indicators of relevance for this thesis, which are expected to be included in a revision of ISO 21929-1. These are therefore included in the list of ISO indicators. In general, ISO contains and mentions a broader spectrum of indicators with social and economic relations.

Table 12 Sustainability indicators included or mentioned in EN (left) and ISO (right)

Main Aspects EN15643-1			Main Aspects: ISO21929-1/-2 x = indirect influence, xx = direct influence, + = unspecified influence			Dimension		
No	Name	Allocation	No	Name	Allocation	SOC	ENV	ECON
1	Abiotic depletion potential	15643-2 (ENV)	1	Emissions to air- Global Warming	21929-1	x	xx	x
2	Acidification of land / water resources		2	Emissions to air- Ozone Depletion		x	xx	x
3	Destruction stratospheric ozone layer		3	Use of non-renewable resources		x	xx	x
4	Eutrophication		4	Fresh water consumption		x	xx	x
5	Formation of ground-level ozone		5	Waste generation		x	xx	
6	Global Warming Potential		6	Change of land use		x	xx	
7	Non-renewable primary energy		7	Access to services		xx	x	x
8	Renewable primary energy		8	Accessibility (1) with disability (2) to and from site		xx		
9	Non-renewable primary energy as raw material		9	Indoor conditions and air quality		xx		x
10	Renewable pri energy as raw material		10	Adaptability		x	x	xx
11	Secondary materials		11	Aesthetic quality		xx		
12	Non-renewable secondary fuels		12	Life Cycle Costs				xx
13	Renewable secondary fuels		13	Maintainability		x	x	xx
14	Freshwater resources		14	Safety		xx		x
15	Reuse		15	Serviceability				xx
16	Recycling		1	Emissions to Water- Eutrophication	21929-1 Annex		+	
17	Energy Recovery		2	Emissions to land, water- Acidification		+	+	
18	Non-hazardous waste disposal		3	Emissions to air- tropospheric ozone		+	+	
19	Hazardous waste disposal		4	Use of renewable resources			+	+
20	Radioactive waste disposal		5	Protection of natural features			+	
21	Exported Energy		6	Ecological quality of the site			+	
1	Accessibility	15643-3 (SOC)	7	Potential to affect surface drainage			+	
2	Adaptability		8	Nuisance on the neighborhood		+		
3	Health and Comfort		9	Outdoor conditions		+		+
4	Loadings on the neighborhood		10	Heat island effect		+	+	
5	Maintenance		11	Participation		+		
6	Safety		12	Value Stability				+
1	Life Cycle Cost	15643-4 (ECON)	1	Social inclusion and acceptability	21929-2	+		
2	Financial Value	15643-2 (ENV) Annex	2	Cultural heritage elements		+		
1	Biodiversity		3	External costs				+
2	Ecotoxicity		4	Job creation		+		+
3	Human toxicity		5	Risk and Resilience		+		+
4	Land use change							
5	Use of non-renewable resources other than pri energy							
6	Use of renewable resources other than pri energy							
7	Sustainably managed materials							
8	Sustainably managed fuels							
1	Sourcing of Materials and Services	15643-3 (SOC) Annex						
2	Stakeholder Involvement	15643-4 ECON Annex						
1	Value Stability, short-term							
2	Value Stability, medium to long term							

2.2.6 Localization of sustainability assessment indicators

In this section, the global indicators are localized through a segment- and geography-specific stakeholder assessment, as introduced through the objective “global thinking, local action” in Section 2.1. The stakeholder assessment was used to confirm or reject indicators suggested in the ISO and EN standards. In line with EN, national or stakeholder requirements exceeding the standards were used to set the minimum benchmark. In some cases, the stakeholder assessment revealed the need for an aspect or indicator that was not yet included or mentioned in the standards. In Figure 16, the systematic localization of requirements and indicators is shown. In line with the priority settings described in the global standard and policy agreements, the highest priority is given to national regulations and stakeholder requirements.

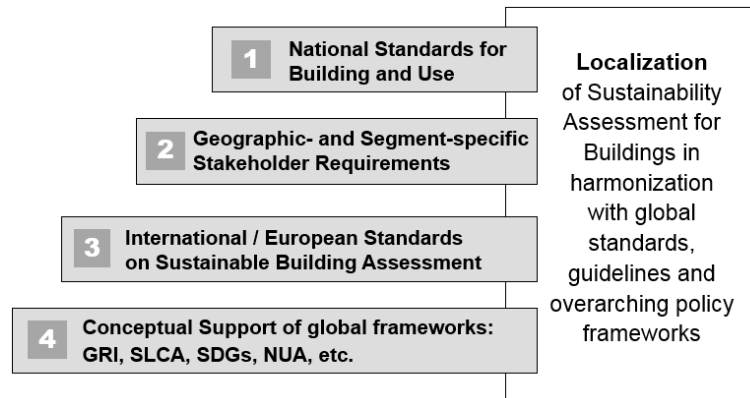


Figure 16 Prioritization and localization principles according to information source

This thesis documents and aims to justify any adjustments made to ensure transparency, as demanded by EN and ISO: “When some aspects are not considered or are excluded from consideration, the reasons for such omission or exclusion shall be clearly explained and justified” (ISO/TS 21929-2). This section provides a narrative explanation. A summary in table format on those indicators deemed irrelevant can be found in Table 34 and Table 35 in the Annex. Indicators that were not applied, but are relevant, are reported as Indicator Not Assessed (INA) (EN15643-1). In the following, the methods for stakeholder identification, data gathering, and data evaluation are described. Thereafter, a discussion of the stakeholder requirements in light of the EN and ISO standard indicators is provided.

- **Method for stakeholder identification, data gathering, and data evaluation**

A wide range of stakeholders have various interests in the building sector (Feige, Wallbaum and Krank, 2011). Significant differences among interested parties or stakeholders exist in terms of their interpretation of the “scope, content, level of detail, and priorities” (ISO 15392, 2008). The definition of stakeholder groups can influence their opportunity to contribute.

Regarding the selection of stakeholders, Fraser *et al.* (2006), Bal *et al.* (2013), and Waas *et al.* (2014) distinguish two general approaches: a top-down or expert-driven approach and a bottom-up or stakeholder-driven approach. A combination of both reflects the most recent scientific recommendations and was applied here. It ensures the comprehensive capture of barriers and opportunities and enables participation and ownership by all involved societal groups. Active consideration was given to groups that possess less decision-making power in current systems but are strongly affected by social housing and its value chains. The disaggregation of stakeholder sub-groups enabled the inclusion of minority groups with legitimate contributions. Furthermore, a realistic approach was followed close to the realities of implementation. Therefore, also groups with high decision-making power in the social housing landscape were involved. Expert and grassroots stakeholders were identified from three clusters of stakeholders: builders and users of traditional bamboo houses, stakeholders involved in using forest products for housing around the world, and stakeholders in the field of social housing in the Philippines. The stakeholder groups within social housing were national and local governments, academia in engineering, architecture, and urban planning, people living in informal settlements, people along the value chain including farmers and construction workers, the private sector in construction of low rise residential housing, NGOs and international agencies, and financial institutions that provide loans for housing.

Acknowledging the diverse types of knowledge and experiences that exist, those with explicit knowledge (e.g., scientists) and tacit knowledge (e.g., traditional practitioners) were brought together. Local, regional and global learning exchange partners were identified and brought together, to form boundary-spanning groups (Carlile, 2004), inspired by diffusion processes of innovation processes (Rogers, 2002).

For the identification of requirements, two forms of exchange were chosen: interviews and dialogues or focus group discussions. Dialogues were used along the life cycle of sourcing, planning, production, and construction. As an initial input for research, stakeholder surveys were conducted. The stakeholder requirements were captured through cognitive interviews following the interview principles for research and evaluation described in Patton (2015). 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 a *guided interview approach* was chosen. In addition to interview data, *field inspections* or *direct observations* were carried out over a 4-years period.

Barriers and opportunities, expressed by stakeholders or documented in field observations, were transformed in a qualitative *content analysis* to elicit the most suitable sustainability indicators for the given case. In line with the structure of ISO/TS 21929-2 (2015), an aspect was coded into one or several dimensions of sustainability. In the case of this thesis, the technology performance and the regulatory requirements were included, along with the environment, society and culture, and economy.

Several sampling strategies were used for second-level sorting, as described in Chowdhury (2014), and these 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 with the present case.

The third level comprised a *literature review and field observations* (where available). These were used to triangulate identified requirement patterns. The content analysis then derived sustainability indicators from the identified patterns. This can be described as *analytic induction*, as it moves from existing concepts to generating a new, case-specific indicator set. A more detailed explanation of this process can be found in Salzer *et al.* (2016). The localization results from the stakeholder process are summarized in the following for the performance of the technology, society, economy, and environment dimensions.

- **Discussion of stakeholder requirements considering EN/ ISO standard indicators**
The fulfillment of *technical aspects* is a requirement in the ISO and EN standards. For this thesis, they were included as core components of the assessment. The use of local raw materials in social housing often lacks technical development for reliable, durable, and legally approved performance. The aspects and indicators of the technical dimension are stated in Table 13. More details are provided in Section 2.3.

The *socio-economic aspects* that can be found in the standards and that were mentioned in the stakeholder assessment are *safety, health and comfort, adaptability, and maintenance*. All four aspects are linked to the economic, environmental and/or technical dimensions, but are categorized as either social or economic aspects for reporting purposes only. The respective indicators are described in the Sections 2.3, 2.5.3, 2.3.5, and 2.5.

An important aspect from the stakeholder assessment was participation. While it is not included in the standards, it is mentioned in the Annexes. Its relevance is therefore acknowledged, but its measurability needs more discussion. Generally, ISO standards go beyond EN standards in the social dimension by mentioning the indicators cultural heritage, social inclusion, and acceptability. These are either mentioned in the Annex of ISO 21929-1 (2011) or are an indicator in the recent release ISO/TS 21292-2 (2015). The broader perspective of ISO resonates to the stakeholder assessment. In this thesis, the aspects are termed *participation and inclusion*, which refers to involvement that particularly addresses power relations and silent stakeholders, *acceptance*, which refers to post-occupation acceptance and market uptake, and *identification and cultural heritage*, which denotes the degree that solutions are culturally rooted.

The aspects of *adaptability* and *maintenance* are highly interrelated across the performance dimensions. Adaptability, according to ISO, refers to a change in size, use, and adaptation to climate change. This thesis only considers changes in size because the building use was fixed (i.e., residential use). Adaptation to climate change is covered through the technical performance of safety and resistance. Moreover, adaptability is related to economic affordability, and the availability of services in a local value chain, and the social acceptance of a technical method. The example of adaptability shows, how the aspect can be disaggregated into four indicators (two economic, one social, and one technical). Two aspects of ISO and EN were found to be less applicable for the given context. These were sound on the neighborhood and accessibility. Accessibility refers to access to a building for those people with special needs. In low-rise housing, access of this sort can be incorporated but is not considered a standard feature because of extreme economic limitations. It is not building technology-specific and may be added where needed. One example of such additions can be seen at Bagong Silangan, a settlement project built by Base Foundation and its partner, the Vincentian Foundation (see Figure 17): a ramp was included to meet the needs of the users. This aspect is not assessed in this thesis.



Figure 17 Accessibility to buildings in Bagong Silangan (picture: Base Foundation)

In relation to accessibility, a different angle of this aspect is highlighted. It was derived from the stakeholder assessment and is also named in the ISO standards: *access to services* and *access to a source of income and education*. These are site-specific aspects with economic, social, and governance implications. As the thesis assesses various projects, these aspects are requirements for building projects. This is mentioned because it is a common deficit in social housing and therefore an important condition for a site. While all Base projects look at these aspects, measurable indicators may help to determine acceptable levels, such as the percentage of income spent to reach the opportunity to earn. The ISO Annex contains two further interesting aspects, heat island effect and outdoor conditions, but would require a further investigation regarding measurability. In addition, ISO/TS 21929-2 includes the aspect *risk and resilience*, which is highly complex with linkages to social, economic, technical, and environmental dimension. The stakeholder assessment clearly highlighted the need for this aspect. Technical research covers the aspects safety and resistance. The economic and environmental dimensions include disaster risk scenarios that would result in a shorter service life of the buildings. The social dimension of risk and resilience is most complex. It is partially captured through the process-oriented aspect of *capacity building and sharing*, which was only identified in the localization and is not found in any standard. The economic dimension was covered through *economics of a local value chain*. It is interrelated to the aspect *Sourcing of Materials and Services*. Here, EN exceeds ISO as it mentions this aspect in its Annex.

With regards to economic aspects, a strong driver in decision-making and accessibility to housing is *initial construction costs (ICCs)*, which are one part of the *life cycle costs (LCCs)*. Because of the relevance of ICCs to the sector, they are mentioned, although they are not covered in the EN and ISO standards. LCCs are a theoretically widely spread concept, which faces various barriers in application, such as potential conflicts of interest between owners and tenants. This thesis generally advocates for life cycle perspectives in social housing, but they are recognized as being at some distance from the realities of the sector.

EN mentions a second economic aspect, *financial value*. In the Annexes of the ISO and EN, the indicator *value stability* is mentioned. The pure economic concept of value as defined in the EN does not resonate well with the social housing context, considering service life and system challenges such as barriers for land tenure or titles (see Section 2.2.1). However, the ISO describes that “value” is conceptually broader and not intended to refer solely to “economic value.” Prior to use of this indicator, its measure would require further discussion.

The economic indicators job creation and external costs were included in ISO/TS 21929-2. *Job creation* has a strong social linkage, next to its economic implication. It relates well to the stakeholder assessment, which derived the aspect *income at local value chain* and is related to *capacity building and sharing*. While external costs are a relevant aspect, their measure requires further discussion. This aspect is not included in the thesis but it is recommended that it be assessed in further research. In the economic dimension, further systemic aspects were highlighted in the stakeholder assessment, which cannot be found in the standards. While the standards look at the systemic influence in the environmental dimensions, the social and economic dimensions focus

on the building itself. Acknowledging the relevance of the construction sector in the economic dimension, four system-related economic aspects are added. These are *economic efficiency*, which is split into *standardization*, *quality control and pace*, the aspect *continuous innovation*, referring to the investment into research and development, the aspect *model to address system barriers*, and the previously mentioned socio-economic aspect of *access to sources of income*. The aspects are based on the long-term perspective of sustainability assessments and the systemic view of social housing as a relevant sector contributing to urban development and urban inequality.

In the *environmental dimension*, EN has the highest level of disaggregation of indicators, whereas ISO specifies fewer indicators and uses higher aggregation levels. This thesis covers most of the environmental aspects through its LCA. The indicators Global Warming Potential (GWP) and Cumulative Energy Demand (CED) are used as proxy measures, as discussed in Huijbregts *et al.* (2010). In addition, the multi-issue indicator Impact2002+ was used, which incorporates 14 single-issue indicators, mentioned in EN. An individual assessment of the single issues remains possible with this indicator. They are reported in their areas of protection: natural resources, climate change, human health, and ecosystems. The LCA indicators have methodological shortcomings on *land-use change*, *scarcity* and *biodiversity*. Biodiversity is mentioned in the EN Annex and scarcity is partially covered by the *protection of a valuable environmental feature* in the ISO Annex. Land use change is an ISO indicator and mentioned in the EN Annex. However, ISO looks at land use change only with regard to the property of the building. This thesis suggests a broader perspective on land use change that also covers the changes caused by sourcing. The paper discusses these aspects but cannot overcome the highly complex methodological challenges in the assessment. Therefore, they are excluded. The harmonization and inclusion of scientifically accepted indicators into LCA is recommended in the future. From the additional aspects and indicators mentioned in the EN Annex, the multi-dimensional indicators *sustainably managed materials* and *renewable materials other than primary energy* are highly relevant to this thesis. These aspects are interrelated to the above-mentioned areas of improvement. As bamboo is not planted but taken from renewable existing stands, the method of harvesting is important to determine whether depletion occurs and has an advantage over plantation wood.

In total, the stakeholder assessment derived 21 aspects of relevance for bamboo-based social housing in the Philippines. Many of these aspects are connected to several performance dimensions, particularly in the social and economic dimension. The disaggregation of the aspects into single-issue indicators produced 98 indicators. The localized sustainability assessment aspects and indicators (LOC) are documented in Table 13. Their relation to the performance dimensions of society, environment, economy, technology, and governance is stated. In the table, an 'x' is used if an aspect was found in ISO, EN, or the stakeholder assessment, and an '(x)' denotes that the aspect was only mentioned in the Annexes of the standards.

Table 13 Aspects and indicators: ISO, EN, and the stakeholder assessment (LOC)

No.	Aspect	Source			Indicator x = indicator included (x) = indicator mentioned in Annex x* = Indicator included in ISO/TS 21929-2 x**= Indicator included, but modified content	Dimension				
		LOC	ISO	EN		SOC	ENV	ECON	TECH	GOV
1	Safety, Risk and Resilience	x	req	req	Mechanical properties of local raw material				1	
		x	req	req	Durability of local raw material				1	
		x	req	req	Resistance Building System (Racking Strength)				1	
		x	req	req	Resistance to extreme impacts: Fire				1	
		x	req	req	Resistance to extreme impacts: Earthquakes				1	
		x	req	req	Resistance to extreme impacts: Typhoons				1	
		x	x	X	Safety against Intruders and Vandalism				1	
		x			Quality and Risk Management				1	
		x			Social Vulnerability of inhabitants	1				
2	Participation & Inclusion	x	(x)	(x)	Resilience through sourcing of local materials	1				
		x			Participation along Life Cycle	1				
		x	x*		Active and Empowering Type of Participation	1				
3	Culture	x	x*		Inclusiveness in Decision-making	1				
4	Acceptability	x	(x)		Inclusion of heritage elements	1				
		x			Social acceptance	1				
5	Capacity building & Sharing	x			Market Demand			1		
		x			Skill level needed	1				
		x			Number of people trained	1				
		x			Increase of future job opportunities			1		
		x			Open Technology					1
		x			People reached through learning exchange	1				
6	Health and comfort	x			People reached through digital platforms	1				
		x	x	X	Thermal Comfort (temperature)	1			1	
		x	x	X	Thermal Comfort (ventilation)	1			1	
		x	x	X	Visual Comfort (Daylight factor)	1			1	
		(x)	x	X	Acoustic Comfort	1			1	
		x	x**	x**	Spatial cost within cost seal (no. of rooms)	1		1		
		x	x**	x**	Spatial cost within cost seal (floor plan size)	1		1		
7	Use Phase Services (Maintenance, Adaptability)	x	x**	x**	Spatial cost within cost seal (ceiling height)	1		1		
		x			Comfort induced energy consumption during use		1	1		
		x	x	x	Technical Adaptation Potential				1	
		x			Lot space enabling expansion			1		1
		x	x	x	Maintenance and Adaptation affordability			1		
		x			Availability of service provider for expansion			1		
		x	x		Acceptability to consult service provider	1				
		x	x	x	Maintenance Need (intervention, frequency)				1	
8	Regulatory compliance	x			Availability of service provider for maintenance			1		
		x	x		Acceptability to consult service provider	1				
9	Building related cost	x	req	req	Compliance to local regulations					1
		x			Approval scheme for innovative technologies					1
10	Economic efficiency of construction	x	x	x	Initial Construction Costs			1		
		x			Life Cycle Costs			1		
11	Equity of sites	x			Standardization			1		
		x			Expenditure for Quality and Risk Management			1		
		x			Pace of construction			1		
		req	x	x	Quality of Transport	1				
12	Local Economies	req			Time and expense to reach job and education	1		1		
		req	x	(x)	Access to basic services and infrastructure	1				
		req			Geohazard assessment of sites					1
		x			Investment into local economy			1		
		x			Expenditure in research on social housing			1		
		x			Partnerships to address system barriers			1		1
		x			Financial model to scale			1		
		x	x		Project based jobs created >6 month			1		
		x	(x)		Jobs sustained through market development			1		
		x	(x)		Quality of jobs created	1				
		x			Percentage of local employment	1				
		x			Sourcing of Material and Services (see aspects 7 and 18 to avoid redundancy)					

Table 14 Aspects and indicators: ISO, EN, and the stakeholder assessment (LOC) cont.

No.	Aspect	Source			Indicator	Dimension				
		LOC	ISO	EN		SOC	ENV	ECON	TECH	GOV
13	Global Warming	x	x	x	Climate Change Mitigation (Global Warming Potential)		1			
14	Natural Resources	x	x	x	Impact2002+ Natural Resources (Non-renewable energy, mineral extraction), Cumulative Energy Demand (Non-renewable primary energy, Renewable primary energy, Non-renewable primary energy as raw material, Renewable primary energy as raw material, Non-renewable secondary fuels, Renewable secondary fuels)		7			
15	Human Health	x	x	x	Impact2002+ Human Health (Human toxicity, respiratory effects, ionizing radiation, ozone layer depletion, photochemical oxidation)		5			
16	Ecosystems	x	x	x	Impact2002+ Ecosystems (Aquatic and terrestrial ecotoxicity, aquatic and terrestrial acidification, aquatic eutrophication, water turbidity, withdrawal and consumption)		8			
17	Waste	x	x	x	Reuse, Recycling, Energy Recovery, Non-hazardous waste disposal, hazardous waste disposal		5			
18	Sustainable material sourcing	x	(x)	(x)	Controlled quantity, transparent and controlled source and supplier, controlled species		1			
19	Renewable resource use	x	(x)		Decoupling growth from resource depletion through non-depleting harvesting practice from rapidly renewable raw material		1			
20	Biodiversity	x		(x)	n.A.		1			
21	Land Use Change	x	x		Shortcomings		1			
						25	31	22	14	6

2.2.7 Valuation of results

Valuation describes the process of weighting results generated within the performance dimensions, and the respective single-issue indicators allocated to them to derive recommendations for decision-making. Many different valuation methods exist. For technology comparisons, for example, the collective term multi-criteria decision-making (MCDM) is often used. Mardani, Jusoh, and Zavadskas (2015) list and compared over 400 MCDM techniques and applications published within a two-decade period. Engineering was ranked the most common field of application. For civil engineering, it was applied to building materials (Akadiri, Olomolaiye and Chinyio, 2013), housing-related choices (Contreras-miranda, Cloquell-ballester and Contreras, 2010; Mulliner, Smallbone and Maliene, 2013; Medineckiene *et al.*, 2015), or renovation choices (Tupenaite *et al.*, 2010). As alternative to hard target numbers, as typically used in MCDM, pareto optimization is a method that identifies solutions with best possible balance (Ostermeyer, Wallbaum and Reuter, 2013). Most of the studies on valuation compare technologies that are already established in the market. Valuation is used as a one-time process of decision-making. This is methodologically different to this thesis, where technology development and its implementation is continuously guided and assessed according to sustainability theory. The process of a one-time valuation bears the risk of introducing subjectivity and uncertainty, exceeding the uncertainty connected to single-issue results.

Valuation must answer the question of who should have the power to decide on the weighting of performance dimensions and indicators and who is making the decisions.

A set of multiple single-issue sustainability indicators often generates the desire to condense the complexity into simpler measures. The process of valuation, however, introduces power

relations. Thus, it can be asked, is an aggregated one-score result required to make effective decisions? When no valuation is provided, it may be interpreted as a default weighting. In such cases, the aggregation may sensitively change the results. The economic dimension, for example, contains only one or two indicators according to EN and ISO. Is it justified then to allocate a higher weighting to these as compared with highly disaggregated environmental indicators? Many social indicators, as another example, are excluded from the standards because they are difficult to measure. Is it justified to exclude these aspects from the weighting, as their assessment in the first place would have been contested or contained a higher level of uncertainty? Last, the comparison of the standards in the environmental dimension shows a much higher level of disaggregation in EN standards compared with ISO. Is it appropriate to evaluate higher data precision with more weight on the overall result? Both EN and ISO standards focus on the analytical part of the quantification and do not provide valuation methods for the aggregation of indicators. ISO 15392 states that it “does not set priorities, [as] prioritization relates to specific concerns,” and that “the overall aim is to minimize adverse impacts in any of the dimensions, while providing the required value.” This definition makes the standards applicable to various geographies and sectors.

Value propositions are generally subject to constant review. Therefore, a valuation is a snapshot that may quickly become outdated. Therefore, a valuation through an author-determined, fixed weighting scheme does not fit the principles of the thesis. This thesis places significant emphasis on the importance of multi-stakeholder dialogues, inclusion, and the continuous use of sustainability in theory and implementation. In this sense, the results shall be used. Based on the principle of EN, the primary aspects of sustainability are generally interpreted on an equal footing. A visual summary of the performance dimensions is provided in the results section with the aim to simplify communication. For detailed insights, references are made to specific sections concerning the performance dimension and published papers, where the results are transparently documented. This open-ended valuation increases the opportunity for learning exchanges within the social housing segment of further geographies in the tropics, where specific value sets may be adjusted to contextual needs.

2.3 Methods to Determine Technical Performance and Regulatory Compliance

The systematic technical research from material to system and building-scale enables the assessment of the alternative building technology used to erect the FE. This is the basis upon which to evaluate the safety and regulatory compliance of a previously undefined forest product with the requirements of an urban built environment. By ensuring that the technology satisfies legal standards and building codes for permanent houses, a comparison with existing building methods is possible. The different scales of technical research are shown in Figure 18.

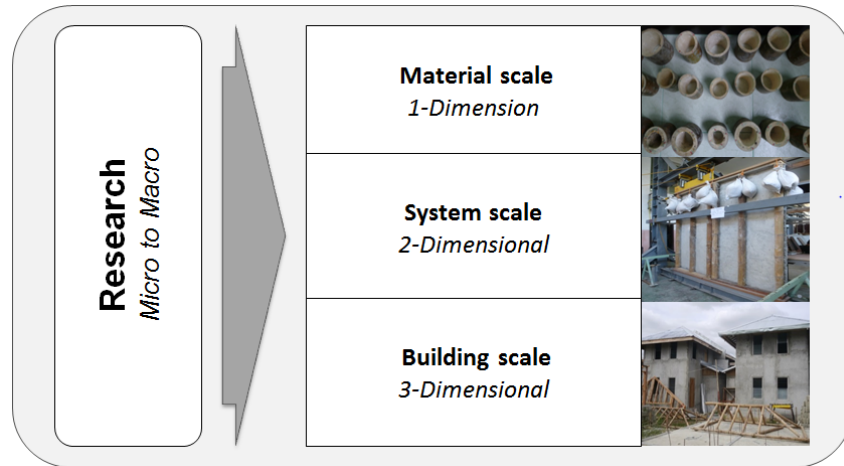


Figure 18: Systemic research of the thesis from micro to macro perspectives

The technical aspects are broken down into issue-specific, quantifiable indicators. The key aspects that motivate the technical research agenda are safety, risk and resilience, regulatory compliance, and the technical performance throughout the life cycle, particularly in the supply chain and during the use. The construction system is measured by its capacity throughout the service life to resist the impacts described in the national regulations; these are adjusted to meet the needs of the respective sites. In EN 16039 (2014), this contains projected loadings such as rain, wind, fire, and where applicable, earthquakes, flooding, or landslides. This thesis acknowledges the need for resistance against mold and insects because of the use of biogenic raw materials. Achievements in this area are not reported in this thesis, but are communicated by the Base Foundation (2018) and its partner Bambou Science et Innovation (BSI) (2017). Regular day-to-day impacts (e.g., vertical and lateral loads, and sun or rain) must be considered to ensure the service life of a building. Thus, for biogenic building materials, it is essential that water and Ultraviolet (UV) impacts are carefully managed. Barriers against capillary water from the ground, safe runoffs for driving rain, and surface water drainage were considered in the house and settlement design. Regarding the UV impact, it is referred to the health and comfort section as well as in the quality and risk management process aspects, where it found consideration. A knowledge gap was identified for bamboo-based housing with regard to fire resistance. This issue has been assessed in a research agenda documented in Section 2.3.3. Taking into account the particular context of the Philippines, extreme winds or typhoons have a critical impact with the potential for high levels of damage. Thus, Section 2.3.4 specifies the methods in this research field. With regard to earthquake resistance, experience and knowledge from Latin America were transferred to the Philippines; there is evidence of a remarkable performance in this aspect. Therefore, this subject is not studied closely in this dimension. With regard to flooding, site drainage is a must for all construction sites. Adhering to the need to be precautionary, it is assumed that occasional minor flooding of up to 300 mm may occur on every site. This is tackled by elevating the bio-based materials using a concrete plinth to protect both the wall elements and people's property from water damage. It is not recommended that buildings are built on sites that flood above this level. Aspects not assessed in the EN standards are safety from explosions and traffic impacts. Overall, the methods range from a literature study and expert exchange, the testing of materials in laboratories to field testing. Both EN and ISO standards mention resistance to climate change. This refers to loadings exceeding the current regulated impact levels. To address this issue, the results of the aspects are classified in 'below', 'meets', or 'exceeds' the requirements set.

The regulatory requirements are defined in the Building Code of the Philippines, the National Structural Code of the Philippines Volume 1 (2015), the BP220 on requirements for social housing in the Philippines, and the Colombian Building Code (NSR AIS) on *bahareque buildings of one and two stories* (2009). Where stakeholder requirements exceeded national requirements, stakeholder needs were used as the benchmark. Where no national requirements existed, recommendations based on global standards were followed. The indicators and their measures are summarized in Table 15. Further insights to specific methodologies are provided in the sub-sections that follow.

Table 15 Technical aspects and issue-specific indicators and their measures

No.	Aspect	Source			Indicator x = indicator included (x) = indicator in Annex x* = ISO/TS 21929-2 x**= Indicator with modified content	Method / Normative Reference	Type
		LOC	ISO	EN			
1	Safety, Risk and Resilience	x	Req	Req	Mechanical properties of local raw material	ISO22157, ISO22156 Characteristic Values and Permissible Stresses	Use
		x	Req	Req	Durability of local raw material	Efficacy test with local insects, penetration depth during treatment, long-term exposure test	Life Cycle
		x	Req	Req	Resistance Building System Racking Strength	EN594, ISO21581 Load-Displacement Performance	Use
		x	Req	Req	Resistance to extreme impacts: Fire	SNI1741, ISO834, JISA1304 Insolation, Integrity, Stability	Use
		x	Req	Req	Resistance to extreme impacts: Typhoon	Full-scale field test in exposed location over three years	Use
		x	Req	Req	Resistance to extreme impacts: Earthquakes	Learning Exchange Colombia	Use
		x	x	x	Safety against Intruders and Vandalism	Surveys, Empiric reports	Use
		x			Quality and Risk Management	Three level quality and risk assurance process (QC forms, quality officer, quality audits)	Life Cycle
6	Health and comfort	x	x	x	Thermal Comfort (temperature)	ISO7726, ISO7730 Physical Measurements	Use
		x	x	x	Thermal Comfort (ventilation)		
		x	x	x	Visual Comfort (Daylight factor)		
		(x)	x	x	Acoustic Comfort		
		x			Comfort induced energy consumption during use	Survey	Use
7	Use Phase Services (Maintenance, Adaptability)	x	x	x	Technical Adaptation Potential	Expert Assessment, Documentation	Use
		x	x	x	Technical Maintenance demand (intervention, frequency)	ISO15686-5 Service Life Planning, Maintenance Plan	Use
8	Regulatory compliance	x	Req	Req	Compliance to local regulations	NSCP Vol I, BP220, NCN, NSCP Vol III	Life Cycle
		x			Approval scheme for innovative technologies	AITECH yes/no	Planning
12	Local Economies	x			Technical requirements for sourcing of materials and services in supply, planning, production, construction, use, EoL	Technical requirements on Supply Chain Analysis and continuous optimization	Sourcing, Production, Construction

In general, the indicators in this performance dimension are well defined and measurable. However, the development of a new building method for social housing in the Philippines is a

process that evolved via numerous iterations and over time. It required a constant balancing of somewhat contradicting requirements regarding the technical, economic, social, and environmental performance dimensions. Furthermore, some of the aspects within the technical dimension were contradictory, such as optimization against typhoons and earthquakes, or the optimization of health and comfort against the sensitive cost ceiling of the building. Another very concrete example is the use of window shutters, which is important against typhoons and heat intake, but has an impact on daily ventilation and natural light. The shape of the building envelope had to balance requirements for symmetry as protection against seismic and wind impacts with consideration of cultural practices like feng shui (e.g., symmetric openings are to be avoided to prevent energy flow leaving the house). Stakeholder opinions were gathered continuously for decision-making in best possible balance.

2.3.1 Material characterization

A crucial step is the selection of a bamboo species for construction. Each bamboo species has characteristic anatomical, chemical, physical, and mechanical properties, which make it more suitable for certain applications than others, and these often explain its empirical utilization (Liese and Koehl, 2015). Five have been documented for empirical use in construction (Rojo *et al.*, 2000). As in timber engineering, a careful selection of the species is important for the specific purpose of full-culm load-bearing frame construction. A highly promising species is *Bambusa blumena* (*B. blumeana*), locally called *Kauayan-tinik*. Its suitability is based on distribution, empiric utilization, affordability, and previous test reports. *B. blumeana* is the most common raw material used by the rural populations to build traditional, vernacular buildings. This indicates its suitability for construction and its affordability for the population, despite its thorny branches that increase the complexity of its harvest. This species is the most widely grown throughout the Philippine archipelago, from Northern Luzon, Visayas, and to Southern Mindanao. It is native to Java, Indonesia, and Eastern Malaysia, and beyond the Philippines, and it is cultivated in Southern China, Peninsular Malaysia, the Moluccas, Sumatra, Borneo, India, and Southeast Asia (Rojo *et al.*, 2000). This type of bamboo is commonly planted in settled areas at low and medium altitudes; it grows along riverbanks, hill slopes, and freshwater creeks; and tolerates flooding and eroded soils. The training and implementation of sustainable harvesting practices for the natural stands of bamboo is crucial (Virtucio and Roxas, 2003).

Design values for bamboo, which are obtained through a standardized comparable norm, will enable its formal approval for the construction of buildings and facilitate its greater acceptance and comparability as a building material (Harries, Sharma and Richard, 2012). ISO 22157-1 (2004) enables the standardized comparison of bamboo species around the world. It has guided studies for Latin American *Guadua* species (Correal D and Arbeláez C, 2010; Zaragoza-Hernandez *et al.*, 2015) and was applied for bamboo species from China, Indonesia, and Thailand (Suhelmidawati *et al.*, 2012; Sompoh *et al.*, 2013; Made Oka *et al.*, 2014; Deng *et al.*, 2016). However, to date, no Philippine bamboo species has been examined according to this standard. Therefore, the scope of this research was to identify the physical and mechanical properties of the economically and technically relevant Philippine bamboo species *B. blumeana* according to ISO 22157-1 (2004). The tests were conducted in the Forest Products Research and Development Institute in the Philippines (FPRDI) (2015). The documented results include the physical properties of relative density, moisture content (MC), and shrinkage characteristics as well as the mechanical properties of bending strength, shear strength, and compressive and tensile strengths parallel to the grain. The results compared with those from other bamboo species tested according to the same standard around the globe. The paper concludes by providing a recommendation for permissible stresses of the selected bamboo species for low-

rise housing according to ISO 22156 (2004). To utilize the mechanical properties of full culm bamboo, a supply chain is required, which produces strength-graded and treated structural material. The selection, quality control, pre-processing, and treatment, and the logistical requirements to source and distribute materials to construction projects were considered.

2.3.2 Construction system

In general, the performance of a building depends on its components and its system response. Having tested and understood the technical strength and weaknesses of the raw material round bamboo, what follows next in the systemic chain of understanding is bamboo connections and the building components built from bamboo. Regarding the strategic utilization and entry of bamboo in the low-rise building sector in the Philippines, an assessment of technically reliable, cost-efficient bamboo-based construction systems, and their connections was carried out. Two research areas were assessed: connections and the racking strength of wall elements.

Numerous researchers and institutions around the globe have studied *connections* for round bamboo, such as (Association of Earthquake Engineers Colombia, 2009; Widyowijatnoko, 2012; Lamus Báez, Plazas Bernal and Luna Tamayo, 2015; Trujillo and Malkowska, 2018). The boundary conditions for connection studies vary strongly. For this thesis, the social housing segment defined the boundary conditions, with limitations on connection costs, available skills, and requirements for maintenance. The connection design for full culm bamboo requires the consideration of the natural variability of bamboo, its embedment strength, and the durability of bamboo and anchors. In learning exchanges with Latin America and Indonesia, balanced options were derived; these were tested in the FPRDI. All typical connections types found in a bamboo-based house were tested according to Colombian test protocols (Trujillo, 2007; Association of Earthquake Engineers Colombia, 2009).

A key performance related to the daily performance and resistance against extreme impacts is the lateral resistance of the shear wall building system. The method for its testing the resistance to lateral loads can be adopted from timber frame engineering. The lateral load resistance was tested according to the static and cyclic test methods on the racking strength of timber frames (ISO 21581, 2010; EN 594, 2011). The applied lateral load cycle is shown in Figure 19.

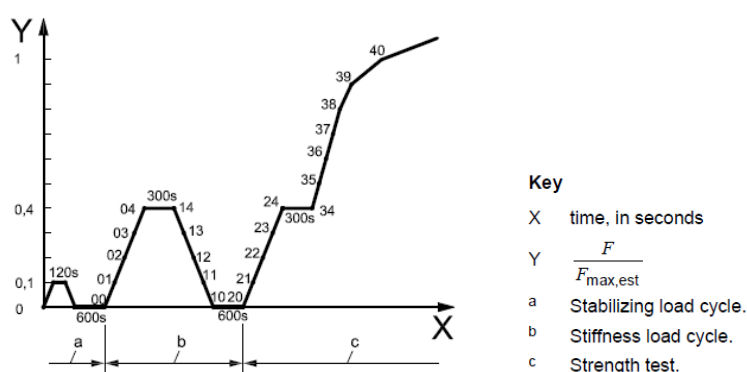


Figure 19 Load curve for racking strength testing of frames: EN 594 and ISO 21581

The samples contained different bracing, plaster carriers, and cladding variations according to the variables in Table 16. A minimum of three tests were conducted for each version of the modified building system. The testing was conducted prior to the implementation of the first

pilot program. It was reiterated after initial implementations to confirm the as-built performance of the most suitable design configuration.

Table 16: Summary of samples for racking strength testing

No	Bracing	Cladding	One or two sides with cladding	Repetition
1	Bamboo	Organic plaster carrier	One side	3
2	Bamboo	Organic plaster carrier	Both sides	3
3	Metal flat bar	Metallic plaster carrier	One side	3
4	Metal flat bar	Metallic plaster carrier	Both sides	3
5	Laminated board	Laminated board	One side	3
6	Laminated board	Laminated board	Both sides	3
7	Bamboo	No	No	3
8	Flat bar	No	No	3
Total				24

2.3.3 Fire resistance

Predictable fire resistance is a requirement for the legal approval and application of bamboo-based building concepts at scale. This research assesses the fire resistance of a selected construction system, as tested in construction system tests. Tests were conducted according to the *National Standard of Indonesia SNI 1741: Testing method of fire resistance for structural components in houses and buildings* (SNI1741, 2011). This standard refers to *ISO 834-1 Fire resistance tests - Elements of building construction* (ISO834-1, 1999) and *JIS A 1304: Methods of fire resistance test for structural parts of buildings* (JIS A 1304, 2011). The SNI standard adopted the same temperature curve as used in the ISO standard, as documented in Figure 20.

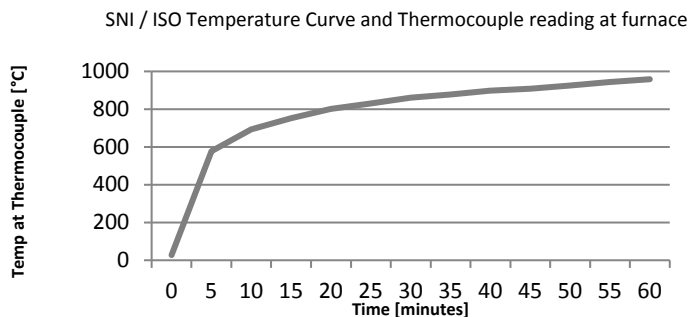


Figure 20 Temperature curve for fire testing in SNI 1741 and ISO 834-1

Bamboo wall cross-sections were tested with samples of 1,050 mm by 1,050 mm and evaluated according to insulation, integrity, and mechanical resistance, as required for elements with separating and load-bearing functions. Figure 21 and Figure 22 show the sample specifications, a picture of the fabricated sample as well as the furnace for testing. Through configuration testing, the following variables and their effect on the performance of the wall system were evaluated: (1) effect of fire retardant on bamboo rounds, (2) anchor options to fix protective cover to the 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 standardized testing, only the variables plaster carrier and number of protective covers were varied (Table 17).

Table 17: Summary of samples for fire resistance testing

No	Bracing	Cladding	One or two sides with cladding	Repetition
1	Metal flat bar	Organic plaster carrier	One side	2
2			Both sides	1
3		Metallic plaster carrier	One side	2
4			Both sides	1
Total				6

The other variables were fixed. The cement plaster provides fire protection, and therefore its thickness is critical to ensure protection of a particular duration. It was designed to provide a protective function that would maintain the minimum allowable bamboo cross-section after 60 minutes of fire exposure. To balance protective function with the dead weight of the plaster, 25 mm of plaster was applied. Given the social housing context in which the most conservative, affordable, and simple sample configuration is required to reflect the affordability criteria, the following as decided:

- A standard plaster mixture was selected without additives.
- No fire retardant was applied to the round bamboo. The surface treatment of the bamboo indicated positive effects but requires more in-depth studies including economic effects.
- Standard nails were used to fix the cover to the structural bamboo

The testing was conducted in partnership with the Institute of Technology Bandung (ITB) (2016) and at the Research and Development Center for Housing and Settlements (PUSKIM) (2015) in Bandung in Java, Indonesia.

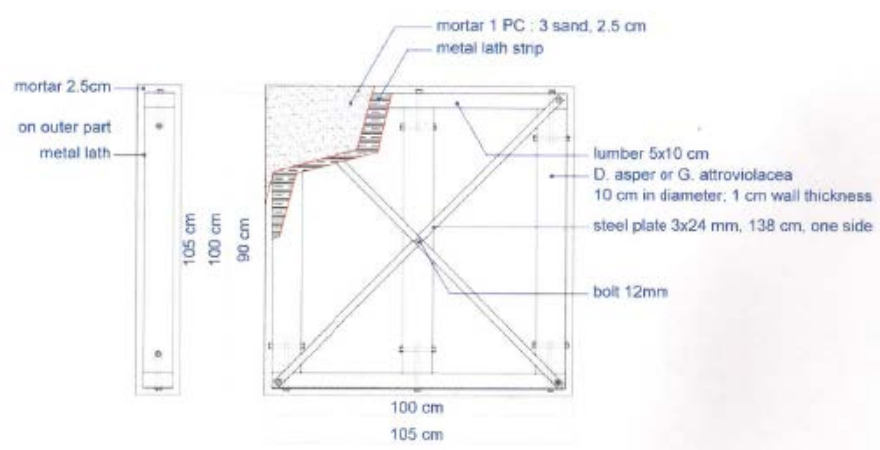


Figure 21 Constructive details for sample with metallic plaster carrier



Figure 22 Sample installation and furnace at (PUSKIM, 2015)

2.3.4 Typhoon resistance

Typhoons cause severe damage to the built environment, particularly to lightweight buildings. In the Philippines, bamboo-based housing, common among rural and urban low-income groups, generally suffers the greatest damage. Failures are related to low weight, weak anchorage and bracing, and the decay of materials. This thesis assessed the improved bamboo-based building method described in the Sections above with regards to its typhoon resistance. The performance of the building methods was confirmed using full-scale real-life typhoon exposure. For this purpose, test houses were built on a wind-exposed lot in the Philippines and observed between 2013 and 2016. *Full-scale field measurements* expose structures to realistic impacts combining wind, rain, and debris. Because of the natural variability of hazard events, a higher number of events must be studied on the same object to draw conclusions. Findings may not enable the assessment of individual variables but highlight a system performance. Long uncertain observation periods, as well as safety and logistic concerns, make these field measurements relatively rare (Kopp, Morrison and Henderson, 2012). In the context of housing in the Philippines, extreme exposure situations exist on an annual basis in high-impact zones. Thus, high testing costs of wind channel testing can be avoided through field measurements. As research is conducted in collaboration with the communities, the advanced performance is demonstrated in direct comparison with the current building practices of the neighborhood and supports acceptance and uptake. From a scientific perspective, greater uncertainty remains because of the natural variability of and distance between storm events. Because of the timely uncertain occurrence and the involved risks, the options to capture the actual performance during the damage events is restricted by certain limitations.

The municipality of Guinobatan in the province of Albay in the Bicol region is situated in the most wind-prone zone, Zone 1, with a basic design windspeed of 250km/h (Association of Structural Engineers of the Philippines, 2015). Three full-scale test houses were designed and built to observe over time the resistance of selected enhanced bamboo-based building methods under typhoon impact. The houses were built in an exposed lot; nearby trees were far enough away so that there was no direct shielding effect. The three houses had the same floor plan and orientation but differed with regard to (1) wall cladding, (2) bracing, and (3) roof shape. The houses are shown in Figure 23.

Test House One	Test House Two	Test House Three
 • Medium weight walls • Lateral bamboo bracing • Bamboo plaster carrier • Mortar cladding • Hip roof	 • Lightweight laminated bamboo panels for cladding and bracing • Gable roof with regular safety factor	 • Medium weight walls • Lateral metal bracing • Metal mortar carrier • Mortar cladding • Gable roof with reduced safety factor
Common Characteristics		
 • Conventional concrete foundation • Quality selected, treated bamboo • Prefabricated bamboo elements • Water protection by design: elevation from surface runoff, water barriers between foundation and walls, a protective cladding and roof overhang • Window shutters • Corrugated metal roof sheets in compliance with urban fire requirements (thatched roofing prohibited), standard gauge for social housing, roof angle above 32° to reduce turbulent wind, medium size roof overhang to prevent uplift		

Figure 23 Test houses one, two, and three and their characteristics

The monitoring covered three elements: (1) wind impacts encountered on the test site, (2) damage survey of the test houses after impact in comparison with expected performance per structural analysis, and (3) damage survey of the built environment surrounding the test site as a reference. The actual wind impacts on the typhoon track nearest to the test site were extracted from the data records of the Joint Typhoon Warning Center (JTWC) (2016) and the Philippine Atmospheric, Geophysical, and Astronomical Services Administration PAGASA (2016). For a classification of the wind speed, the Saffir-Simpson Hurricane Wind Scale (SSHWS) was used. According to the SSHWS, Categories 3, 4, and 5 have extensive, extreme and catastrophic damage potential, respectively, with 10-minute maximum sustained wind speeds above 178 km/h. For bamboo-based houses, the vulnerability curves of the Philippine government predict a failure likelihood of 99% for wind impacts above Category 3.

2.3.5 Health and comfort

The overall objective of the aspect health and comfort is to provide an assessment of the living quality and well-being in social housing. It is an aspect that is included in ISO and EN standards, and contains the following indicators: thermal, visual, acoustic, spatial comfort, and air quality. According to the stakeholder assessment, indoor thermal and spatial comfort are most relevant for the given context. For Malaysia, Djamila (Djamila, Chu and Kumaresan, 2013) found that over 80% of occupants accepted indoor air temperatures in a range of 27°C to 32.5°C. A comfort temperature near 30 °C was calculated using various recognized approaches. On this basis, it was assessed:

- Thereafter, the following specific research questions were raised:

- The assessment of thermal comfort in social housing was conducted in a settlement in partnership with the grassroots group HPFPI (2017). In *reference measurements*, the site, design, and occupation specific variables influencing thermal comfort in social housing were evaluated by capturing 20 social houses made of concrete. In *comparative measurements*, thereafter, the common building method concrete was evaluated in parallel to three alternative building methods, namely steel frame, soil-cement blocks and cement-bamboo frames. The concrete and soil-cement houses are considered heavy weight building methods, with a reduction of 10% mass from the concrete hollow block to the prefabrication elements because of thinner wall thicknesses. The steel- and bamboo-frame houses are classified light to medium weight, with approximately 25 to 30% of the dead weight of the concrete hollow block unit. For each type of building method, four units and their inhabitants were evaluated. The small volumetric houses reflected the typical social housing segment in the Philippines. During three climatic seasons in 2015, 20 houses (covering the four building types) were analyzed: cool, hot, and rainy season. Figure 24 illustrates the reference (top) and comparative (bottom) assessment with its objectives and variables.

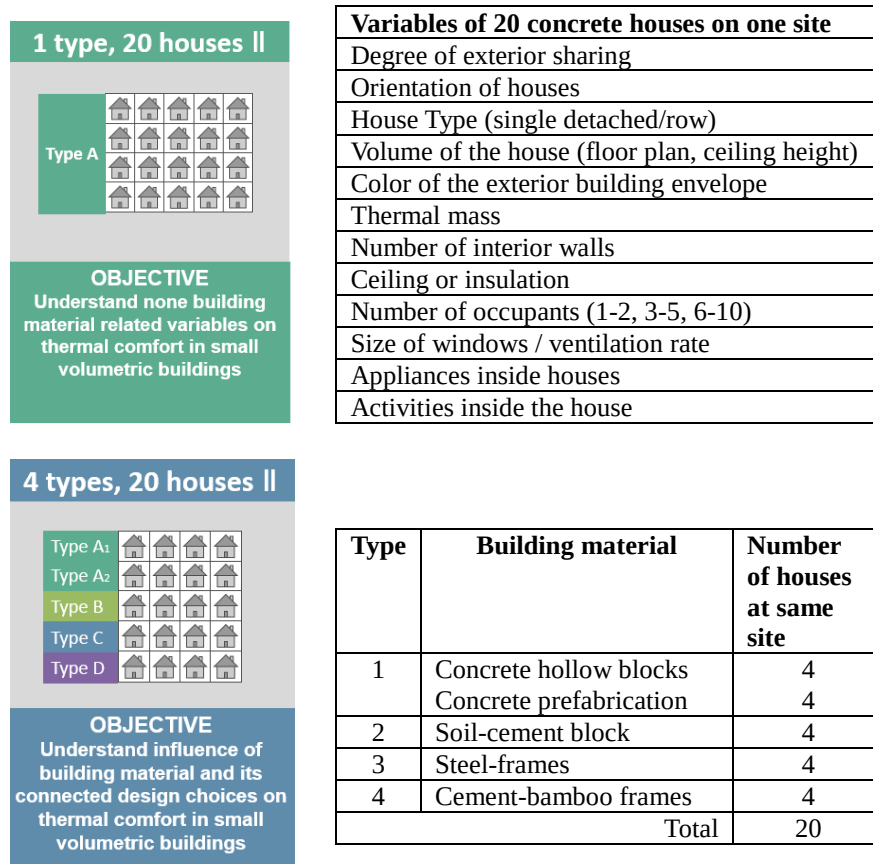


Figure 24 Thermal comfort assessment: reference (top) and comparative (bottom)

The physical measurements of thermal indoor comfort captured for this study were the air temperature, in °C, and the relative humidity, in %, according to ISO 7726 (2001). The temperature was taken at 1.5 meters height. ISO 7726 recommends a height of 1.7 meter as typical height of the head of a standing person. This was reduced to reflect the lower head zone of average standing persons in the Philippines. For each house and story, one data logger of the type Sirius, with a precision of +/- 0.5°C and +/- 5% RH and continuous 5-minute recording, was installed in the center of the main living space. A weather station was installed at one fixed location of the settlement with distance of 3 to 280 meters from the individual sample houses.

The physical results, during the reference and the comparative measurement, were correlated with *one-time and daily surveys* about the inhabitants' sensation and behavior. The adaptive approach was applied, considering the geographic and social context. In the one-time surveys, profiles of the household were documented with their income types, expenditure, health, gender, age distribution etc. The sample size of forty families included the twenty units captured in the physical measurements but exceeded it for a more statistically relevant sample size. In daily surveys, only in the units of the physical measurements, the type of indoor activities, occupation, indoor heat radiating sources and the clothing was captured. The respondents were asked to describe their comfort perception on the ASHRAE 7-point sensation scale of warmth (ASHRAE, 2017) with 3 being hot, to 2 warm, 1 slightly warm, and 0 neutral, to -1 slightly cool, -2 cool, and -3 cold, respectively. Perception and behavior was then correlated to the diurnal cycles of exterior and interior thermal comfort measurements. ISO 7730 was followed for the analytical determination and interpretation of thermal comfort under local comfort criteria (ISO 7730, 2005). For the detailed one-time and daily survey forms it is referred to Salzer *et al.* (2018).

In correlation to the thermal comfort, the visual and spatial comfort were assessed. Visual comfort, or the daylight factor, is a design related aspect. It influences the energy consumption during the use phase of houses, because of lesser or more artificial lighting used, and needs consideration in the design of buildings. The existence of natural light was evaluated with the recommendations of scientists between 50 to 300 lux in indoor environments. During two times of the day, in the morning and the afternoon, the lux was measured at 1.1 m height of a typical table surface. Spatial comfort refers to the dimensions and the perceived space in the houses. The total floor plan area, the number of rooms, and the ceiling height are the measurable parameters. The spatial comfort is highly interrelated with the affordability of and thermal comfort inside social houses and is usually strongly limited. The regulatory minimum floor plan area is 18 square meters, the minimum ceiling height for social housing is 2.00 meters (Housing and Land Use Regulatory Board of the Philippines, 2008). Any exceedance of these minimum benchmarks was considered positive for spatial comfort and influenced the thermal comfort too.

2.4 Methods to Determine Social Performance

The social aspects are strongly interrelated to other performance dimensions and are challenging to translate into quantifiable indicators. The standards specify that where quantitative results are not available as indicators, a descriptive, qualitative approach can be adopted. In EN 15643-3 and EN 16309 (explaining calculation methodologies for social performance), only the building in operation or use phase is covered (EN 16309, 2014). There are ambitions, as mentioned in the standards, that the social performance dimension shall be extended to the complete building life cycle. ISO goes further and specifies social performance

aspects of concern along the Life Cycle Phases. However, little guidance is provided on the concrete measures to be taken. This thesis seeks to contribute to the debate by suggesting measures, while also acknowledging that they might be contested and can further be optimized. The indicators have been identified through the stakeholder assessment accompanying the thesis and the implemented projects over a 4-year period. Twelve direct or indirect social aspects were identified, as shown in Table 18. These are broken down into indicators, which are justified more in detail in the sub-sections to follow.

Table 18 Social aspects and issue-specific indicators and their measures

No.	Aspect	Source			Indicator x = indicator included (x) = indicator in Annex x* = ISO/TS 21929-2 x**= Indicator with modified content	Measure	Type
		LOC	ISO	EN			
1	Social aspects on Safety, Risk and Resilience	x			Social Vulnerability of inhabitants	Number of houses damaged, and people injured in bamboo settlements compared to outside	Use Phase
		x			Resilience through sourcing of local materials, skills and logistics	Ability to build ad-hoc >5'000 houses post-disaster	Life Cycle
2	Participation & Inclusion	x	(x)	(x)	Participation in Sourcing, Planning, Production, Construction	Documentation of participatory activities along life cycle	Life Cycle
		x			Active and Empowering Type of Participation	Documentation of decision-making processes	Life Cycle
		x	x*		Inclusiveness	Documentation of minority group involvement	Life Cycle
3	Identification and Cultural heritage	x	x*		Inclusion of heritage elements	Traditional materials or shapes used Yes/No	Life Cycle
4	Acceptability	x	(x)		Social acceptance	Post-Occupation Survey shows >90% satisfied or highly satisfied, does not regret choice of building technology	Use Phase
5	Capacity building & Sharing	x			Skill level needed	Standard training possible without skill background	Life Cycle
		x			Number of people trained	Number of registered participants	Life Cycle
		x			People reached through learning exchange	Communities of practice formalized and effective	Life Cycle
		x			People reached through digital platforms	Number of users online	Life Cycle
6	Health and comfort	x	x	x	Thermal Comfort (temperature)	Degree Celsius in centre of building at 1.6m above ground	Use Phase
		x	x	x	Thermal Comfort (ventilation)	m/s range for natural ventilation	Use Phase
		x	x	x	Visual Comfort (Daylight factor)	Lux indoor	Use Phase
		(x)	x	x	Acoustic Comfort	INA	Use Phase
		x	x**	x**	Spatial comfort within cost seal	No of rooms with partitions, sqm floor plan area, ceiling height	Use Phase
7	Use Phase Services (Maintenance, Adaptability)	x	x		Acceptability to consult service provider for maintenance or expansion	% of non-adequate interventions or expansions with different building technology after occupancy	Use Phase
11	Equity of sites	req			Time and expense in % of daily wage to reach income opportunity	Max. 2 hour in capital, max. 1 hours in province to reach, Max. 15% of salary	Use Phase
		req	x	(x)	Availability of water, energy, sanitation, solid waste management, access to basic services	Access to basic infrastructure and services upon completion of houses	Use Phase
		req			General risk and geohazard assessment of site	Geohazard assessment of government or expert	Planning
12	Local Value Chains and Economies	x	(x)		Quality of jobs created	GRI standards (salary, working time, social security, health and safety, etc.)	Life Cycle
		x			Local employment	% local staff of complete staff	Life Cycle

2.4.1 Safety, risk, and resilience

Safety, risk, and resilience is the merger of two aspects that are related to the four performance dimensions. Technical safety is a measurable aspect and can be broken down into indicators such as fire, earthquakes, and typhoons. For the social dimension of safety, the standards include safety against intruders and vandalism. These considerations confirm context relevance as revealed in the stakeholder assessment. However, safety in terms of illumination, waste storage, and alarm systems were deemed not applicable.

The highly complex aspect of *risk and resilience* was added in ISO/TS 21929-2, exceeding the interpretation of safety in the EN standards and ISO 21929-1. A range of social indicators can be identified for risk and resilience. These become particularly obvious when *considering the value chains created through building*, and not only the building in use. The safety aspect can be extended to the value chain, covering sourcing, including harvesting and bamboo treatment, prefabrication, construction, and end-of-life. Attention was set to chemical treatment, protection from dust in the prefabrication of wall elements, and their maximum weight for manual installation. A quality management system for such risky processes shall be proven to be in place and effective. In general, broader value chain aspects were found to be highly relevant, tackling overall resilience in a disaster-prone country. The ability to recover from disasters through locally sourced materials and local skills is a highly valuable capability. Linkages to the aspects capacity building and the sharing and sourcing of materials and services also exist. Measures could be the percentage of locally sourced materials and workers per building. Furthermore, regarding the governance aspect, government services concerning disaster preparedness and communication were identified as a need. As an additional measure, the inclusion of minority groups catered to by such government services on disaster preparedness can be measured. A measure regarding the contribution of value chains to reduce social vulnerability seems to require further discussion but adds value to the given context. The socially related indicators of safety, risk and resilience are included in Table 18.

In addition to building material-related safety, the site-specific aspect of continuous *access to utility supply* is included in the safety dimension as *economies and social equity of a site*. Compared with EN standards, a different interpretation is applied to access to utilities. While the standard refers to technically managed buildings, which should also manually manageable, this thesis refers to access and continuous servicing through basic infrastructure and services such as water, energy, sanitation, and solid waste management.

2.4.2 Participation and inclusion, acceptability, and identification and culture

This section suggests methods for three aspects of participation and inclusion, identification and cultural heritage, and overall acceptability. Because of their connections, these are discussed in one section.

Participation is an important aspect acknowledged both in the stakeholder assessment and the Annexes of both standards. The standards describe it as an aspect that is not ready for inclusion as a standard because there is still some debate regarding its measurability.

ISO/TS 12720 (2017) defines six phases of decision-making along the life cycle of buildings: strategic planning, project definition, design, construction and handover, operation and maintenance, and end-of-life. This thesis adds the sourcing of materials and services to this understanding. During these phases, questions are to be raised, stakeholder feedback is obtained, and conclusions are drawn to best meet the needs of the stakeholders.

For this thesis participation is considered in fabrication and construction, but furthermore also in sourcing, participatory planning, skills trainings, demonstration houses, post occupation surveys, and customer acceptance tests. In the course of four years, various participative approaches were implemented, such as focus group discussions on harvesting and prefabrication ($n > 20$), design and project planning workshops ($n > 12$), and pilot houses at the beginning of each construction project ($n > 8$). Furthermore, stakeholder opinions were captured, among others, through cognitive interviews for which the interview principles for research and evaluation of Patton (2015) were followed. Depending on the background and context of the stakeholder group, either a less-formal or a more structured ethnographic interview type, or an interview guide approach was chosen. Special care was set on the formulation of the questions in the interview guide, to be simple, non-irritating, understandable in a cross-cultural context, bias-free, and open-ended. Probing questions were included in the interviews to verify viewpoints. Both descriptive or knowledge-based questions and interpretive or attitudinal questions were included. In addition to interview data, focus group discussions and workshops, field inspections or direct observations were carried out over a period of four years to capture stakeholder requirements and views. These were documented in written and pictured field reports, following the field observation guide for qualitative analysis.

To close the loop between the participatory project cycles, backward integration is needed prior to a new project loop. The backward integration of the individual to a community opinion is a sensitive process. As Chambers (2014) highlights, the “the pervasive significance of power in forming and framing knowledge” requires “critical reflexivity and methodological pluralism”.

EN and ISO standards have a product-orientation but also highlight the importance of decision-making processes and involvement too. As a wide range of stakeholders has an interest in the building sector (ISO 15392, 2008), significant differences among interested parties or stakeholders exists, particularly in terms of their interpretation of “scope, content, level of detail, and priorities”. Regarding the choice of stakeholders, (Fraser *et al.*, 2006; Bal *et al.*, 2013; Waas *et al.*, 2014) two general approaches are followed: 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 in this thesis. It ensures the comprehensive capture of barriers and opportunities and enables the participation of and ownership by all involved societal groups. Table 5, in the conceptual framework, shows a comparison of the main stakeholder groups in the context of the thesis compared with the general groups mentioned in ISO12720.

In addition, different kinds of participation exist ranging from nominal, over passive and active, to empowering participation, and distinguish by the degree of involvement and enabled decision-making (Agarwal, 2010). Indicators were used to capture and distinguish the level of quality achieved through these participatory activities. This is closely related to the aspect of identification, wherein it is assumed that participation, but particularly active and empowering participation, increases the degree of identification and ownership for a project.

ISO extended participation in ISO/TS 21929-2 by the aspects of acceptability and inclusion. *Inclusion* refers to the equity objective of the standard, reminding stakeholders of the need to consider power relations in decision-making and its address. Highlighted is the need to ensure that minority or vulnerable groups are included (e.g., the poor, women, minority groups, and silent stakeholders). For more details on the methods of stakeholder participation and inclusion, it is referred to Salzer *et al.* (2016).

Acceptability resonates with the results of the stakeholder assessment, wherein the construction sector is described as conservative and comparatively slow in the uptake of innovations. End-user acceptance of a building technology is crucial in the market uptake. It is suggested that it can be measured with survey techniques about market responses and post-occupation satisfaction. In the course of four years, four cycles of acceptance testing are conducted.

The above aspects are complemented by the aspect of *identification and cultural heritage*, which is only found in ISO. This thesis adopts that aspect but changes its interpretation. The stakeholder assessment revealed that cultural heritage is an area of protection, particularly in a country that has experienced centuries of colonialism. The suggested indicator measures the degree to which culturally rooted materials are used to address today's needs. It also includes the skill aspect of culturally rooted materials, in which local practices are incorporated to the highest degree possible without compromising other aspects such as ICCs, scarcity, and safety. The indicators of participation and inclusion, identification and culture, and acceptability are included in Table 18.

2.4.2 Capacity building and sharing, and job creation

The social aspect of *capacity building and sharing* is related to the economic aspect of *job creation*, both of which are being discussed in this section. It has further links to the aspects outlined in Sections 2.4.1, 2.4.2 and 2.5.3. Overall, the indicators in this field aim to create positive social impacts through local value chains from farmers up to construction workers, which create income, skills and jobs. Thereby, the ethical dimension is relevant to assure minimum standards for workers on farms and construction sites (e.g., work ergonomics, working hours, salary, safety, and social services). For all indicators, the scale and quality of activities is measured. For learning exchanges, knowledge sharing is not assumed to be a fixed product, but a socially constructed process in which people and culture are at the center. The following methods are applied for learning exchanges as described in Lennie and Tacchi (2013):

- *Perspective-making*, describes the process of a group that strengthens its knowledge
- *Perspective-taking*, describes the process in which group members learn about the knowledge of others
- *Communities of practice*- encourage innovation, share explicit and tacit knowledge, facilitate group and individual learning

While the direct output of capacity building and sharing can be measured (i.e., the number of registered participants in trainings), their long-term impact for society is difficult to track (i.e., the effect of using the obtained skills to build better housing). The provided suggestions are understood to be optimized over time to better tackle the long-term impacts, not only the outputs. They are yet to be included at this stage with the recommendation to increase their consideration in future debates. The socially related indicators of capacity building and sharing and job creation are included in Table 18.

2.4.3 Equity of sites

As important requirements for all social housing projects, the aspect of the equity of a site was incorporated. This aspect includes the following indicators: accessibility to basic services and infrastructure as well as access to and from the site. Access to basic services should exist from the moment of use of buildings for all social housing projects. As a measure for access to and

from a site, EN and ISO standards suggest the distance to the next pick-up location. Adjusting to the realities of large urban agglomerates in emerging economies, the suggested modification is the indicators time and money spent to obtain opportunities to earn an income or an education (under the economic dimension) as well as quality of travel (the social dimension). In addition, the indicator equity of sites should include a geohazard assessment by a government body or expert group, to avoid future inequalities by excluding high-risk zones. The site-specific aspects are captured as requirements for building projects in the planning stage. The socially related indicators of equity of sites are included in Table 18.

2.5 Methods to Determine Economic Performance

The economic dimension contains eight aspects, of which some are predominantly economic and others are highly interrelated with one or more dimensions of sustainability. The indicators related to building costs are broken down into ICCs and LCCs. Further aspects are the economic efficiency of construction processes and building sites, and the investment into local value chains. The definition of economic performance goes beyond the provisions in the standards, where a focus on the building-fabric exists. An overview of all economic aspects and indicators and their measures is shown in Table 19.

Table 19 Economic aspects and issue-specific indicators and their measures

No.	Aspect	Source			Indicator x = indicator included (x) = indicator in Annex x* = ISO/TS 21929-2 x**= Indicator with modified content	Measure	Type
		LOC	ISO	EN			
4	Acceptability	x			Market Demand	Market demand- bamboo-based building projects annually increasing within environmentally sustainable limits	Life Cycle
5	Capacity building & Sharing	x			Increase of future job opportunities	Certification of skills obtained through acknowledged through. Survey on job history after training	Life Cycle
6	Health and comfort	x	x**	x**	Spatial cost within cost seal	Floor Plan exceeding min. req. of Government, ceiling height exceeding min. req., number of rooms min. two	Use Phase
		x			Comfort induced energy consumption during use	Scenario LCA, post-occupation surveys	Use Phase
7	Use Phase Services (Maintenance, Adaptability)	x			Lot space enabling expansion	Available space without violation of set-backs	Use Phase
		x	x	x	Maintenance and Adaptation affordability	Comparable or below conventional costing	Use Phase
		x			Availability of service provider for expansion	Trained service provider accessible	Use Phase
		x			Availability of service provider for maintenance	Trained service provider or inhabitant trained for needed interventions	Use Phase
9	Building related cost	x			Cost seal Social Housing in the Philippines (Initial Construction Costs)	400'000PHP for land and housing unit	Cradle to Construction
		x	x	x	Life Cycle Costs (incl. Maintenance, Comfort induced Use Phase expenditure, EoL economics)	According to ISO15686-5 Estimated Service Life 25 years	Life Cycle
10	Efficiency of construction	x			Standardization	QC forms for prefabrication filled, quality checks done	Cradle to Construction
		x			Expenditure for Quality and Risk Management	Number of incidences and USD for rectification	Life Cycle
		x			Pace of construction	Number of days per house	Construction

Table 20 Economic aspects and issue-specific indicators with their measure cont.

No.	Aspect	Source			Indicator	Measure	Type
		LOC	ISO	EN			
11	Equity of sites	req			General risk and geohazard assessment of sites	Evaluation by government or expert	Planning
		req			Time and expense in % of daily wage to reach income opportunity	Travel time to job (one way < 2-hours capital, <1-hour province)	Use Phase
		req	x	(x)	Availability of water, energy, sanitation, solid waste management, access to basic services	Requirement at completion of houses	Use Phase
12	Local Economies	x			Investment into local economy / Sourcing of Service along value chain	Number of jobs and financial value created per USD spent	Life Cycle
		x			Expenditure in research on social housing	USD spent locally in social housing R&D	Research
		x			Partnerships to address key system barriers local, national, regional, global	Number of partnerships North-South, South-South, National across segments	Life Cycle
		x	x		Project based jobs created >6 month	Number of jobs created	Cradle to Construction
		x	(x)		Jobs sustained through market development	Model to maintain skill level for value creation, e.g. worker pool etc.	Cradle to Construction

2.5.1 Building costs

ICCs are a strong driver in decision-making in the social housing segment. They accumulate the costs in the life cycle phases of sourcing, production, and construction. As a benchmark, the officially defined financial limit for social housing in the Philippines, defined by the Housing and Land Use Regulatory Board (HLURB) is PHP 400,000, or approximately USD 8,000 for *land and housing* (Housing and Land Use Regulatory Board of the Philippines, 2008). While land prices vary widely according to location, a cross check through several social housing projects resulted in a 2:3 ratio for housing and land, respectively. This results in a cost limit of PHP 265,000 per house.

The ISO and EN standards both agree on the relevance of LCC, which are calculated according to ISO 15686-5 (2017). The life cycle phases of production and construction, maintenance and servicing and end-of-life are considered. These costs can be differentiated into costs for the building operation, and the utilities. In the case of social housing, the cost positions considered are *temporary works, permits, direct costs and labor* for construction, partially building technology related to *cooling, power, and light* for operations, the *repair and replacement* of components under maintenance and *demolition and disposal* at end-of-life. Scenarios for the service life duration reflect the higher risks and uncertainties inherent in the social housing segment in emerging economies. They are only of interest when they cause a particular building technology to have a shorter service life than in current practice. According to ISO15686-5, land costs are excluded from LCCs and belong to non-construction costs, which fall under whole life costs (WLC). The latter are beyond the scope of the thesis. For an overview of the terminology with regard to costing according to ISO and EN and cost positions, please refer to ISO15686-5 (2017). The economic indicators of building related costs are included in Table 19.

2.5.2 Efficiency of construction processes and sites

Economic efficiency describes the characteristics of the building process. It is suggested that it includes the indicators of *standardization, quality control, and pace of construction*, which are

common indicators in formal construction. Their consideration is important but needs to be balanced with the other requirements of social housing. Bottom-up community-driven approaches may consider these indicators less relevant than other stakeholders such as NGOs in reconstruction and governments. Transparency in the performance may enable a context-specific assessment of their importance. Section 2.4.3 outlines the economic contribution to the aspect equity of sites. The economic indicators for efficiency of construction and equity sites are included in Table 19.

2.5.3 Local economies and sourcing of materials and services

The aspect *local economy building* is multi-dimensional, impacting on the social, economic, environmental, technical, and governance dimensions. The development of markets along construction- and building-use-related value chains is not assessed in EN and ISO. However, in the latest ISO release on the sustainability of buildings, (ISO/TS 21929-2, 2015), the aspects of *job creation* and *resilience* are included. Both aspects are strongly influenced by local economies and value chains. The value of *job creation* was also highlighted in the stakeholder assessment. It further relates to the social aspect *capacity building*, which was raised as a stakeholder concern.

The multi-dimensional aspect of *sourcing of materials and services*, mentioned in the Annex of EN, can also be related to the building of local economies. While EN highlights its relevance, it also touches on the debate concerning its measures. This thesis includes the origin of documented raw materials, or their traceability, as suggested in EN. Linking to Sections 2.4.1 and 2.4.2, the aspect of the qualification of suppliers is included. Quality control systems must be in place, particularly for the chemical process of bamboo treatment against insects in compliance with safety and environmental standards in this field. The ability of a supply chain to produce quality bamboo of a structural grade is another indicator, which can be assessed through Quality Management Systems. This includes the selection, quality control, pre-processing, and treatment, and logistics required to source and distribute material to construction projects. Last, the confirmation of sustainable harvesting practices is to be covered through an indicator, which could be linked to LCA. For the socially related indicators concerning the sourcing of materials and services, these refer to the social indicator *resilience of local value chains* (Table 18).

All these aspects relate to the need to include the wider system aspects of value chains in the social and economic dimension of sustainability assessments of buildings. This need exceeds the perspective of the raw material bamboo. The use of (alternative) local raw materials, particularly in emerging economies, often hits systemic barriers because value chains are not established, to scale, or sustainable. Kunz *et al.* (2008) describes the relevance of humanitarian supply chains in a pressured post-disaster context. The perspective of humanitarian agents is provided, for which post-disaster situations occur geographically- and timely unplanned. As such, supply chains cannot be established according to the regular principles of logistics. For them, the period of permanent reconstruction, with some distance from a disaster, enables the transition of practices. This thesis takes the perspective of those countries with a permanent high exposure to risks. While it cannot generally be predicted when disasters will occur, the risk is known, and it is therefore important for societies to be prepared. The indicator *investment into local value chains* for construction captures the strengthening of a country's, region's, or community's capacity, in times of no disasters, to respond to future needs. Scientific studies support, that local value chains in house reconstruction can have positive macroeconomic effects, and in addition to enhancing the local capacity to use knowledge (Matopoulos, Kovács

and Hayes, 2014). Matopoulos *et al.* (2014) highlights, however, that local sourcing has to face various challenges and complexities. Policy frameworks for developing countries on sustainable housing and cities, such as (UN-Habitat, 2012), expresses the need for local building materials to go beyond pilot stages, so that their replication will reach a relevant scale and impact through local value chains (UN-Habitat, 2012).

Further systemic indicators suggested for incorporation are *continuous innovation*, the *availability of service providers during the in-use stage of buildings*, and *collaboration to address system barriers*. Continuous innovation is measured through monetary and human resource investment in research and development for social housing in emerging economies, and in Section 2.5.4, the aspect of service providers in local value chains is discussed further. The economic indicators of local market development are included in Table 19.

2.5.4 Maintenance and adaptability

Adaptability and maintenance aspects are found in both standards and are related to all four performance dimensions. What they measure, however, requires interpretation for the local context.

Maintenance is related to all four performance dimensions. From a technical viewpoint, it refers to the technical need for maintenance interventions and a particular frequency to assure the functionality of the building over its service life. Maintenance interventions and their frequency are related to the materials, the building method, and the design of the building. Maintenance demand is documented in a maintenance plan. The results on this aspect are not reported separately in the results section but are included in the SLP Section 2.2.3. The environmental and economic implications are covered through scenarios in LCA and LCC assessments. An indicator is suggested on the availability of qualified service providers to conduct the maintenance. This is particularly important when the maintenance requires a certain skill level and the building technology is not widely used in the market. Moreover, the acceptability of maintenance from a qualified service provider is included, as well as the risk resulting from noncompliance to a maintenance plan. Usability during maintenance interventions is less relevant in this context.

Adaptability in the EN standards focuses on the avoidance of an obsolete function, while this thesis focuses on adaptability for quality of living and positive social development. Adaptability from a technical viewpoint refers to the technical possibility to adapt to a change in user needs. Regarding the social housing context, this mainly concerns the incremental expansion of the buildings. Closely connected to a change in size is the question of whether buildings in the social housing segment meet user requirements in the first place and whether individual needs can be appropriately addressed in mass housing schemes in general. The incremental expansion, as commonly seen in social housing schemes, is considered a reality because of the limited space per family. It is mainly motivated by social trends in occupation, such as an increase in family size. At the highest organizational level, the availability of additional land and the orientation of the building on the lot are examined. This is also a regulatory aspect because compliance with minimum requirements is necessary to prevent adverse effects on safety and social aspects. Stakeholders describe both vertical and horizontal expansion as relevant. In this thesis, vertical expansion was excluded because of the cost implications on the initial construction costs. Expansion requires strengthening or expanding the foundation, additional exterior walls with load bearing connections to the original house, and adjustments in the roof, representing the most relevant requirements with technical, skill and capital implications.

The adaptability aspect also looks at change to interior walls, wherein the social acceptance of permanent shear walls was assessed. Furthermore, the standards include change in use, which is not assessed in the thesis, as houses are for residential purpose only. The inclusion of a small businesses operated from inside the houses could possibly be included as an area of future study.

Another aspect of adaptability in the standards is adaptation to climate change. This is covered through the aspects of health and comfort, safety, risk, and resilience.

The benchmarks for the assessment of the maintenance and adaptability aspects are traditional bamboo buildings in the Philippines and concrete construction in the social housing segment. Both aspects have a technical dimension, but are interrelated to the social, economic and environmental performance dimensions. The indicators of maintenance and adaptation are included in Table 18.

2.6 Methods to Determine Environmental Performance

The environmental impact of the building stock is relevant. Particularly in emerging economies, where a majority of new buildings will be constructed, the social building stock has its relevance. The informal construction sector is a major service provider for the construction of affordable housing. Life cycle thinking is not yet established, however (UNEP and UN-Habitat, 2015). The research examines the environmental performance of social housing throughout its life cycle on Cradle to Grave perspective. Locally available, alternative building concepts could potentially reduce the environmental impact of the construction segment. This thesis contribution 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 use of alternative building technologies using local materials. Next to Cement–Bamboo Frames, also the alternative building methods soil–cement blocks, and coconut board-based houses are assessed. For more details on the other building methods, it is referred to the respective publication.

Through an inventory analysis all mass and energy flows throughout the life span of a functional equivalent (FE) are accumulated. Life cycle assessment models are implemented and evaluated with the software SimaPro, using the single-impact indicators GWP, from the International Panel for Climate Change (IPCC), and CED. The latter provides a good general indication of LCA results (Huijbregts *et al.*, 2010). The first, is one of the most frequently used single impact indicator and retrieves savings of CO₂ equivalents (IPCC, 2014). Both indicators are recommended by EN 15978 (2011). In addition, the multi-score indicator Impact2002+ was applied with its mid-point categories natural resources, ecosystems, and human health. These mid-point categories cover many of the single-issue indicators mentioned in EN, which were assessed individually and aggregated. According to EN 15978, the life cycle phase product and construction process (A), use stage (B), end-of-life (C) and supplementary information beyond the building life cycle (D) have been assessed. The Phases B1 and B5-B7 are excluded from the assessment with reasons being the following: Theoretically calculated inflows from standard construction procedures used in phase A have been verified with 3 years of empirical data from implemented construction projects. For phases B, C and D, attention was given to service life, use-phase, allocation of waste products, biogenic carbon and land-use assumptions. Scenarios reflect the actual situation in the emerging economy. Processes, such as heat recovery from thermal utilization, which are not existing nor near to implementation, were excluded. 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 of the assessment. The aspects *risk and resilience* are highly complex and multi-dimensional. Scenarios for a shorter service life were incorporated in this environmental performance assessment. The aspects and indicators measured through the LCA in the environmental performance dimension are summarized in Table 21.

Table 21 Environmental aspects and issue-specific indicators

No.	Aspect	Source			Indicator x = indicator included (x) = indicator in Annex x* = ISO/TS 21929-2 x**= Indicator with modified content	Measure	Type
		LOC	ISO	EN			
6	Health and comfort	x			Comfort induced energy consumption during use	LCA Scenario	Use Phase
13	Climate Change	x	x	x	Global Warming Potential	LCA with IPCC GWP 100a	Life Cycle
14	Natural Resources	x	x	x	Non-renewable energy, mineral extraction	LCA with Impact2002+ Natural Resources	Life Cycle
					Non-renewable primary energy, Renewable primary energy, Non-renewable primary energy as raw material, Renewable primary energy as raw material, Non-renewable secondary fuels, Renewable secondary fuels	LCA with Cumulative Energy Demand (CED)	Life Cycle
15	Human Health	x	x	x	Human toxicity, respiratory effects, ionizing radiation, ozone layer depletion, photochemical oxidation	LCA with Impact2002+ Human Health	Life Cycle
16	Ecosystems	x	x	x	Aquatic and terrestrial ecotoxicity, aquatic and terrestrial acidification, aquatic eutrophication, water turbidity, withdrawal and consumption	LCA with Impact2002+ Ecosystems	Life Cycle
17	Waste	x	x	x	Reuse, Recycling, Energy Recovery, Non-hazardous waste disposal, hazardous waste disposal	LCA Scenario	Life Cycle
18	Sustainable sourcing	x	(x)	(x)	Controlled quantity, transparent and controlled source and supplier, controlled species	LCA Scenario	Sourcing
19	Use of renewable resource	x	(x)		Scenario connected to land use (Decoupling growth from resource depletion through non-depleting harvesting practice from rapidly renewable raw material)	INA	Cradle to Construction
20	Biodiversity	x		(x)	Contribution to debate. Shortcomings of LCA	INA	Sourcing
21	Land Use	x	x		Shortcomings of LCA, scenarios included	INA	Life Cycle

2.7 Regulatory and Governance Aspects

Selected aspects go beyond the four performance dimensions and are related to regulatory aspects and overall governance. The regulatory requirements of the Philippines have provided minimum performance benchmarks for this thesis. Beyond that, systemic barriers are strongly influenced by housing policies and ‘institutional sustainability’ (UN-Habitat, 2012). While this field goes beyond the scope of this thesis, selected regulatory and governance aspects are highlighted in Table 22. These are directly related to the social housing segment regarding scale and repetition. A discussion shall be stimulated concerning how their assessment for further sustainability assessments can be incorporated.

Table 22 Regulatory and governance aspects and issue-specific indicators

No.	Aspect	Source			Indicator x = indicator included	Method / Normative Reference
		LOC	ISO	EN		
5	Capacity building, sharing	x			Open Technologies	Dissemination platforms Activities to inform and actively involve the population
7	Use Phase and Service Life	x			Concept for expansion and urban sprawl	Policy considerations for incremental expansion without safety risks
8	Regulatory compliance	x	req	req	Compliance to local regulations	NSCP Vol I (National Structural Code, Design Loads for Buildings in the Philippines) NCN (National Code of Colombia on Design)
		x			Approval scheme for innovative technologies	AITECH (in the Philippines) NSCP Vol III (Code for Residential Buildings)
		x			Adequacy of social housing	Minimum standards for social housing that better reflect the needs of the people
12	Local Economies	x			Partnerships to address key system barriers local, national, regional, global	SDG 17
		x		n.A.	Sourcing of Services and Materials Permitting along value chains	National Regulations of the Department of Environment and Natural Resources on Bamboo Use and Transportation

3 Results and Discussion

The section presents and discusses the results for the performance dimensions related to the sustainability of social housing. An overview of the scientific contributions and dissemination platforms is provided in Figure 25.

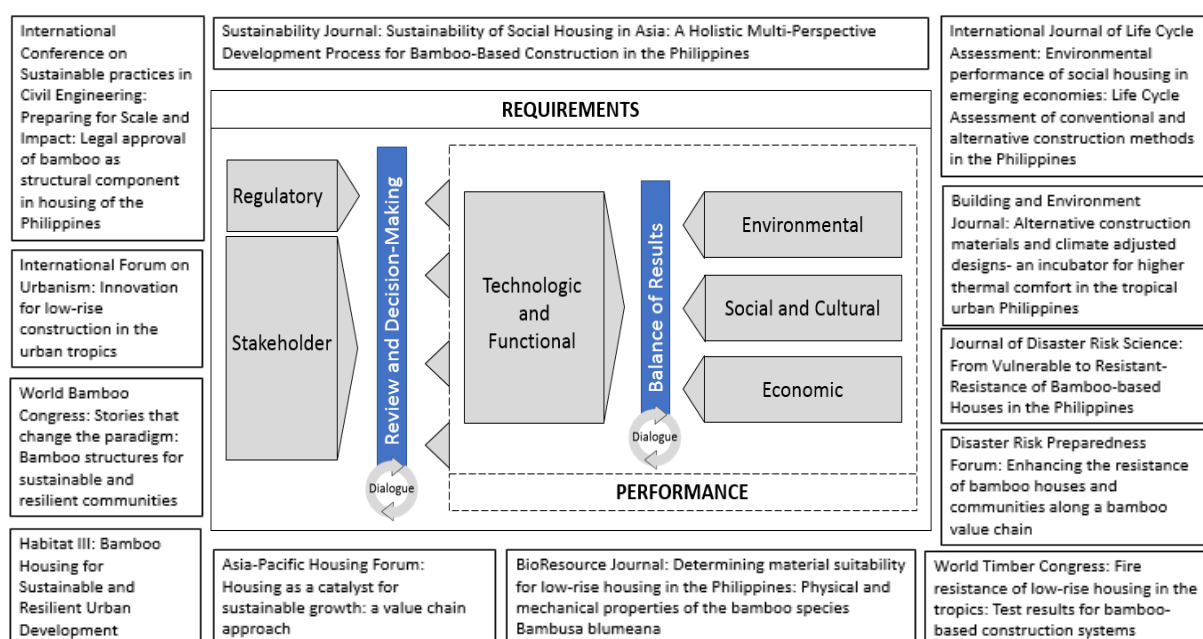


Figure 25: Overview about research contributions according to the holistic framework

All results are summarized along with key findings in the following sub-sections. For comprehensive insights, reference is made to respective publications. Spider graphs are provided to summarize the results in a qualitative manner; however, they do not replace the need for precise results and serve solely to enable readers to obtain an immediate understanding

and overview of the results. The ranking in the spider graphs is obtained by transcribing the results on to a scale of zero to 10. Category 10 is only provided for indicators that are remarkable in their performance, exceeding the relevant requirement. The space between the categories is of a qualitative nature. Because of the inhomogeneous nature of the indicators, it is not possible to define a fixed percentage of exceedance across all indicators. Relevant indicators that were not assessed because of a lack of data or methodology are categorized as zero. Indicators that were not considered relevant are omitted. The ranking categories are described in Table 23.

Table 23 Performance ranking in qualitative spider graph

Ranking	Ranking Name	Ranking description
0	INA	Indicator not assessed, but attested as relevant
2	Clearly below requirements	Minimum performance clearly not met
4	Below requirements	Minimum performance not met, but not far below
6	Meets requirement	Minimum performance met
8	Exceeds requirement	Performance exceeds requirement, providing additional benefits
10	Clearly exceeds requirements	Outstanding performance in relation of minimum requirement

3.1 Results and Discussion of Technical Performance

In this section, the results of the technical performance dimension are presented and discussed according to the aspects and indicators introduced in Section 2.3. The technical dimension contained predominantly quantitative indicators, justified by national or global regulatory requirements. It includes the aspects material characterization, construction system, resistance against fire, typhoons and earthquakes, and technical performance during use, which includes thermal comfort, maintenance needs, and adaptation options.

An important entry point for the use of bamboo in construction is chemical treatment and protection by design because degradation would otherwise limit its life span. Negative implications stemming from insufficient protection against aging have been confirmed both through accelerated laboratory testing (Huang et al. 2014) and long-term studies with exposure to outdoor applications (Cardona et al. 2002; Beraldo 2016). The achievements on enhanced treatment in the Philippines enabled to obtain better quality with lower operational, health, and environmental risks. These results are not part of the scientific work of the thesis, it is referred to the Base Foundation (Base Foundation, 2018) and Bambou Science et Innovation (Bambou Science et Innovation, 2017).

Through a quality selection process of full culm bamboo of the species *B. blumeana*, the raw material was transformed into strength-graded structural material for construction. Its favorable mechanical properties were embedded in a performing building system, which complied with resistance categories against fire and extreme storm impacts. It has excellent seismic resistance, which has been proven previously in Latin America. In the Colombian studies, exceptional seismic resistance was empirically documented, and this was then supported by extensive laboratory testing at the system and building level (Lopez Munoz, 2000). While traditional construction methods already showed superior performance, technical improvements were recommended to increase resistance to achieve a high-level performance. In summary, a robust, redundant, and highly energy-absorbing system has been shown to deliver outstanding earthquake resistance.

Through a mixed materials approach with a mortar cover, the buildings provided a new level of safety compared with traditional bamboo houses in rural areas. A rigorous quality and risk management process by the Base Foundation (2018) enabled a similarly high level of quality to be maintained throughout the sourcing, planning, production, construction, and service processes inherent in the building and use of the houses. Standardization and prefabrication enabled efficient process chains with reduced exposure to harsh outdoor conditions. In use, the system showed much lower maintenance requirements than traditional bamboo houses and can be compared with conventional buildings. This was complemented by a high level of perceived and measured thermal comfort while in use. In summary, the technical results enabled the meeting of regulatory requirements, which led to legal approval for the construction system. This was obtained in 2016 through the Accreditation for Innovative Technologies for Housing (AITECH) of the Philippine Government (National Housing Authority of the Philippines, 2015). Such approval applies to innovative building methods that are not included in the National Structural Code of the Philippines (NSCP).

This thesis does not claim that improved building resistance can replace preparedness and communication campaigns. A pro-active typhoon warning system and timely evacuation has been shown to limit the number of casualties in the typhoons that were assessed as part of this thesis (National Disaster Risk Reduction and Management Council, 2014, 2016). As the effect of climate change is predicted to further increase the hazard exposure of Asia-Pacific (Mahmood, 2009), the importance of comprehensive, integrated preparedness agendas will continue to grow. More insight into individual technical performance results is provided in the following sub-section. All technical results are shown in Figure 26. The results are reported in detail in the sub-sections to follow.

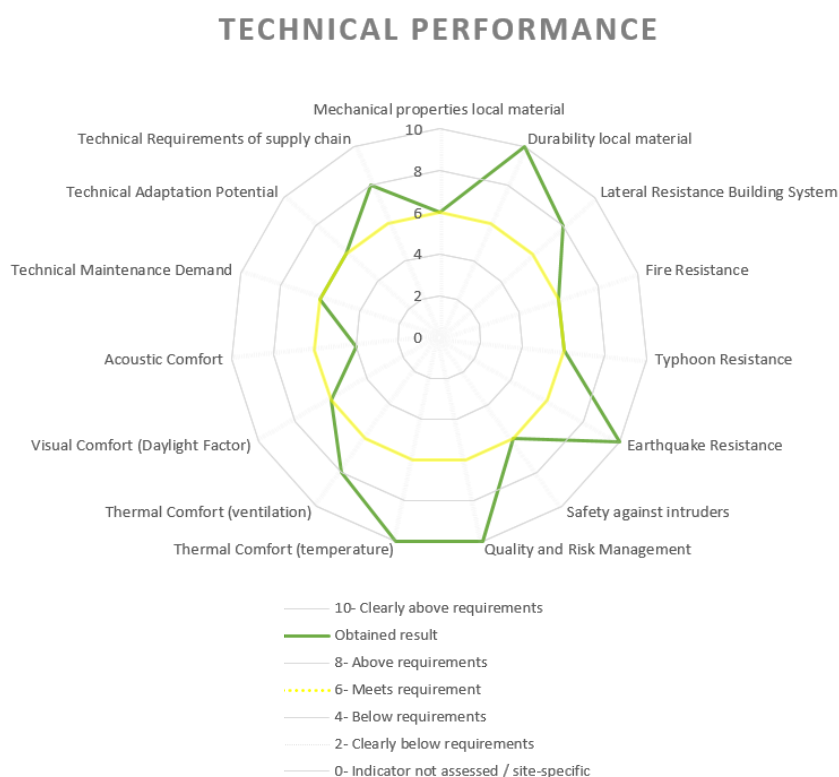


Figure 26 Results of the technical performance dimension: Spider Graph

3.1.1 Material characterization

The section summarizes the mechanical properties obtained from testing the bamboo species *B. blumeana*. The average density was observed to be 570 kg/m³. It significantly increased from the butt to the top of the culm. This increase is attributed to the change in percentage of vascular bundles to parenchyma. Liese (1974) specified that the total number of vascular bundles decreases steadily with the height of the culm, whereas at the same time their closeness increases, and the parenchyma content decreases. With the relative density being an important indicator property for mechanical properties (Janssen 1980; Espiloy 1992; Trujillo 2017), the increase positively affects the mechanical properties toward the top. In comparison with other bamboo species tested in green condition according to (ISO 22157-1, 2004), the relative density of *B. blumeana* is in the medium range. *Guadua velutina* (*G. velutina*) and *Guadua amplexifolia* (*G. amplexifolia*) have 25% and 15% lower relative densities, respectively (Ordóñez-Candelaria and Barcenás-Pazos 2014), whereas that of *G. aculeata* is comparable to that of *B. blumeana* (Zaragoza-Hernández *et al.* 2015). For *G. angustifolia* Kunth and *P. pubescens*, 30% and 26% higher relative densities were reported by Correal and Arbeláez (2010) and Deng *et al.* (2016), respectively. Sompoh *et al.* (2013) compared the relative density of *B. blumeana* with other species and reported 7% to 10% lower results for *Bambusa bambos* (*B. bambos*), *Dendrocalamus asper* (*D. asper*), and *Dendrocalamus hamiltonii* (*D. hamiltonii*). Compared to the results for *B. blumeana* of Sompoh *et al.* (2013), tested in green condition, the relative densities for *B. bambos*, *D. asper*, and *D. hamiltonii* were 34% to 44% higher, which highlights the change of properties below the Fiber Saturation Point (FSP) of bamboo species. For the physical properties, it is referred to (Salzer *et al.*, 2018).

The mean compressive strength parallel to the grain was 36.4 MPa, and the characteristic strength value 20.0 MPa, as documented in Table 24. The characteristic compressive strength compares to the strength class C22 for sawn timber (EN338 2016). The compressive strength according to Espiloy (1992) was 16 % higher, while Latif *et al.* (1992) found 26% lower compressive strength of *B. blumeana*. The results of Espiloy (1992) and Latif *et al.* (1992), remain difficult to compare to directly, as a merger of the Indian Standard IS 6874 (1973) with a modification of the ASTM D143-94 standard (1994) as well as the Indian Standard IS 6874 (1973) alone was applied for the Philippines and Malaysia, respectively. The compressive strength for *G. angustifolia* kunth was comparable to *B. blumeana* (Correal and Arbeláez 2010), while it was 15% higher than for *G. aculeata* (Zaragoza-hern *et al.* 2015).

The mean tensile strength parallel to the grain was 162.3 MPa, and the characteristic strength value 94.9 MPa. In global comparison, results of tensile strength varied the most across species with a range of 59 to 227 MPa.

The mean shear strength was 7.9 MPa, and the characteristic strength value was 5.1 MPa. The results of five other bamboo species tested in green condition ranged from 3.1 to 7.6 MPa. Test results of nine bamboo species with samples near or below the FSP and in dry conditions ranged from 5.7 to 13.6 MPa. According to the current study, the shear strength of *B. blumeana* is at the upper end of a previously defined range for green samples.

The mean bending strength was 62.8 MPa, and the characteristic strength value 34.6 MPa. The obtained bending strength values were characteristically high, reflecting the flexibility of bamboo. Due to the long internode distance of *B. blumeana* culms, the wooden saddle supports transferring the load from Universal Testing Machine to the bamboo, caused crushing failure in some samples. Such incorrect failure modes were consequently excluded from the assessment. 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 the requirement of a symmetric load distribution. The mean results of nine other bamboo species, tested in green and dry condition according to (ISO 22157-1, 2004), ranged from 61 to 95 MPa. The mean *B. blumeana* results of the current study were therefore at the lower end of the range. Pictures from the testing are shown in Figure 27.



Figure 27 Shear, tension parallel and bending testing of *B. blumeana*

In summary, the characteristic strength values of *B. blumeana* were as follows: compressive and tensile strengths parallel to the grain ($f_{c,0,k} = 20$ MPa and $f_{t,0,k} = 95$ MPa), shear strength ($f_{v,k} = 5$ MPa), and bending strength ($f_{m,k} = 34.6$ MPa); in addition, the mean MOE and the MOE at fifth percentile were $E_{\text{mean}} = 13100$ MPa and $E_{0.05} = 8600$ MPa, respectively. The mechanical performance of *B. blumeana* can be considered suitable for structural application in low-rise housing. The compressive and tensile strength along the grain and bending strength of *B. blumeana* demonstrate the potential of bamboo for construction. Construction methods must be found, which consider the low shear strength of bamboo culms especially in connections (Latif *et al.* 1992).

Overall, the performance of *B. blumeana* was in the expected range of previous studies on full bamboo culms used for structural purpose. *Requirements for low-rise housing are therefore met.* Figure 28 visualizes selected mechanical properties of various bamboo species, including *B. blumeana*.

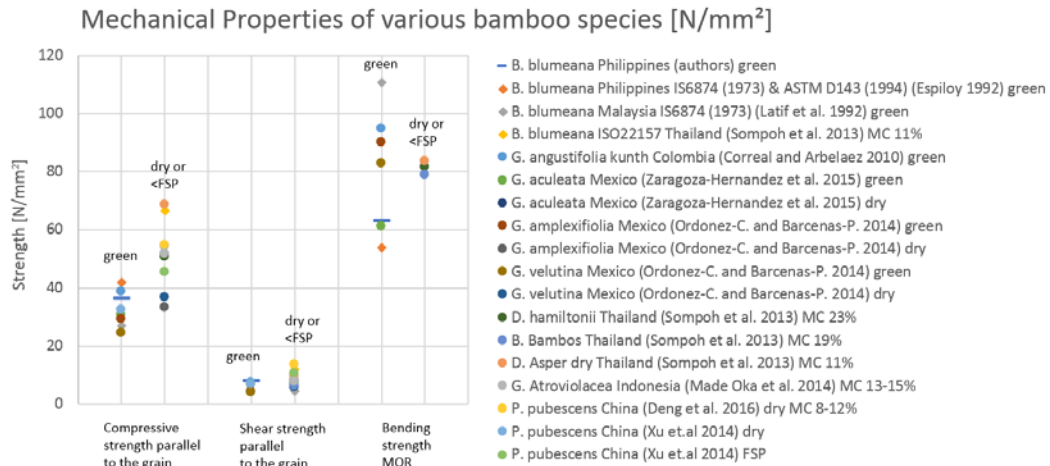


Figure 28 Mechanical Properties of various bamboo species (Salzer *et al.*, 2018)

In the left column of Table 24, the characteristic strength values for *B. blumeana* bamboo are stated as obtained from the testing. In line with the limit state design principle, permissible stresses for using *B. blumeana* bamboo in low-rise construction in the Philippines were derived. Given the natural variability of bamboo, conservative safety factors were used. The suggested permissible stresses stated in this work are only applicable for construction for quality-controlled, mature *B. blumeana* bamboo culms from the Philippines.

Table 24: 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	ρ_{mean}	570kg/m ³	ρ_{mean}	570kg/m ³

3.1.2 Construction system

The use of full culm bamboo in a *building system* is an essential step to unlock the potential of the raw material. The Colombian connection system (Colombian Institute of Technical Norms, 2006; Association of Earthquake Engineers Colombia, 2009) covered in the building code was found to be most suitable to meet the sector requirements. Its durability and modest maintenance were particularly well covered, compared to more temporary lashing techniques as found in Asia. Through local testing in the Philippines following Latin American test protocols, the connection design was determined and quantified in its performance for the design of Philippine bamboo-based structures. The testing of embedment strength and a three connection types is seen in Figure 29 and Figure 30.



Figure 29 Embedment test (top left), and testing of connection types (right)



Figure 30 Testing of connection types cont.

The system performance of cement-bamboo frames was tested in *racking strength tests*. The characteristic lateral load bearing capacity is the basis to calculate the minimum length of walls along both building axes. A total of 24 wall elements were tested in the racking strength tests. Unexpected failure modes because of the test set-up or the fabrication method were overcome in iterations of test cycles. These experiences provided relevant information for implementation and influenced the quality control procedures of the Base Foundation. Fifty percent of the wall elements were tested prior to pilot implementation. The samples contained different bracing, plaster carriers, and cladding variations, with two samples shown in Figure 31. In the course of testing, the use of bamboo rails and bracing was replaced by timber rails and metal bracing to meet time, skill, and production cost constraints, and to increase standardization. The effects of such decisions were assessed and balanced with respect to the social, environmental, and economic dimensions. The use of laminated bamboo boards for cladding was not continued because of durability, availability, and glue concerns. Their technical racking strength performance was in a similar range to the plastered version. The testing was reiterated after initial construction projects to confirm the as-built performance of the most suitable design configuration. On average, the racking strength tests conducted in the Philippines confirmed a resistance of 10 kN per running meter of the wall material, using a double cladded frame. A typical test result, confirmed in three similar test samples, is shown in Figure 32. The racking strength results are to be used with safety factors and serve as input in the structural design of

houses in the Philippines. The results are only applicable to this particular building system, when the tested connections are used and quality control in production is applied.



Figure 31 Racking strength tests of two kinds of bamboo frames

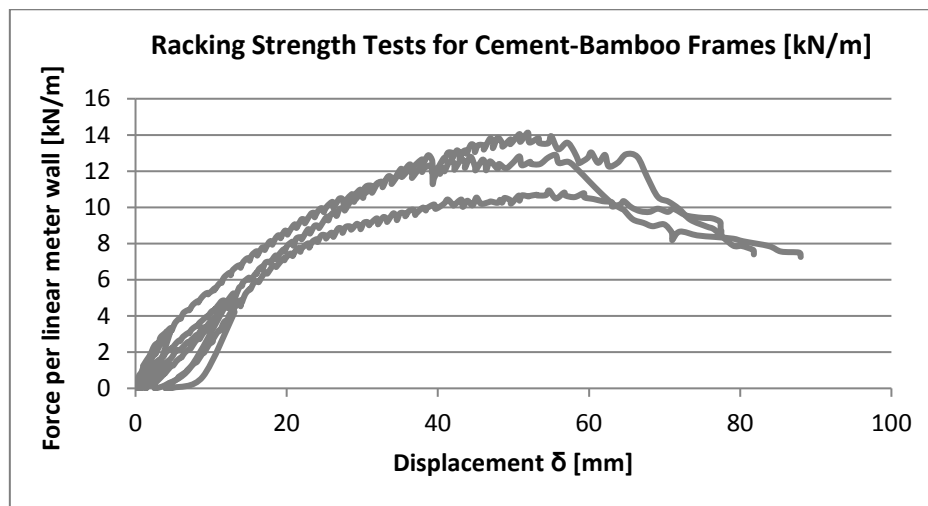


Figure 32 Load-displacement graphs of selected cement-bamboo-frame tests

The redundancies of the shear wall system ensure a robust performance and provide significant potential for a high level of energy dissipation. While *clearly exceeding the minimum requirements* of resistance against lateral impacts, the building system also possesses further advantages. Shear walls can be prefabricated in a standardized way, replicable in a quality-controlled protected environment. Manually, they can be easily installed on site in a timely manner. The steps of this process are documented in Figure 33. Base Foundation (2018) operations prioritize local employment and capacity building rather than mechanization, although this may be adjusted by the value set of the respective partner. Their light weight enables construction workers, irrespective of gender and age, to participate in the construction process.



Figure 33 Construction process from selection and prefabrication to installation on site

3.1.3 Fire resistance

The results summarized in this section are documented in Salzer, Wallbaum, and Tambunan (2016). They were obtained through 1-hour fire impact tests and are reported according to the following categories: Insulation (I), Integrity (E), and Mechanical Resistance (R).

Insulation (I): Figure 34 displays the temperature increase over time on the unexposed side of the construction of a sample with organic plaster carrier (dashed line) and one with a metallic plaster carrier (solid line). All tested samples received an insulation fire rating of 60 minutes. The maximum reading of a thermocouple at the side not exposed to fire was 80°C after 60 minutes, with other thermocouples ranging from 50°C upwards depending on the thermocouple location. Thus, 80°C is clearly below the maximum allowable temperature according to the accepted levels of 140°C (average) and 180°C (max). the organic plaster carrier had an insulating effect that showed a slower increase in temperature compared with the metallic

plaster carrier. Given that the performance of both samples was sufficient, insulation was not deemed a critical variable for the wall system.

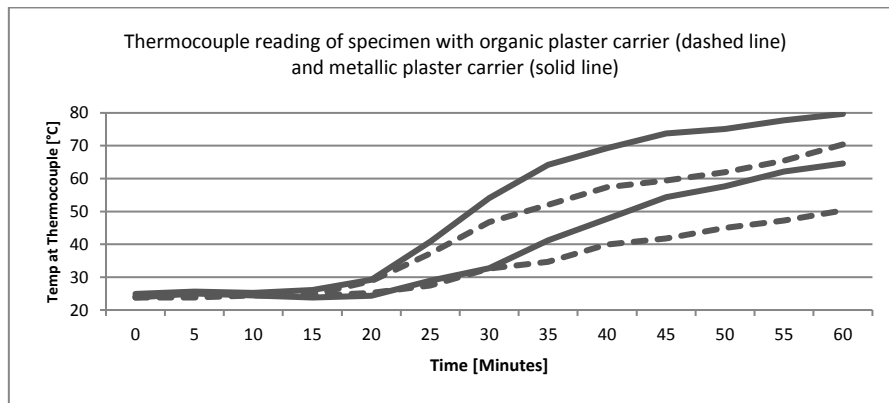


Figure 34 Thermocouple reading of samples with two types of plaster carrier

The performance of the sample with cladding on only one side was less conservative in comparison with the two-sided sample. Temperature readings increased after 10 minutes, compared with 20 minutes for the two-sided version. A maximum temperature of 100°C was obtained after 60 minutes. Because the results of all samples remained the acceptable temperature range, this result was assessed as satisfactory provided that the sample with one-layer protection is exposed to fire from its protected side.

Integrity (E): The integrity of all samples was maintained during the testing. No flame spread occurred on the side unexposed to fire, regardless of the type of plaster carrier test or whether single or double cladding was used. However, an assessment of the fire exposed and unexposed surfaces during and after the testing indicated a different behavior between the organic and metallic plaster carriers. Under the impact of fire, the sample with the organic plaster carrier suffered strong cracking and the partial flaking of plaster portions. The occurrence of wider cracks on the surface exposed to fire increased the risk of linear heat peaks. Both effects were significantly reduced in the metallic plaster carrier sample. A visual assessment of the crack pattern and crack width indicated less cohesion between the organic plaster carrier and its plaster cover. The left and middle photos in Figure 35 show the surfaces of the organic and metallic plaster carrier samples, respectively. Cracks were also observed on the side that was not exposed to fire, as shown on the right.



Figure 35 Surface integrity after testing with organic and metallic plaster carriers

For the sample where the structural bamboo rounds were unprotected at the unexposed side, the plaster layer on the unexposed side was an important feature that suppressed flame spread and fulfilled the integrity criterion. Thus, no flame spread occurred for 60 minutes despite the structural bamboo beginning to show some effects from the fire on the exposed side, as shown in Figure 36.

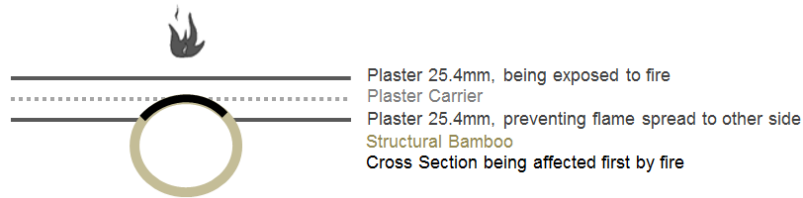


Figure 36: The effect of the plaster layer on the side not exposed to fire

It should also be mentioned that the possible effects of the reduced penetration depth of the anchors holding the cover because of the charring of the bamboo were less visible when tested without load; only a mechanical test after fire exposure enabled its evaluation. According to Eurocode 5 (2016), a minimum anchorage penetration of 10 mm is required for timber structures. If this requirement is followed for bamboo with a typical bamboo wall thickness of 10 mm, any kind of charring would be equal to a failure, although its structural capacity would enable for a reduced cross-section.

Mechanical Resistance (R): Because the test stand in PUSKIM (2015) did not provide testing under load, the mechanical resistance was assessed through the determination of the effective cross section of bamboo after 60 minutes of fire exposure as shown in Figure 37. Testing under load is recommended as described in ISO 834-1 (1999). Although various levels of charring were identified for the sample, ranging from no charring to punctual, linear, or regional charring of up to 5mm, the load bearing capacity of the 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 relating to compression test results were conducted.



Figure 37 Bamboo cross-sections after test and classified according to charring rate

It should be noted that the increased organic matter of the sample with the organic plaster carrier produced longer smoldering periods and enabled higher flame spread across the wall than the sample with the metallic plaster carrier. Both characteristics are a critical risk factor for the mechanical resistance of the wall assembly and favor metallic plaster carriers. For the sample with the two-sided cladding, the additional layer of 25 mm of plaster enhances compartmentation. However, because the structural bamboo poles in the wall center began charring after the failure of layer one, the second layer provides fire protection from both sides of the walls but does not increase the protective function.

Fire resistance is a critical requirement for building technologies using organic structural members. Research shows that cement-bamboo frame walls can *comply with existing minimum regulatory requirements*. Because of the hollow shape and thin walls of the bamboo material, the fire resistance of bamboo walls must be obtained via a protective cover. Regarding 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 the sufficient protection of structural supports. Through experimental fire testing, an appropriate system configuration was derived and relevant criteria determined: (1) usage of a 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 the side unexposed fire to avoid flame spread in case of interior bamboo exposure; and (4) an anchorage system ensuring the performance of the protective cover for walls of a limited thickness.

For all samples, insulation performance was good. Regarding integrity performance, the metallic plaster carrier performed better than the organic one. The charring of bamboo must be completely prevented to ensure compliance with the minimum penetration depth of anchors holding the protective cover on the bamboo. For mechanical resistance, a post-impact assessment of the mechanical resistance of bamboo poles showed that initial charring does not immediately determine the load bearing capacity of the system at risk and could possibly be considered for system performance. Furthermore, the test stand used was unable to test mechanical resistance during fire exposure. Thus, further testing under load is recommended. Studies to determine necessary safety factors and reduced mechanical properties for structural bamboo are also recommended. In addition to the active resistance of the building system, passive protection through risk reduction is recommended for bamboo-based housing projects. Structures using round bamboo for load transfer should be embedded in a holistic fire safety concept that considers the realities of social housing settlements.

3.1.4 Typhoon resistance

The results summarized in this section are reported in Salzer and Wallbaum (2018), which has been accepted for publication and is currently under review. Acknowledging the existing strength of bamboo-based building, such as its earthquake resistance, this thesis focused on addressing weaknesses such as its *storm resistance*. Between 2013 and 2016, the houses were in the damage zone of four major typhoons. Their respective tracks in proximity to the test houses are displayed in Figure 38. The typhoons passed the test houses at a distance of 17-52km, with one typhoon at category 1 and 3, and two at category 4. The maximum sustained wind speeds were 120-213 km/h. Typhoons Nock-ten and Rammasun were category 4 typhoons with wind speeds above 200 km/h when they passed the test houses only 22 km and 17 km away, respectively. Data collected by JTCW (2016) and PAGASA (2016) are processed and documented in Table 25.

Table 25 Typhoons near the test houses, 2013-2016, based on JTWC and PAGASA

Date Month/ Year	Name		at max along the track		at the closest distance to the site					at the site (estimated)		
	Local	Global	Cat SSHS	Vmax [km/h]	Cat SSHS	Vmax [km/h]	Distance [km]	Radius Eye [km]	Radius Vmax [km]	Signal Pagasa	Zone	Vmax
11/13	Yolanda	Haiyan	5 ST	315	5 ST	287	220	37	28	3	OR	60
07/14	Glenda	Rammasun	5 ST	287	4 TY	213	17	37	28	3	EYE	213
11/14	Ruby	Hagupit	5 ST	259	1 TY	139	52	28	28	3	IR	120
11/15	Amang	Mekkhala	1 TY	130	TS	83	12	-	-	1	IR	83
12/15	Nona	Melor	4 TY	230	3 TY	194	45	19	19	3	IR	160
12/16	Nina	Nock-Ten	5 ST	259	4 TY	213	22	19	19	3	EYE	200

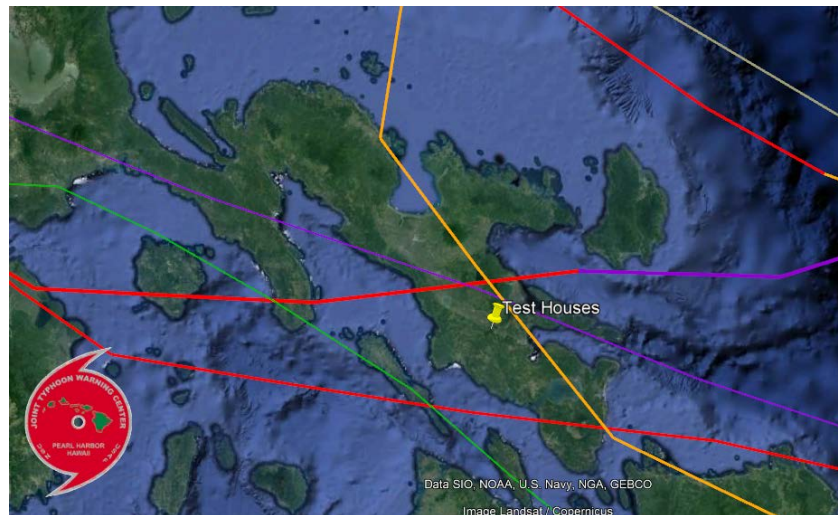


Figure 38 Typhoons near the test houses, 2013-2016, based on JTWC and PAGASA data

Damage from Typhoons Rammasun and Hagupit were ranked as two of the 20 costliest typhoons to hit the Philippines between 1974 and 2014 (Weather Philippines, 2015). The inspection of damaged or destroyed lightweight houses in the municipality and neighborhood of the test houses confirmed common failure types. On average, three out of every twenty buildings were damaged. In all four typhoons, lightweight structures suffered the most damage in the rural and semi-urban settlements close to the test houses. The test houses were reviewed after the four typhoons with the criteria (1) structural integrity and (2) usability and maintenance efforts. According to the vulnerability curve for bamboo houses under typhoon impact, 82% of all bamboo buildings would fail above 120 km/h and 97% with a wind impact of 150 km/h (PAGASA DOST, 2014). The houses in this test study resisted four typhoons with wind speeds above 120 km/h, with three of the four typhoons exceeding 150 km/h. All three houses were found to have suffered no structural failure, while lightweight houses collapsed directly next to the test houses or suffered severe damage, as documented in Figure 39.



Figure 39 Test houses before (top) and after Typhoon Rammasun (bottom)

Thus, the improved bamboo-based building methods withstood exposure to real-life typhoon impacts over the course of 4 years. The development and testing of more advanced, yet affordable bamboo-based building methods provided visual proof of enhanced storm resistance and with that they *comply with legal and social minimum requirements*.

3.1.5 Health and comfort

The results summarized in this section are taken from Salzer *et al.* (2018). That study analyzed the indoor comfort of conventional and alternative low-cost houses and studied the impact of discomfort on user behavior and adaptation. The comparative assessment included concrete, steel frames, and soil-cement and cement-bamboo frame houses. Sensor readings according to ISO 7726 (2001) taken in typical low-cost houses in one settlement over the course of three tropical seasons warm-humid, hot-humid, and hot-wet were compared. For each house type, four houses of the same building method, design, and orientation were monitored. The physical results correlated with a survey investigating inhabitants' sensations and behavior according to ISO 7730 (2005).

The results, in general, must be seen in light of the challenging impacts affecting the inhabitants of the various types of social houses. The demanding climatic conditions of the tropics were combined with a, on average, higher number of family members residing in a small space. The wish for privacy contradicts the need for effective ventilation and natural lighting, as partitions and ceilings would enclose small partitions. As the readings were taken in an actual settlement, variables could not be fully isolated but had several interrelations such as a larger number of family members with a less favorable building design. 20 parallel readings enabled to create an understanding of the variables influencing the indoor temperature.

To reduce the distortion of variables in the building technology comparison, a *reference measurement* was conducted with 20 conventional buildings, assessing and quantifying influential exterior, occupancy, or design-related variables. It was found that generally, small volumetric buildings such as social houses are subject to significant heat intake. This is particularly true because metal roofing sheets without insulation are commonly used across all building types. In the reference testing, it was shown that passive cooling through the

orientation of buildings and exterior shading can have a substantial impact on indoor thermal comfort. Furthermore, variables with considerable influence included climate-adjusted designs of the building envelope with an increased ceiling height and effective natural ventilation. However, these aspects are often limited in high-density and low-cost buildings. There were also constraints on natural ventilation because of concerns on safety and driving rain. A typical cluster performance could be identified as well as minimum and maximum variations, both of which are shown in Figure 40. Only houses from the typical cluster performance group were chosen for the comparative assessment, to ensure that the comparison was based on typical performance.

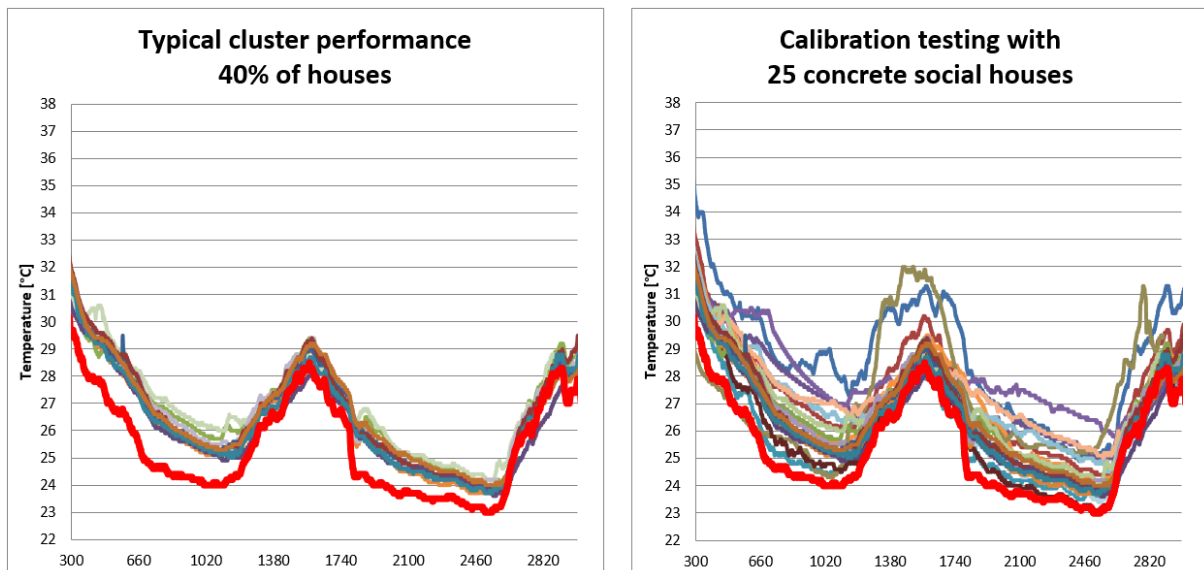


Figure 40 Natural variability and identified cluster performance from the calibration

The *comparative measurements* excluded differences in orientation and exterior shading, and documented the number of occupants in the houses. Thus, all building technologies were closer to their typical cluster performance. The obtained performance was driven by the building technology, the building design, and the building use. One characteristic with considerable influence on thermal comfort is thermal mass. In the tropical climate of the Philippines, thermal mass is generally less favorable than in more temperate climates (UN-Habitat, 2012). In a temperate climate, thermal mass is generally favorable to buffer heat variations by absorbing and releasing it with time delay. Buildings in temperate zones and higher thermal mass remain cooler during the day and warmer during low night temperatures. In the tropics, a buffer of heat-peaks during the day would be favorable. However, its steady release of heat during the night is not, as a fast cool-down during the evening is very important for inhabitants. Because there is less outdoor temperature fluctuation between day and night, the buffering function of thermal mass is less effective. Compared with concrete and soil-cement houses, steel frame and bamboo-based buildings showed a faster cool down during the evening, particularly in the second floor.

However, at the same floor, the thermal conductivity of the steel frame caused a significantly higher temperature peak during the daytime. Overall, the second floor of bamboo-based houses showed a temperature curve closer to the outdoor measurement. During the daytime it did not heat up like steel frame houses, but it had a similarly fast cool down during at night. This

performance can be understood as a combination of the building material and the house design. On the material side, the low thermal conductivity of the bamboo and its light mass were favorable. In combination with effective ventilation and an increased spatial comfort with higher ceilings, this can lead to less radiation heat at the main standing and working heights of inhabitants. The behavior of the buildings is showcased for a typical diurnal cycles during the hot season in Figure 41. Overall, bamboo-based buildings provided a naturally comfortable, climate-adjusted compromise in the tropical context.

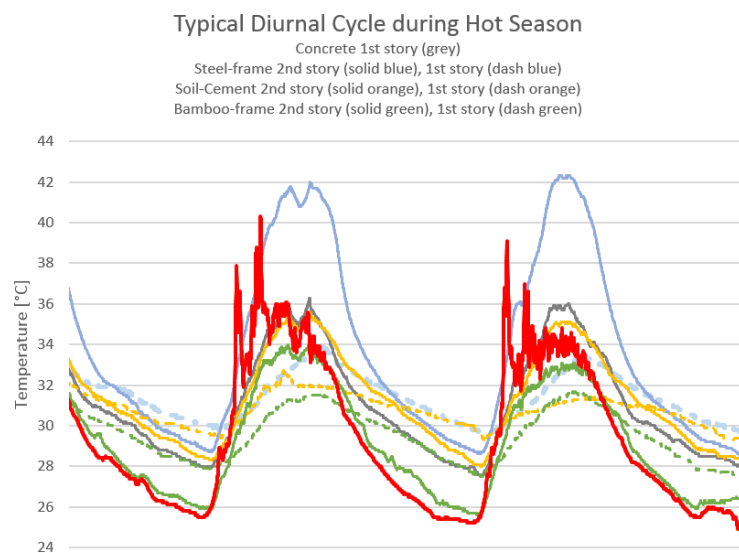


Figure 41 Comparative readings for four building technologies during two diurnal cycles

According to the ASHRAE7-point sensation scale of warmth (ASHRAE, 2017), more than half of the inhabitants felt hot or warm inside their naturally-ventilated homes (Figure 42). During the hot season, this share increased to above 80%. The existence of great discomfort or even danger on the health and well-being of occupants was shown by applying the heat index to the physical measurements. Sailor (Sailor, 2014) states that “one of the fundamental purposes of buildings is to serve as protection from the ambient environment”. Several houses lost this protective function, as surveys confirmed the adaptive behavior of leaving the houses because of great discomfort.

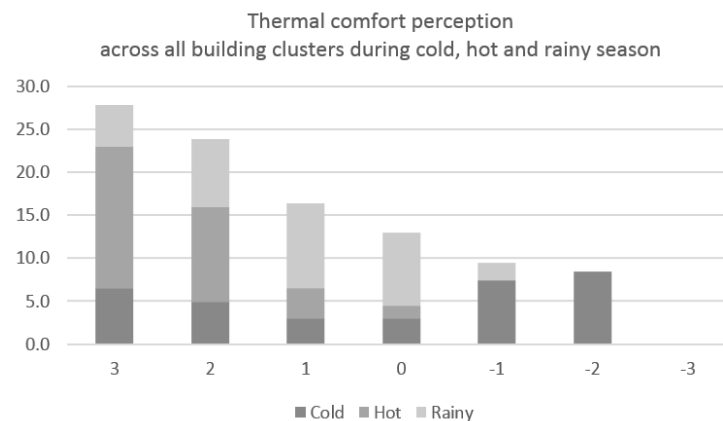


Figure 42 Thermal comfort perception [%] during cool, hot, and rainy season

On average, the inhabitants in bamboo-based and soil-cement houses provided a more positive response on the perceived comfort. The felt ventilation was important for the perceived comfort. In many cases, however, the effective use of windows was disabled because of the inhabitants' higher priority on privacy, safety, and protection from rain. An integrated approach to design is therefore needed considering these requirements in the planning stage.

80% of the respondents expressed plans to invest into enhancing the comfort inside their houses. The most frequent interventions were the installation of a ceiling, the purchase of an aircon unit (albeit mostly not affordable to date), and the purchase of additional fans, with 59%, 30% and 18% respectively. The share of respondents expressing such intentions was increasing with the level of discomfort felt. Inhabitants of bamboo-based houses reported that air conditioning is no more a top priority in their list of future expenses. It is not yet established whether such intentions can be measured in expenditure profiles of inhabitants in the long run. Further studies on longer time horizon, sample size, and geographic locations are recommended.

Inhabitants of informal and social housing are often the most vulnerable to the effects of extreme weather impacts such as heat. A conscious choice of planners and decision-makers is needed to define climate-adjusted minimum requirements and select appropriate materials for social housing. With these findings, the *typical performance of bamboo-based social housing was considerably exceeding expectations*. Furthermore, this is a field of high research relevance, as it addresses potentially more energy-efficient living styles of large groups of inhabitants in emerging economies.

3.2 Results and Discussion on Environmental Performance

The results that are summarized in this section are documented in (Salzer *et al.*, 2017). The cement-bamboo-frame house was compared to a conventional concrete house (RCC/CHB) typical for the social housing segment. Besides that, two further alternative building technologies, soil-cement block houses (SCB) and coconut panel houses (Coco), were included in the assessment both highlighting further potentials of underutilized local raw materials. For more details on the alternative technology of coconut panels, it is referred to (Böger *et al.*, 2017; Salzer *et al.*, 2017). The assessment of phases A–B–C–D with GWP, resulted in a 35% reduction of environmental impact for soil–cement blocks, 74% for cement–bamboo frame, and 83% for coconut board-based houses relative to the concrete reference house. In absolute terms, this relates to a reduction of 4.4, 9.3, and 10.3 t CO₂ equivalents over a service life of 25 years. CED showed higher impacts for the biogenic construction methods coconut board and cement–bamboo frames of +8.0 and +4.7%, while the soil–cement technology was evaluated –7.1% compared to GWP. Sixteen of 17 midpoint categories of Impact2002+ confirmed an overall reduction potential of the alternative building methods, with the midpoint category land occupation being the exception rating the conventional practice over the alternatives.

The major impact is caused by Modules A1-A5 with 78%–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 (Carpenter *et al.*, 2013). 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. 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+.

The application of these indicators, 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. In Figure 43 the results are visualized, according to the four building methods, the indicators used and the life cycle phases. The figure visualizes, that for quality controlled alternative building methods of comparable life span, the cement-bamboo frame construction provides significant *advantages clearly exceeding conventional practices*.

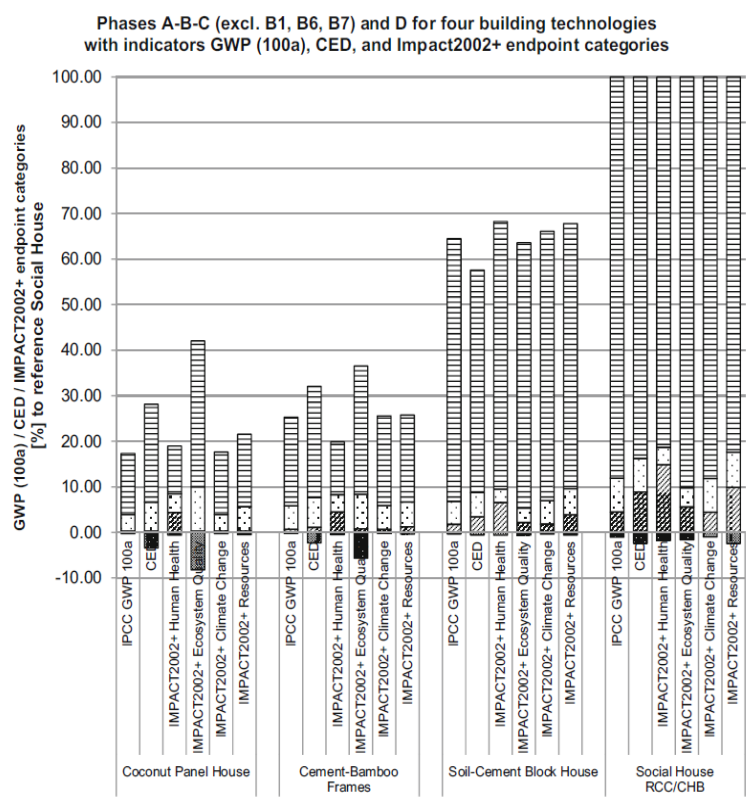


Figure 43 Comparison Phases A-B-C-D, GWP (100 years) | CED | Impact2002+ in [%]

The validity of inflow data to 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 *life span of 25 years*. The importance of the variable service life spans was visualized via scenarios with reduced life spans 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 life span. 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 (International Network for Bamboo and Rattan, 2011).
- 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 (Guest *et al.*, 2013; Pawelzik *et al.*, 2013). 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 (Hellweg and Frischknecht, 2004). In a recent scientific investigations, it was reemphasized that no adoption of “optional” carbon storage, as mentioned in (European Commission Joint Research Center, 2010), is recommended (Vogtländer, Velden and Lugt, 2013). The IPCC GWP indicator removed consideration of biogenic CO₂, given the argument that emissions will re-enter the atmosphere sooner or later and that crediting is not in line with (IPCC, 2014) global mass balance and provisions of the ISO 14040 (2006), based on precaution.
- The assumption of extra carbon sequestration in additional global forest areas, as suggested in (Vogtländer, Velden and Lugt, 2013), 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.

In 2015, the Philippines submitted its NDCs to the Paris Agreement. By the year 2030, a CO₂ reduction of 70% is intended. Measures to reduce the impact of buildings have therefore strong national relevance. Through the thorough Life Cycle Assessment, accompanying several development and project cycles, environmental benefits were quantified and documented. It is concluded that the alternative construction technologies have substantial potential to reduce the environmental burden caused by the social housing sector. The service life of the alternative technologies in comparison to the typical conventional social houses plays a vital role for it. LCA for emerging economies needs to incorporate realistic scenarios applicable at their current state or belonging to the most probable alternatives to ensure valuable results. Larger uptake of

the technology needs to be carefully assessed and accompanied with further studies on biodiversity, scarcity and land use. The indicators use of renewable materials and sustainably sourced raw material are highly relevant. Since they are only mentioned in the Annex of the EN standards, these should be included for standardization in the assessment. A summary of the environmental performance is documented in Figure 44.

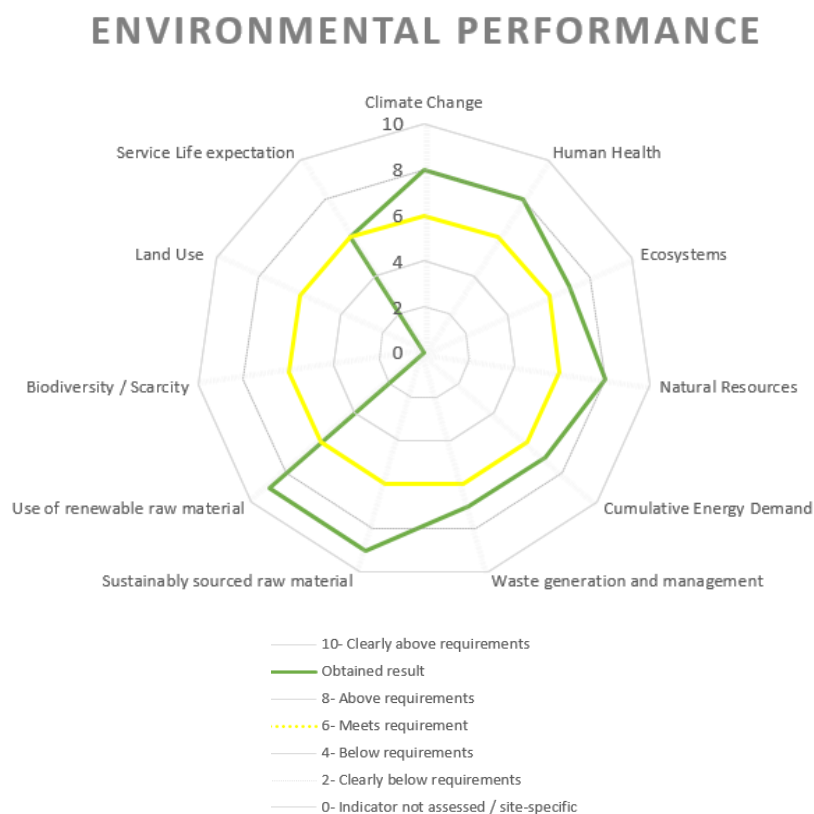


Figure 44 Results of the environmental performance dimension: Spider Graph

3.3 Results and Discussion of Social Performance

In this section, the results on the social performance dimension are presented and discussed according to the aspects and indicators introduced in Section 2.3.5. The social dimension contained the highest number of aspects, for which a measurable assessment is contested and not covered by the codes. Several aspects, which are of agreed importance, are only mentioned in the Annex of the standards including participation and inclusion (EN and ISO), identification and cultural heritage, risk and resilience (ISO only), and the sourcing of materials and services (EN only). Other aspects have been derived from the stakeholder assessment and are not mentioned in any of the two families of standards (e.g., capacity building and sharing). Table 26 provides a compact overview of the results in the social dimension. A more detailed report can be obtained by referring to the Annex.

Table 26 Outline of social performance results

No.	Aspect	Indicator	Description of achievement	Assessment
1	Safety, Risk and Resilience	Social vulnerability of inhabitants	Adaptation to climate change is multi-dimensional and required more than the enhanced resistance of houses. Partnerships with government and civil sector organizations were needed for holistic embedment. A reduction in social vulnerability has not yet been assessed in the settlements, but significant potential exists.	Not assessed
		Resilience through the sourcing of local materials, skills, and logistics	Resilience can be measured, among others, through the ability of communities and regions to respond to post-disaster needs with their own human and material resources. The geographic boundary determines the thresholds for its assessment. Ad hoc workers and the ability of a local government to build 3,000 houses may seem significant, but 10,000 houses on national scale still seems small. This highly multi-dimensional aspect requires further discussion.	Not assessed
2	Participation and Inclusion	Participation in sourcing, planning, production, construction	Qualitative reviews performed at the end of construction projects documented in which phases' particular forms of participation were considered. The technology development process placed a significant emphasis on participation along all life cycle stages (sourcing, production, construction), expanding the definition of the building life cycle to a participatory technology development cycle (adding research, planning, and review loops at completion of construction projects). Qualitative assessments showed that the type of participation changes with each project and life cycle stage. It was found that the type of participation can be further strengthened in some cases from informative to more active and decision-making types, where applicable. The inclusion of groups focuses on the users of the buildings and varied across projects according to the specific context; for example, projects for indigenous, the elderly, disabled or with a gender focus. Along the life cycle, inclusion was less visible, but the training of female workers and youth employment among farmers are already visible, but can be further strengthened.	Clearly above requirement
		Active and empowering participation		Above requirement
		Inclusiveness		Above requirement
3	Culture	Inclusion of heritage elements	The use of a culturally rooted material in research, planning and building was above the norm in social housing projects. As results, local researchers and students were compelled to conduct research about the material (n=12). There was a turnaround in the decline of traditional skills and these were improved for applications with high market demand. Local and national government (n=3) recognized it as remarkable example of investment in local culture.	Clearly above benchmark
4	Acceptability	Social acceptance	Surveys among the buildings' inhabitants after 1–3 years of occupation (n=44) showed that a majority of people were satisfied with the houses with 2%, 16%, 45%, 36% of low, average, high, and very high satisfaction, respectively.	Above requirement
5	Capacity building and Sharing	Skill level needed	All projects (n=8) showed that it was possible to work with teams where 80% of workers have no basic skills at the start of the project, if a small core team of bamboo and timber carpenters is available. More than 700 people received training in various projects along the value chain from sustainable harvesting to quality-controlled prefabrication and construction. Learning exchanges across provinces in the Philippines (n=5), and countries (n=2) are ongoing. This aspect can be further strengthened, particularly among countries and through digital platforms of exchange.	Above requirement
		Number of people trained		Meets requirement
		People reached through learning exchange		Meets requirement
		People reached through digital platforms		Not assessed

Table 27 Outline of social performance results cont.

No.	Aspect	Indicator	Description of Achievement	Assessment
6	Health and comfort	Social impact of thermal comfort with regards to temperature	The adaptive thermal comfort in naturally ventilated buildings in the tropical Philippines was assessed. Surveys (n=45) showed that in comparison with diverse types of social houses in the neighbourhood, an increased thermal comfort level was perceived. Further studies are required to prove long-term effects of this perceived comfort. Initial indications show a lower priority setting for air conditioning among the participants. Often natural ventilation did not perform as well as designs suggest because of contra productive measures stemming from the requirements safety from intruders, protection from driving rain, and privacy concerns. Theoretic concepts of ventilation, irrespective of the building type, should be assessed to ensure they meet actual priorities. While ventilation studies are highly complex and could not be determined with sophisticated methods in the informal settlements, the perceived ventilation expressed by the inhabitants seemed comparatively good. Openings in the roof and a steep roof facilitate air movement. Because of the flexibility to build higher ceilings with minor increase in cost (as the same standard price per bamboo pole applies irrespective of a length of 2.00m or 2.44m), spatial comfort lead to higher thermal comfort through less radiation heat. Acoustic comfort was not assessed but is recommended to receive attention in research and the early stage planning of new projects. In the context of naturally ventilated social housing, acoustic comfort is particularly relevant inside the small housing units to achieve a sense of privacy	Clearly above benchmark
		Social impact of thermal comfort with regards to ventilation		Meets requirement
		Social impact of visual comfort		Meets requirement
		Social impact of spatial comfort		Above requirement
		Social impact of acoustic comfort		Below requirement
7	Use Phase Services (Maintenance, Adaptability)	Acceptability to consult service provider for maintenance or expansion	On-site assessments of in-use buildings (n=52) determined the level of maintenance and expansion, with or without trained service providers. Maintenance levels varied across the individual buildings, but mainly affected conventional materials like iron roof sheets. Service providers need to be more visible, else conventional expansion is applied. Here market development needs further strengthening on assuring the availability and acceptability of such service providers.	Clearly below requirement
11	Equity of sites	Time and expense in % of daily wage to reach income opportunity	These aspects were assessed project-based. Social housing sites are not seldom far outside city centers. 'In-city solutions' that are not on high-risk lands, have therefore highest quality. This was not achieved in all sites, but site-specific geohazard assessment assured a minimum level of safety. Beyond that, the measures of time and expense to reach jobs and education are recommended for each project site. Access to basic services and infrastructure was a requirement at the start of the project. Multi-stakeholder dependencies and delays in implementation were recorded, which also affected the early months of building use. Implementation prior to construction is therefore strongly advisable.	Assessed Site-specific
		Availability of water, energy, sanitation, solid waste management, access to basic services		Assessed Site-specific
12	Local Economies	Quality of jobs created	Regulatory standards were applied on minimum wage, working hours, health and safety standards, etc.	Meets requirement
		Local employment	A high percentage of local employment was achieved in all projects (n=8). A core team of trainers, representing 5%–15% of all employees, was sufficient to train local project-based community workers. Because poor rural farmers only have access to labor-intensive employment, the level of local employment reached a higher quantity and quality than comparable value chains	Above requirement

There is some debate regarding the translation of many social aspects into measurable issue-specific indicators. This thesis contributes to the discussion while inviting further dialogue and research. The standards of the Global Reporting Initiative (2016) have a much broader basis to

reflect the impacts created in the social dimension and were used as reference. With the objective to contribute to overall empowerment, reduce inequality in standards of living, working, and involvement, and improve overall societal resilience, the social performance dimension has many aspirational aims. System change is expected to occur gradually. The holistic approach of this thesis may positively influence the preparedness of people to future impacts, especially when knowledge is shared and discussed on suitable platforms. The social housing segment is still largely determined by a perspective that only extends to the completion of the houses. The suggested indicators help to provide more substance to long-term directed projects aiming at the reduction of vulnerability through a system and life cycle perspective in social housing. Figure 45 qualitatively illustrates the results.

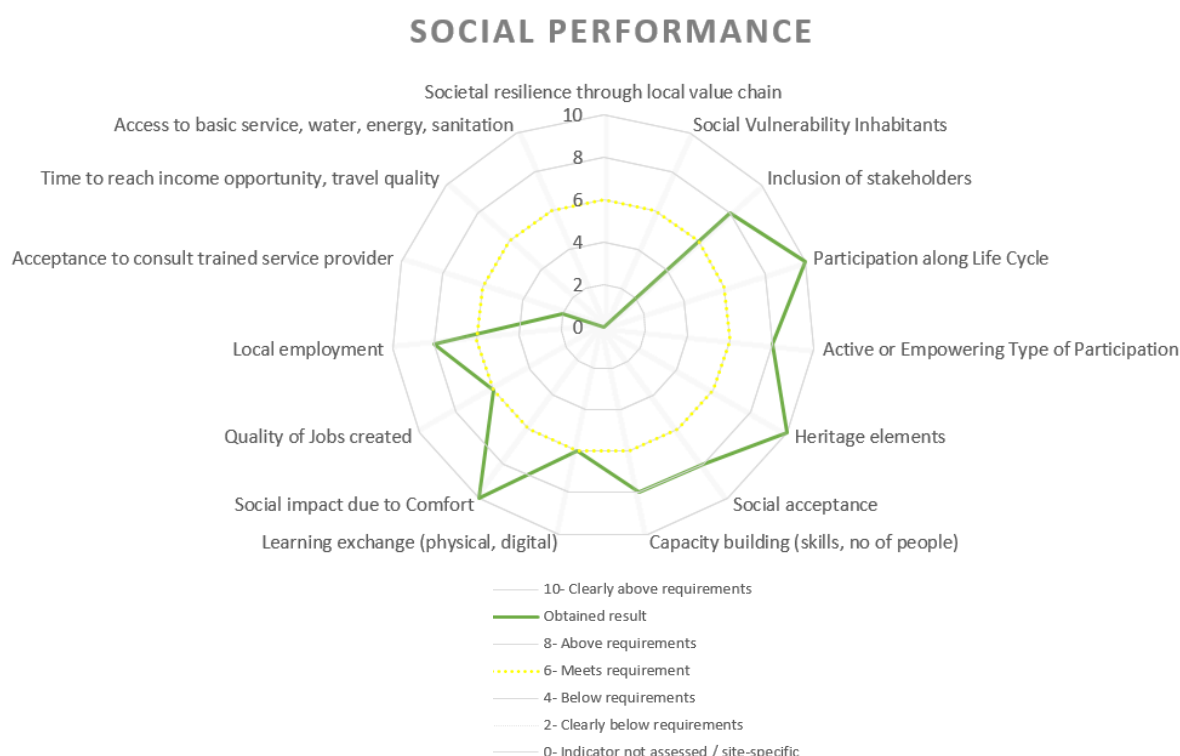


Figure 45 Results of the social performance dimension: Spider Graph

3.4 Results and Discussion of Economic Performance

In this section, the results of the economic performance dimension are presented and discussed according to the eight aspects introduced in Section 2.5. In the EN and ISO standards, the economic performance indicators focus on life cycle costing and economic value of buildings. Regarding the concept of LCCs, the standards exceed the general market acceptance, wherein initial construction costs are still considered more relevant. This thesis bridges the gap between theory and practice and includes ICCs (alongside LCCs) as a key driver in the segment. Existing technical solutions within the conventional construction sector are technically effective but costly options, and mostly above the affordability of affected families or governments. Instead of downscaling or reducing the quality of conventional solutions, this research looks at enhancing the performance of an affordable local building method. In review of eight construction projects, cost savings of 5%–40%, depending on bamboo price and location, may be obtained compared with conventional concrete and steel construction. In the initial

technology adaptation phases, however, training and learning curves outweighed this effect on direct costs. In comparison with temporary bamboo houses, the advanced building method is costlier. The ceiling for ICCs was met with segment requirements defined by the Philippine government of PHP 400,000. In the course of the projects, the direct costs were continuously lowered and are expected to further improve via increasing experience, scale, and skill level.

Cost savings are obtained through a life cycle perspective, considering the enhanced durability of the bamboo-based buildings and the risk of loss in temporary structures. However, life-cycle thinking is not yet established among stakeholder groups in the social housing segment and therefore ways must be found to address the incremental nature of social housing (see the aspects of economics and human skills). In terms of LCCs, scenarios were designed to cover maintenance, energy consumption during the use, end-of-life, and general service life. Less frequent maintenance is an improvement compared with the traditional use of bamboo, however the costs are on average higher because conventional materials like cement cladding and corrugated roofing sheets need to be maintained. In comparison with conventional construction, the effort is the same. Compliance with the bamboo treatment process was highlighted, as on-site retreatment induces further unscheduled costs to assure performance throughout the planned service life. It was shown that the technical performance is an important requirement to enable a service life comparable to conventional building technologies. The nonexistence of energy recovery in the country, made end-of-life scenarios have only a marginal positive influence. Reduced labor time to dismantle, partially reuse, or recycle material could not outweigh in relevance.

Beyond the costing achieved per house, the value chains connecting rural bamboo supply with urban housing needs provide economic benefits through local skill and material use and lasting local economies. In Table 28, the results of the economic performance dimension are summarized, and Figure 46 illustrates the same.

Table 28 Outline of economic performance results

No.	Aspect	Indicator	Description of Achievement	Assessment
4	Acceptability	Market Demand	Bamboo-based building projects annually increasing in volume, within environmentally sustainable limits	Above requirement
5	Capacity building & Sharing	Sustain jobs through market development	Survey on job history after training requires more years of experience and pro-active market development	Not assessed
6	Health and comfort	Spatial comfort within cost seal	At same cost seal: Floor Plan expanded from 18 to 24 sqm min size, ceiling height increased from 2.0m to 2.2-2.6m. Two rooms with partitions provided.	Clearly above requirement
7	Use Phase Services (Maintenance, Adaptability)	Lot space enabling expansion	Site-specific and usually not possible. Area for improvement, closely connected to governance and land tenure	Below requirement
		Maintenance and Adaptation affordability	Service life performance evaluation conducted including maintenance interventions (n=4). Lesser frequency possible than for traditional bamboo housing, but higher cost per intervention. Pricing in range of conventional maintenance.	Meets requirement
		Availability of service provider for expansion and maintenance	Availability of service providers across various regions needs pro-active market development approach.	Clearly below requirement
9	Building related cost	Cost seal Social Housing in the Philippines	Empiric assessment of as-built costing of (n=8) projects Cost seal kept with 400'000PHP unit. Continuous optimization ongoing.	Meets requirement
		Life Cycle Costs	Scenario based. Life Cycle Costs indicating savings, particularly with comfort in use scenarios (see aspect 6)	Above requirement

Table 29 Outline of economic performance results cont.

No.	Aspect	Indicator	Description of Achievement	Assessment
10	Efficiency of construction	Standardization	With a macro-economic, long-term perspective, the economic performance assessment of the thesis was expanded to assess economic efficiency of processes and sites and the building of local economies. Three traceable layers of quality control in prefabrication reduced performance risks and exposure time of elements and people to sun and rain on the construction site. With increasing training and skills, the manual installation of prefabrication wall elements allows to increase the construction time. Empiric based. High replicability through prefabrication.	Clearly above benchmark
		Expenditure for Quality and Risk Management	Incidences documented and gradually declining with learning curve.	Below benchmark
		Pace of construction	Learning curve in each project shows improvement. 3 days for panel installation. Conventional foundation and finishing. Low skill level of beginning of project accepted in favour of local employment and capacity building.	Meets requirement
11	Equity of sites	Time and expense to reach job and school	Travel time to job (one way < 2-hours capital, <1-hour province), generally found high importance of inhabitants	Assessed site-specific
		Availability of basic infrastructure and services	Requirement at completion of houses. Time delay and multi-stakeholder accountability are challenge.	Assessed site-specific
12	Local Economies	Investment into local economy / Sourcing of Service along value chain	Number of jobs and financial value created per USD spent	Clearly above benchmark
		Expenditure in research	Investment into local research and local research partnerships (n=4) created synergy effects of capacity building and innovation. Students and researchers getting involved. Feedback loops between implementation and research enabled an informed research agenda.	Clearly above benchmark
		Partnerships enabling scalability	Three North-South, Two South-South partnerships, two of three regions in the Philippines, covering eight provinces with ongoing learning exchange	Above benchmark
		Project based jobs created, min.6 month or longer	On macro-economic level, the bamboo value chain was found comparable to construction, a labor-intensive sector. An in-depth assessment of how project-based jobs can be sustained in the industry through long term market development will be a relevant indicator for the future. A translation of money spent in the bamboo value chain into jobs seems meaningful. A standardized ratio could not yet be determined, due to highly varying efforts for training at the first place.	Above benchmark
		Jobs sustained through market development		Not assessed

ECONOMIC PERFORMANCE



Figure 46 Results of the economic performance dimension: Spider Graph

3.5 Results and Discussion of Regulatory and Governance Aspects

The regulatory aspects *compliance to local regulations* and *legal approval* were named in the stakeholder assessment. A building code for bamboo-based construction in the Philippines will enhance nationwide acceptance by academe, governments, communities in need of housing, and the private sector.

The drafted code is named *Philippine Provisions for Cement-bamboo Frame Houses of One and Two Stories*. It was formulated for inclusion in the National Structural Code Volume (NSCP) 3: Housing, which currently shortly before its first release (Association of Structural Engineers of the Philippines, 2018). The design provisions recommended in the draft document are based on the results of this thesis 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 Section E and G of the *Colombian Code for Seismic Resistant Residential Buildings NSR-10* (2009). Author rights of NSR-10 belong to the *Asociación Colombiana de Ingeniería Sísmica (AIS)*. Its utilization for adaptation to the Philippines was granted for the draft formulation as part of a learning exchange. The document contains further provisions of *Peruvian Technical Norm NSR-1 (E.100)* from the *Ministry of Housing, Construction and Sanitation of Perú (MHCS)* (2009). Because the approval of standards requires time and the involvement of professional and government institutions, the bamboo section is still being processed. However, technical requirements are fulfilled, and formulations have been drafted to showcase the potential path of development.

A high-level policy dialogue with respective institutions in the Philippines must follow for social and institutional acceptance. Beyond the regulatory approval, institutional sustainability has to be achieved for impact at scale. Selected contributions to this broad and complex

requirement can be found for the aspects capacity building and sharing, the equity of sites, opportunities during the use phase of buildings, and the building of local economies.

Beyond the regulatory dimension of governance, further systemic aspects are included that were considered such as capacity building, dissemination of innovation, the acknowledgement of an incremental approach to construction, equity of sites and the building of local economies. The systemic components exceed the scope of this thesis and only selected aspect were considered. Aspects such as institutional sustainability are included, to highlight their importance, but are not assessed in this thesis. All aspects are summarized in Table 30 with further illustration in Figure 47.

Table 30 Requirements and contribution to governance

No.	Aspect	Indicator	Method / Normative Reference	Assessment
5	Capacity building and sharing	Technology Openness	To reach the affected population with findings from Science and Technology, effective means of dissemination need to be found. In (Strayhorn <i>et al.</i> , 2012), the uptake of different educational tools was assessed and accessible, easily understandable pamphlets containing best practice examples recommended. Creating a trickledown effect of a culture of safety was found to be a key priority by (Chatterjee <i>et al.</i> , 2015). Multi-stakeholder participation, as a consensus among many, is a need for implementing improved construction methods at scale. In the given context, the Open Development approach of (Base Foundation, 2018), wherein quality approved concepts are shared openly, in combination with exchange and sharing platforms, has potential to reach out to many and promises an entry point to an improved resilience of the society.	Above requirement
7	Use Phase and Service Life	Concept for expansion and urban sprawl	No conceptual approach enabling gradual expansion within legal terms, particularly for near or in-city sites.	INA
8	Regulatory compliance	Compliance to local regulations	Design Loads of the NSCP Vol I are met and approved by City Authorities through building permits.	Meets requirements
		Approval scheme for innovative technologies	Existence of an approval schemes for building technologies in the Philippines outside of the National Structural Code. Approval for alternative local raw materials and building methods obtained for national wide use.	Clearly exceeds requirements
		Minimum adequacy of social housing	Improved definition and enforcement of national standards on minimum requirements for social housing	INA
11	Equity of sites	Risk and geohazard assessment of sites	Disaggregated risk maps and coordinated approval of sites were contributed through expert consultations.	Meets requirements
12	Local Economies	Partnerships to address system barriers	Local, national, regional, and global partnerships were formed and planned to be further expanded.	Above requirements
			Institutional sustainability	INA
		Sourcing of Services and Materials Permitting along value chains	Review of bamboo as a forest product versus a commodity to be further discussed.	INA

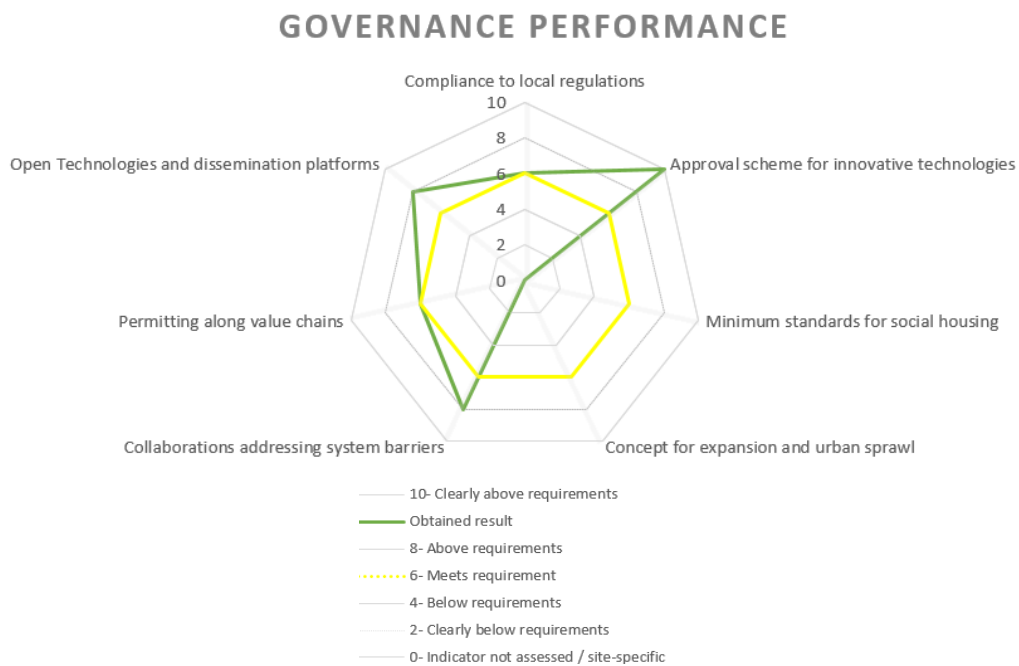


Figure 47 Results of the governance performance dimension: Spider Graph

3.6 A Summary of Specific Results and General Discussion

The section summarizes the issue-focused research and implementation results according to the four performance dimensions and discusses the approach in general. This explanation is not intended to provide total insight to the respective results; it focuses on the core indicators. A comprehensive overview of the specific results is provided in Sections 3.1 to 3.6.

The selected bamboo species has shown suitable structural properties for low-rise residential housing. A robust, flexible yet strongly anchored building method of medium-weight was derived balancing the complex and partially contradicting multi-dimensional requirements. In combination with quality-selected, treated bamboo culms and climate-adjusted house designs, the construction of reliable and durable homes was enabled. These are homes that can withstand the impacts of their environment. The walls received a fire resistance rating of 60 minutes through a mixed-materials approach and the protection of the structural components. Full-scale test houses withstood various storm impacts from four typhoons with 120–213 km/h wind speeds, without any structural damage and only minor maintenance effort. In contrast, nearby traditional bamboo structures were destroyed. Through the obtained research results, legal approval for the innovative building technologies in the Philippines was obtained. Based on the Colombian Building Code for Bamboo, and the Philippine material properties and design loads, the National Structural Code of the Philippines was drafted and is under discussion by local authorities and professional organizations.

An LCA showed significant environmental advantages compared with conventional concrete houses of the same segment, with a 74% reduction in carbon emissions per house. Surveys and physical measurements confirmed that through the climate-adjusted design and materials, higher comfort levels inside the house were achieved. This may impact the use-phase energy consumption of the inhabitants because energy consuming appliances lost importance in a priority setting. It also has the potential to influence a family's well-being in society, as health expenses may decrease; however, this has to be shown in long-term studies. Active participation

was applied throughout the research and implementation activities and, despite common perceptions, acceptance barriers were overcome among involved stakeholders.

The value chain approach, wherein informal urban communities benefited from accessing more adequate housing, created synergies with rural farmers and urban workers; the workers gained further skills and income opportunities. Using a renewable local material further strengthened local economies along the bamboo-value chain. The new level of physical resistance of the buildings and the availability of human skills and quality raw materials has the potential to positively influence the resilience of Philippine communities in the future. This value proposition was obtained while meeting the social housing bracket of PHP 450'000 for housing and land. While the direct costs are more expensive than temporary buildings, they are more affordable than conventional buildings of the same quality. With a LCC perspective, the most significant cost savings are visible in the extended life span of the houses. However, life-cycle thinking is not yet established in the social housing segment and does encounter sensitive system barriers.

Because adequate housing is only one component contributing to sustainable settlements and resilient communities, this thesis advocates holistic, integrated projects bottom-up and policy advocacy top-down. A summary of all aspects and indicators with their overall assessment results is provided in Table 31.

Table 31 Summary of results in all performance dimensions

No.	Aspect	Source			Indicator x = indicator included (x) = indicator in Annex x* = ISO/TS 21929-2 x**= Indicator with modified content	Dimension					Assessment Clearly above (CA) Above req (AR) Meets req (MR) Below req (BR) Clearly below (CB) Not assessed (INA)
		LOC	ISO	EN		SOC	ENV	ECON	TECH	GOV	
1	Safety, Risk and Resilience	X	req	Req	Mechanical properties				1		MR
		X	req	Req	Durability of material				1		CA
		X	req	Req	Racking Strength System				1		AR
		X	req	Req	Resistance to Fire				1		MR
		X	req	Req	Resistance to Earthquakes				1		CA
		X	req	Req	Resistance to Typhoons				1		MR
		X	x	X	Safety Intruders, Vandalism				1		MR
		X			Quality and Risk Management				1		CA
		X			Social Vulnerability inhabitants	1					INA
2	Participation & Inclusion	X			Resilience of the society	1					INA
		X	(x)	(x)	Participation	1					CA
		X			Type of Participation	1					AR
3	Culture	X	x*		Inclusiveness	1					AR
		X	x*		Heritage elements	1					CA
4	Acceptability	X	(x)		Social acceptance	1					AR
		X			Market Demand			1			AR

Table 32 Summary of results in all performance dimensions cont.

No.	Aspect	Source			Indicator	Dimension					Assessment
		LOC	ISO	EN		SOC	ENV	ECON	TECH	GOV	
5	Capacity building & Sharing	X			Skill level needed	1					AR
		X			Number of people trained	1					MR
		X			Future job opportunities			1			INA
		X			Openess of Technology					1	AR
		x			People in learning exchange	1					MR
		x			People on digital platforms	1					INA
6	Health and comfort	x	x	x	Thermal Comfort (temperature)	1			1		CA
		x	x	x	Thermal Comfort (ventilation)	1			1		AR
		x	x	x	Visual Comfort (Daylight factor)	1			1		MR
		(x)	x	x	Acoustic Comfort	1			1		BR
		x	x**	x**	Spatial cost (no. of rooms)	1		1			AR
		x	x**	x**	Spatial cost (sqm)	1		1			CR
		x	x**	x**	Spatial cost (ceiling height)	1		1			CR
		x			Energy saving during use		1	1			AR
		x	x	x	Technical Adaptation Potential				1		MR
7	Use Phase Services (Maintenance, Adaptability)	x			Lot space enabling expansion			1		1	INA
		x	x	x	Maintenance / Adaptation costs			1			MR
		x			Availability of service provider			1			CB
		x	x		Acceptability of service provider	1					CB
		x	x	x	Technical Maintenance demand				1		MR
		x			Availability of service provider			1			CB
		x	x		Acceptability of service provider	1					CB
		x	req	req	Compliance to local regulations					1	MR
8	Regulatory compliance	x			Approval innovative technology					1	CA
		x			Minimum adequacy standards					1	INA
		x			Cost seal Social Housing			1			MR
9	Building related cost	x	x	x	Life Cycle Costs			1			AR
		x			Standardization			1			CA
10	Efficiency of construction	x			Expenditure for Quality Control			1			BB
		x			Pace of construction			1			MR
		site	x	x	Quality of Transport	1					site-specific
11	Equity of sites	site			Time and expense to job / school	1		1			site-specific
		Req	x	(x)	Availability of basic services	1					site-specific
		req			Geohazard assessment site					1	site-specific
		x			Investment into local economy			1			CA
12	Local Economies	x			Expenditure in research			1			CA
		x			Partnerships to address barriers			1		1	AB
		x	x		Project based jobs created			1			AB
		x	(x)		Jobs sustained through market			1			INA
		x	(x)		Quality of jobs created	1					MR
		x			Percentage of local employment	1					AB
		x			Sourcing of Services	ref	ref	Ref	1	1	INA
13	GWP	x	x	x	Global Warming Potential		1				AB
14	Natural Resources	x	x	x	Impact2002+ Natural Resources, Cumulative Energy Demand		7				AB AB
15	Human Health	x	x	x	Impact2002+ Human Health		5				AB
16	Ecosystems	x	x	x	Impact2002+ Ecosystems		8				AB
17	Waste	x	x	x	Reuse, Recycling, Energy Recovery, Non-hazardous waste disposal, hazardous waste disposal		5				AB
18	Sustainable sourcing of material	x	(x)	(x)	Controlled quantity, transparent and controlled source and supplier, controlled species		1				CA
19	Use of renewable resource	x	(x)		Decoupling growth from resource depletion through non-depleting harvesting practice from rapidly renewable raw material		1				CA
20	Biodiversity	x		(x)	n.A.		1				INA
21	Land Use	x	X		Shortcomings		1				INA
						25	31	22	13	6	97

Based on the results in the performance dimensions, a reflection on the overall concept of the thesis is made. The holistic conceptual framework of the thesis names four performance dimensions, embedded into the dimension of governance. This definition is comprehensive and soundly grounded on the global influencers of this thesis. Broad consensus exists on the relevance of the economic, social, and environmental dimensions for the assessment of

buildings. It is anchored in global framework agreements such as the 2030 Agenda (2015), as well as in the international and regional standards for sustainability assessment of buildings ISO 15392 (2008) and EN 156431-1 (2010), national assessment schemes, which have more than a single-issue focus such as by the German Society for Sustainable Building (DGNB) (2018), and proprietor service providers such as the Building Research Establishment Environmental Assessment Method (BREEAM) (2018), or sustainability assessment schemes for a specific applications such as post-disaster housing (International Federation of Red Cross and Red Crescent Societies, 2018). The inclusion of cultural aspects, whether assessed as a separate dimension or merged with the social dimension, is found in the most recent ISO/TS 21929-2 (2015) or when assessment schemes are discussed for global application such as by UN-Habitat (2012). This consideration may be less applicable in Europe and is therefore not found in the EN standards. The governance aspect ‘compliance with regulations’ is formulated in the ISO and EN standards as a prerequisite. A broader definition of the governance dimension is defined by UN-Habitat (2012), under the term ‘institutional sustainability’. Such a broad view on governance is excluded from the standards, because of their focus on single projects. In social housing, where systemic barriers need to be overcome and scale plays a large role, the broader definition offers holistic initiatives more opportunities to express their contributions. In common with this thesis is the acknowledgment of system barriers and bottlenecks for scale, which go beyond the life cycle of buildings and require systemic address. The EN standards have a remarkable level of depth regarding environmental performance and served as guidelines in this dimension. However, an expert approach is clearly needed for its assessment. On the positive side, this expert approach makes the environmental dimension transparent and quantitative. Because of the international framework of ISO, a larger number of its aspects cover stakeholder requirements in the social and economic dimensions than those in EN. Beyond ISO, the stakeholder assessment identified more indicators that are relevant in the social and economic dimensions. These have been included in the assessment, while acknowledging that they require further discussion. Many of these are also found in GRI standards for business reporting (Global Sustainability Standards Board, 2016) or link to the vague, but comprehensive aspects in the global policy frameworks. This thesis further stresses the role of technology and functional compliance. The field of alternative building materials relies too often on environmental, social, and economic potential, but lacks investment into research and compliance with technical standards on par with conventional building practices. Therefore, particularly for social housing, the technology performance dimension should be reported as part of all sustainability assessments. That said, it is acknowledged that social housing is not a technology challenge, but rather achieving technical performance in a complex set of multi-dimensional requirements. Thus, harnessing the potential of technology and innovation is important (UNESCAP, 2016c).

The number of indicators should not be viewed as a barrier to implementation. A core set of indicators highlights those aspects that need to be considered. Beyond this, indicators are voluntarily, and express concerns found in implementation that will help meet the requirements and assist holistic approaches to formalize their contribution to strong sustainability. They increase awareness of the relevant dimensions. This thesis avoids fixed weighting schemes but provides sufficient transparency to enable stakeholder dialogue. It invests in the translation of complex, scientific single-issue findings into visual, condensed messages, which highlight areas of strength and those that need further attention and debate. Lennie and Tacchi discuss an evaluation and communication framework for development. The components of assessments are partially aligned to the general principles of ISO 21931-1 (2010), in which the objective is a holistic, learning-based, emergent and local approach considered from a long-term perspective. The standards demand transparency and standardization for comparability. Lennie

and Tacchi (2013) also highlight the importance of a realistic, critical approach when considering the power relations in decision-making processes. Sustainability assessments have to be embedded in the governance dimension, informing and contributing to systemic barriers and opportunities. However, they should also not lose ground regarding their tangible, scientific, and reliable foundations on the basis of transparent documentation based on standardized format. In Datt (2017), the measurement of poverty reduction in the Philippines is discussed. It is shown that multidimensional measures beyond the income dimension, including education, health, standard of living and livelihood, can better express the multi-dimensional aspect of poverty reduction. Indicators, weighting schemes, and aggregation differences among methods were of importance in the absolute result, but showed the same trend. Ultimately, indicators must be able to express the multi-dimensionality of complex matters. Weighting schemes and aggregation have the potential to change overall results. In this thesis, the general advocacy for the areas of concern has the highest priority and seeks to stimulate awareness, dialogue, and research and action on the ground.

Overall, it wishes to be an example for localizing and applying sustainability theory to a specific context and with that contribute to the opportunity for more inclusive and sustainable development of social housing and empowered communities, as demanded by UN-Habitat (2017). It advocates direct investment towards combined approaches of research, application, and dialogue, and to shift the focus to the building of local value chains for future preparedness. Emerging and developing economies are the ones with the largest growth in new floor plan area (GABC/UNEP, 2016). Alternative pathways to growth are required and can be found. The lack of data can be addressed through longer-termed North-South and South-South research collaborations, while scientific objectives need to balance realities on the ground. An uptake of the innovation potential at scale is facilitated by addressing critical requirements and barriers identified through systemic involvement of stakeholders with convening and decision-making power, and through the active inclusion of stakeholders with legitimacy but low decision-making power.

4 Conclusions

In this section, conclusions are drawn about the *performance dimensions* technology, society, economy, environment, and governance, as well as the *overall conceptual framework* of this thesis. This conclusion is inspired by the statement made by the WCED (1987):

“In essence, sustainable development is a process of change in which the exploitation of resources, the direction of investments, the orientation of technological development; and institutional change are all in harmony and enhance both current and future potential to meet human needs and aspirations.”

The *technical performance* dimension contained clearly quantifiable indicators, justified by regulatory requirements. The results provided evidence about the structural qualities of the Philippine bamboo species *B. blumeana*. The racking strength testing of the wall system confirmed a resistance that enables the design of houses to withstand seismic and typhoon impacts common to the Philippines. The test houses were exposed to real-life typhoon impacts, and therefore the ability to resist these impacts was confirmed and the results addressed important legal and social requirements. Through in-depth system understanding and specific optimization, compliance with the fire resistance requirements for residential buildings was obtained. In actual use, the buildings showed significantly lower maintenance requirements than traditional bamboo houses and offer the option of quality-controlled expansion.

Furthermore, they achieved a high level of climate-adjusted thermal comfort. The use of full culm bamboo in a robust and reliable building system enabled the meeting of technical, functional, and regulatory requirements. As a result, legal approval for the building method in the Philippines was obtained from the Philippine government in 2016. Various opportunities in the environmental, social and economic dimensions have now been unlocked. Based on a quality-controlled implementation process, a comparable life span to that of conventional building practices in the segment is predicted. The processes and skills to implement quality housing has evolved and been disseminated in more than 500 housing units constructed by the Base Foundation (2018) and its partners.

The *social performance* dimension has the most aspects *not* covered by the codes. This thesis contributes to the debate while inviting further discussion and research on the topic. The participatory approach behind this thesis is highlighted, in which building technologies were developed together with local grassroots organizations and communities. The process of blending participatory research with technical evidence has been particular for this thesis. Construction skills were enhanced and disseminated via collaborative efforts and over time. This positively influences the preparedness of involved people regarding future impacts. Instead of a shortsighted perspective, which ends with the construction completion, this paper advocates for the lasting reduction of vulnerability through a system and life cycle perspective on social housing. An entry point to such a system change was provided. To reach the affected population with findings from science and technology, effective means of dissemination must be found. Multi-stakeholder participation, and an open development approach such as that advocated by the Base Foundation (2018), enables discussions and the dissemination of quality approved concepts through national and global learning exchanges and sharing platforms. Next to the active resistance of the building system to impacts, the market development of bamboo-based construction has the potential to enhance DRR and societal preparedness. The market has yet to prove whether services such as the quality-controlled expansion of bamboo-based houses will be socially acceptable.

The *economic performance* dimension of EN and ISO focus on LCCs and the value or value stability of buildings. LCC is, however, a concept far from general market acceptance, and the upfront costs for the initial construction have much greater relevance. This thesis bridged the gap between theory and practice and included ICCs as a key driver in the segment. In comparison with temporary bamboo houses, the advanced building method is costlier. However, the cost ceiling for social housing in the Philippines is met. Cost savings are achieved from a life cycle perspective, shown through the enhanced durability of bamboo-based buildings and the reduced disaster risk. It has been proven difficult to shift the current view held by policymakers and humanitarian responses, but efforts are being made to change their perspective from “preparing to respond to hazards and planning for recovery” to “proactively address the vulnerability of societies” (Briceno, 2015). The restructuring of marketing mechanisms for sustainable pre-disaster measures are, however, essential (Stephan, Norf and Fekete, 2017). Next to human resources, material resources are very scarce in post-disaster reconstruction, which considerably hinders recover (Chang *et al.*, 2011). The approach in this thesis makes use of bamboo, an available material commonly used by the poor. As it grows in all regions of the Philippines, value chains for strength-graded, treated bamboo can be proactively established and will be available for all future responses in the country. The benefits of local skills and material use go beyond the costing achieved per house and strengthen lasting local economies. Value chains connect the rural bamboo supply with urban housing needs and have the potential to enhance the quality of all three types of owner-driven, donor-driven, and contractor-driven housing projects. Through a pro-active approach to preparedness, the urgency and tremendous need following a disaster will no longer hinder the need to make changes to

the system. Beyond the costs for materials and buildings in operation, this thesis looked at construction as an essential contributor to the social, economic, and environmental fabric of cities, from both positive and negative perspectives. Therefore, the economic performance assessment was expanded to include the economic efficiency of construction and sites and measures to assess local economies. Such measures include investment into research on social housing and local market development, local capacity building, the creation and sustenance of jobs, accessibility to and from a site with economically viable and timely acceptable means, and the formation of partnerships that address system barriers. A connecting element of adaptation and mitigation is the durability of buildings and their ability to perform throughout their intended life span despite exposure to extreme impacts. By merging DRR (through more resistant and durable bamboo-based construction) with ecological objectives (through carbon reduced building), a strong social norm is created that aligns to the interconnectedness of the major recent policy frameworks. Reflections over the past 30 years of shelter strategies for DRR have highlighted the relevance of survivors being agents, not victims (Fan, 2012), as practiced in this approach.

The *environmental performance* dimension assessed bamboo-based building in comparison with the common practice of concrete buildings in social housing in the Philippines. Through a thorough LCA, capturing several iterations of implemented building projects, environmental benefits were quantified and documented. Acknowledged proxy indicators such as the GWP and the CED were used and significant benefits were shown. Further environmental indicators mentioned in EN were captured through the aspects of ecosystems, climate change, human health and natural resources of the indicator impact2002+. All single-issue indicators found in impact2002+ showed advantages, with the exception of land use. Further research on the relevant but contested indicator land use, as well as on the aspects of biodiversity and scarcity, are recommended. Measures to reduce the impact of the building sector have strong national relevance. In 2015, the Philippines submitted ambitious targets for its Intended Nationally Determined Contribution to the United Nations. These can only be achieved by addressing the building sector, which has the greatest potential for low-cost GHG mitigation, irrespective of world region. With IPCC scenarios showing that the non-annex countries in Southeast Asia have the greatest predictions for emissions growth in the building sector (IPCC, 2014), the environmental performance assessment of the alternative building methods delivers an important contribution to the debate. Implications of systemic changes at scale need further consideration.

The *general and conceptual conclusions* are documented as follows, building on the specific conclusions above. This thesis was motivated to deliver a contribution to the increased application of local raw materials for construction. Global policy frameworks, such as SDGs and NUA, highlight local materials as one area for action. The building sector is particularly interesting as an entry point for sustainability optimization using local materials, as it is a major consumer of resources, driver of economic growth, and measure of social inequality. ISO states that, “many sustainable development objectives do not directly relate to and yet are clearly influenced by the built environment” (ISO 15392, 2008). Social housing, a sub-segment of building with high demand and complex system barriers, was hardly considered for sustainability optimization in the past. As the concept of sustainability is inherently connected to geographic context, this thesis looked at the rapidly growing economy of the Philippines as a concrete example with frequent disasters, high social inequality, and partially untapped potential in its raw materials. Thus, the general objective of the thesis was to guide the development and assessment of a bamboo-based building technology for social housing in the Philippines, according to the multi-dimensional requirements of sustainability.

The conceptual framework of the thesis was aligned to the EN and ISO standards on the sustainability assessment of buildings. The global guidelines were localized through a geographic- and segment-specific multi-stakeholder process. Performance dimensions environment, society, economy, and technology were translated into 21 sustainability aspects related to social housing in the Philippines. More than 90 single-issue indicators were identified to measure these aspects. Most of these are not compulsory but should be viewed as offering opportunities to describe and quantify relevant contributions to sustainable building. For this to be demonstrated not only theoretically, this thesis had a strong focus on using the concept in an applied context. This is based on the understanding, that *sustainability is a process, rather than an outcome. For it to evolve, it needs to be applied.* While the thesis contributes to the debate on indicators and measurability, it is the localization, implementation, and continuous use of sustainability for 4 years that delivers major contributions.

This thesis adopted a life cycle perspective, considering the impact during a building's planning, production, construction, use, and end-of-life. As none of the building projects studied here reached their end-of-life, and only few years of occupation were assessed, scenarios were created for use in those life cycle phases. Moreover, the thesis started before and went beyond the life cycle of one building project. Because the thesis looked at the potential of a raw material, technical research about the building method was an essential element of the thesis in balance with the other performance dimensions. Furthermore, as the use of local raw materials hardly meets requirements in the first place, it is advocated that sustainability assessments must include evidence of technical fulfillment to ensure common ground for an evaluation or comparison with conventional methods. Sustainability theory was used for decision-making in eight development and project cycles. The Base Foundation, an initiative supported by the Hilti Foundation, and the partners of it in the Philippines implemented the building projects. Because of the project cycles, the thesis focused on building material-related aspects and indicators. Site-specific aspects and indicators were considered by defining them as requirements. The close link between research and implementation enabled continuous multi-stakeholder dialogues reviewing a transparent value proposition. This has helped to bridge the gap between ambitious theory and realistic implementation.

The research results across the four performance dimensions provide a solid basis for considering advanced bamboo-based building concepts as a reliable and sustainable construction solution. By meeting technical, functional and regulatory requirements, the opportunities in environmental, social and economic dimension can be unlocked. The thesis does not focus on valuation but suggests that the performance dimensions are considered equally following the strong sustainability approach. At this juncture, it is essential that the balancing of requirements is done transparently, while the substitution of dimensions is strongly discouraged. In research utilization, the balance may be adjusted according to context specific and subjective value sets. Thus, this thesis provides guidance for decision-makers as consumers, policy-makers, humanitarian agencies, and construction-professionals in the Philippines.

Widening the perspective from the Philippines to the urban tropics around the world, significant potential for *learning exchanges* to further geographies exist. Both the overall approach and selected learnings are suitable for transfer to other countries. However, as it was practiced for this thesis and the geographic context of the Philippines, the different types of knowledge that exist in further countries need to be considered for knowledge translation. As expressed by Jones *et al.* (2009), the "sectoral and political context and actors involved need to find consideration" for the specific country context.

Significant effort was made for the assessments presented in this thesis. It therefore can be concluded that a comparable assessment for an individual building project would be too comprehensive for practitioners. This thesis therefore rather aims to serve as conceptual framework and inspiration for holistic, replicable initiatives, that target to create impact at systemic scale.

Long-term effects through active participation are empirically proven (Maly and Shiozaki, 2012). The building methods that are tested here advocate the active involvement of people. The common denominator of recent policy frameworks on climate change, DRR, and sustainable urban development is that they describe highly complex and interconnected future global challenges. Becker and Reusser (2016) describe disasters as opportunities for social change, and explain how disaster-related transitions can be achieved if multi-level perspectives are considered. By merging disaster risk preparedness (through more resistant and durable bamboo-based construction) with ecological, social and economic objectives, a strong social norm is created that aligns with the interconnectedness of the major policy frameworks. As the effect of climate change is predicted to further increase the hazard exposure of Asia-Pacific (Mahmood, 2009), comprehensive, integrated preparedness agendas will continue to gain relevance. The building methods tested in this paper are suggested as a contribution to integrative planning and are intended to increase knowledge sharing and communication among actors, as well as encourage the active involvement of people. Thus, the results of this thesis are to be embedded in a broader context of DRR and sustainable development. As closure of this thesis, an interpretation is provided to which SDGs a contribution is made (Figure 48).

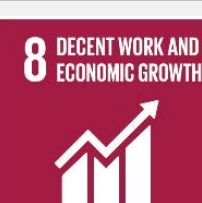
	• Job opportunities for the poorest: rural farmer and urban poor • Lasting local economies • Inclusion into decision making and creating perspectives		• Climate adjusted indoor comfort • Ability to learn, work, recover and feel safe
	• Evolving declining traditional knowhow based on bamboo as a culturally rooted material for utilization for today's needs • Local ownership in building local capacity		• Inclusion in job opportunities • Gender sensitive layouts
	• Partnership of housing projects with clean water and sanitation initiatives (requirement for this thesis)		• Partnership of housing projects with affordable energy initiatives (requirement for this thesis)
	• Create local income and economies • Link rural with urban through value chains • Scalable and reproducible		• Investment in R&D in social housing context • From temporary to durable, vulnerable to resistant, improvising to standardizing, left behind to continuous improvement
	• Interrupting vicious cycles of vulnerability • Dignity through participation, culturally accepted solutions, and legal address		• Proactive disaster risk preparedness • Compliance to policies and regulations • Impact on the right to adequate housing in adequate settlements and cities
	• Reduce pressure on scarce resources, practice sustainable harvesting, Innovate context safe chemical treatment • Link rural with urban concerns through local value chains, use local skills to create products for local needs		• Life Cycle Optimization to prove reduction of GHG emissions and support materials with less embodied energy • Climate-adjusted house designs for an energy reduced use phase
	• Bring together people • Advocate at all layers of society • Social acceptance and regulatory impact enabling gradual system change		

Figure 48 Bamboo-based sustainable social housing: An entry point to 13 of 17 SDGs

5 Future Research

This section highlights specific research fields of relevance in the performance dimensions of technology, society, economy, and environment. It further highlights the need for research in the general field of the sustainability assessment of social housing. This section is not a comprehensive overview, but provides insights into specific key areas.

This thesis has provided comprehensive research results on an investigation into bamboo-based building technology. Further research fields exist that seek to continuously advance this building method.

- The thesis covered the most common bamboo species in the Philippines. The testing of additional bamboo species in the Philippines and around the world according to ISO 22156 and ISO 22157 (ISO 22156, 2004; 2004) will strengthen the reliability of full culm bamboo in construction. In the Philippines, where bamboo is harvested to the annual regeneration quantities of natural stands, the determination of further species will increase the harvestable amounts. Furthermore, the review of test protocols of the existing standards are recommended and under progress. In ISO 22157, shear strength is calculated assuming the development of four shear planes. It was noted that the actual failure observed in most samples occurred in just one plane. It is recommended that tests are conducted on optimized protocols for shear strength delivering failures in all tested shear planes. The tension perpendicular to the grain in bamboo has been rarely studied. It is, however, critical for the performance of a structure. To date, perpendicular tension is not included in ISO 22157. Research on the test protocols for this property has been performed and should be used to form an evidence base for a testing protocol in the standards (Sharma, Harries and Ghavami, 2013; Dela Cruz *et al.*, 2018). Research on the resistance of bamboo-based housing against extreme impacts remains a rarely touched field. Similarly, fire, storm, and flood resistance are fields that demand further research. For fire resistance, for example, studies investigating the ignition time and charring rates of various materials and the fire testing of wall elements under load are important to conclude modification factors for structural bamboo under fire. Also the determination of connections against fire and full-scale testing are fields of interest.
- Guiding policy frameworks such as SDGs and NUA highlight the potential of using local building materials. By making the ecological niche reliable and socially acceptable, while maintaining an economic advantage, the use of local building materials will be supported. Research can enable that technical, functional, and regulatory requirements are met. By doing so, barriers for uptake are reduced.
- The indicators in the social and economic dimensions of the standards on sustainability assessment require further research and discussion. An extensive list of indicators is mentioned in the Annexes of the standards. These are not included in the codes largely because of the uncertainty surrounding their measures for assessment. Scientific inputs, stakeholder dialogue, and applied examples are needed to create a commonly accepted basis for inclusion. The issues surrounding measurability and the high interrelation of aspects should be no reason to exclude and thereby further undervalue those fields. Generally, a review of the standards in those two dimensions is required. A discussion is needed regarding to what degree can EN and ISO measure the social and economic sustainability of a building by only looking at the building project or settlement. The systemic effects of construction value chains on the overall socioeconomic fabric of nations, regions, and the world lack consideration. Research fields such as humanitarian supply chains can be expanded to cover rural–urban value chains under the perspective of disaster preparedness.

- Today, bamboo-based construction in the Philippines is applied with steady growth within the limits of sustainably reproducing natural stands. The ongoing decay of a rich biodiversity in Southeast Asia requires careful consideration of any large-scale system change (Sodhi *et al.*, 2010; Webb, Slik and Triono, 2010). Thus, caution should be exercised concerning large-scale resource use. The commonly used indicators in LCA that address biodiversity, land use change and scarcity are not sufficiently comprehensive and systematic (Curran *et al.*, 2011; Michelsen, Cherubini and Strømman, 2012; Finkbeiner *et al.*, 2014). Although improved integration in LCA is garnering more attention (e.g., Koellner *et al.* (2012)), the current shortcomings regarding these aspects and the existence of more elaborate methods outside of LCA (Lindner *et al.*, 2012) are also recognized. A lack of such data is not unique to this paper and has been acknowledged as a major gap in LCA today (Finkbeiner *et al.*, 2014). Thus, development in this field should be monitored and updated LCA results should be presented once an expert approach is validated and acknowledged.
- It is also of value to reduce data uncertainty for the use and end-of-life stages in the social housing sector. Use-phase consumption is likely to rise with a substantial number of people transitioning from the lowest to greater-consuming middle-income levels. The user behavior of inhabitants at the base of the pyramid living in naturally ventilated low-cost houses has never been systematically assessed nor captured in LCAs. Indications in this thesis have shown that a building's use phase will not have the same importance over its life cycle. However, because of the high relevance of the field, further research on its share and particularly on the possibility to positively minimize its increase is recommended. Energy use in the tropics is mostly determined by the cooling load. Energy use in the tropics is mostly determined by the cooling load. Future fields of research include climate-appropriate building materials, climate-adjusted building designs, and exterior passive measures. Air conditioning is mostly unaffordable for the studied low-income settlements, albeit socially attractive. Possibly, user behavior is not influenced by the type of building envelope or indoor comfort, but instead limited by poverty. The effect of increased indoor comfort has yet to be quantified and understood in detail.

The sustainability of social housing is a broad and complex issue at the nexus of poverty, climate change, disaster risk, rural–urban linkages, resource consumption, societal inequality, and economic opportunities. In the following, future research and collaboration on the social housing field in general are highlighted.

- In general, the *social housing sector*, at the intersection between informality and formality, receives insufficient attention from researchers. Thus, recognition of its relevance for its economic, environmental, and social contributions to sustainable development is a starting point for further research. System barriers and opportunities need to be better understood through investment into research and development.
- *Sustainability is a continuous optimization process*, in which multi-dimensional requirements need to be balanced in the best possible way. To bridge the gap between ambitious theory and realities on the ground, research and practice need to become more closely aligned and sustainability theory should be actively used as a tool for decision-making processes over time. The iteration between research, implementation, and stakeholder dialogue has proven to be a successful model for future activities.
- *Multi-stakeholder dialogue*, which includes decision-makers, minority groups and silent stakeholders, is essential to address complexity and to holistically balance the

requirements. The interconnectedness of aspects such as climate change, green building, inclusiveness, and resilience, require integrated approaches for sustainability assessment. Inclusive stakeholder dialogues can determine the most appropriate value set for a given context.

- The EN and ISO standards on *sustainability assessment for buildings* are based on a life cycle perspective of buildings. However, the system effects of value chains in the construction sector are not yet sufficiently considered in the social and economic assessment dimensions. Selected indicators have been suggested in this thesis, such as efficiency in construction, equity of sites, economies of local value chains, capacity building and sharing, the quantity and quality of job creation, and access to and from a site, to name a few. Further research on the interaction of construction with the fabric of cities and countries is needed. Social indicators in particular require more debate regarding how they should be measured. The difficulties in measurability often result in the non-consideration of the aspects, which sends contrary signals. Approaches that achieve higher levels of measurability through disaggregating complex problems support a transparent discussion about value propositions. The said indicators are recommended for further discussion and optimization over time.
- Under the principle *global thinking, local action*, global concepts provide the framework for local action. Involvement and identification are important to *localize* complex and ambitious global frameworks to the specific geographies and the segments, such as social housing. Of equal importance is the need to ensure the *backward integration* of local experience into global action frameworks. Partnerships and South-South and North-South learning exchanges and platforms for sharing are all important areas that require further action.

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7⁵ Annex

The Annex contains all papers in the order specified in the List of Publications. It further specifies selected additional content that was not included in the main body of the text.

Table 33 Differences in the Building Life Cycle Stages according to EN and ISO

Building Life Cycle Stages		Description of differences at Sub-Stages	Relevance for thesis
A0	Pre-construction	Stage does not exist in ISO and not consistently exist in EN (e.g. not in EN15643-2)	Not applied
A1-A3	Production Stage	Aligned	
A4-A5	Construction Stage	'on site extraction' exists only in ISO	EN standard followed
B1-B7	Use Stage	'maintenance' and 'repair' are merged in ISO 'operational energy' and 'operational water' are merged in ISO and called 'operations and management' 'decommissioning' exists only in ISO	EN standard followed Operational water excluded, operational energy as scenario EN standard followed
C1-C4	End-of-Life	're-landscaping' exists only in ISO	EN standard followed
D	Beyond the system boundary	Stage does not exist in ISO	Where applicable, reported separate

Table 34 Indicator of ISO and their use for this thesis

Main Aspects: ISO21929-1/-2				Dimension		
Assessment Legend: A- Assessed A (cumulative)- Assessed, but displayed only cumulative INA- Indicator not assessed NR- Not relevant WN- Where needed S- Site-specific				Legend x- indirect relation xx- direct relation +- unspecified relation		
No	Assessment	Name	Allocation	SOC	ENV	ECON
1	A	Emissions to air- Global Warming	21929-1	x	xx	x
2	A (cumulative)	Emissions to air- Ozone Depletion		x	xx	x
3	A (cumulative)	Use of non-renewable resources			xx	x
4	A (cumulative)	Fresh water consumption		x	xx	x
5	A (cumulative)	Waste generation		x	xx	
6	INA	Change of land use		x	xx	
7	A (site-specific)	Access to services		xx	x	x
8	(1) WN, (2) S	Accessibility (1) with disability (2) to and from site		xx		
9	A	Indoor conditions and air quality		xx		x
10	A	Adaptability		x	x	xx
11	NR	Aesthetic quality		xx		
12	A	Life Cycle Costs				xx
13	A	Maintainability		x	x	xx
14	A	Safety		xx		x
15	INA	Serviceability				xx
1	A (cumulative)	Emissions to Water- Eutrophication pot	21929-1 Annex		+	
2	A (cumulative)	Emissions to land or Water- Acidification pot			+	
3	A (cumulative)	Emissions to air- tropospheric ozone formation potential		+	+	
4	A	Use of renewable resources			+	+
5	INA	Protection of valuable individual natural features			+	
6	INA	Ecological quality of the site			+	
7	INA	Potential to affect the surface drainage			+	
8	INA	Nuisance caused by the building on the neighbourhood		+		
9	INA	Outdoor conditions		+		+
10	INA	Heat island effect		+	+	
11	A	Participation		+		
12	NR	Value Stability				+
1	A	Social inclusion and acceptability	21929-2	+		
2	A	Cultural heritage elements		+		
3	INA	External costs				+
4	A	Job creation		+		+

Table 35 Indicator of EN and their use for this thesis

Main Aspects EN15643-1			
Assessment Legend: A- Assessed A (cumulative)- Assessed, but displayed only cumulative INA- Indicator not assessed NR- Not relevant WN- Where needed S- Site-specific			
No	Assessment	Name	Allocation
1	A (cumulative)	Abiotic depletion potential	15643-2 (ENV)
2	A (cumulative)	Acidification of land and water resources	
3	A (cumulative)	Destruction of the stratospheric ozone layer	
4	A (cumulative)	Eutrophication	
5	A (cumulative)	Formation of ground-level ozone	
6	A	Global Warming Potential	
7	A (cumulative)	Non-renewable primary energy	
8	A (cumulative)	Renewable primary energy	
9	A (cumulative)	Non-renewable primary energy as raw material	
10	A (cumulative)	Renewable primary energy as raw material	
11	A (cumulative)	Secondary materials	
12	A (cumulative)	Non-renewable secondary fuels	
13	A (cumulative)	Renewable secondary fuels	
14	A (cumulative)	Freshwater resources	
15	A (cumulative)	Reuse	
16	A (cumulative)	Recycling	
17	A (cumulative)	Energy Recovery	
18	A (cumulative)	Non-hazardous waste disposal	
19	A (cumulative)	Hazardous waste disposal	
20	A (cumulative)	Radioactive waste disposal	
21	A (cumulative)	Exported Energy	
1	NR	Accessibility	15643-3 (SOC)
2	A	Adaptability	
3	A	Health and Comfort	
4	NR	Loadings on the neighbourhood	
5	A	Maintenance	
6	A	Safety	
1	A	Life Cycle Cost	15643-4 (ECON)
2	NR	Financial Value	
1	INA	Biodiversity	15643-2 (ENV) Annex
2	A (cumulative)	Ecotoxicity	
3	A (cumulative)	Human toxicity	
4	INA	Land use change	
5	INA	Use of non-renewable resources other than primary energy	
6	A	Use of renewable resources other than primary energy	
7	A	Sustainably managed materials	
8	INA	Sustainably managed fuels	
1	A	Sourcing of Materials and Services	15643-3 (SOC) Annex
2	A	Stakeholder Involvement	
1	NR	Value Stability, short-term	15643-4 (ECON) Annex
2	NR	Value Stability, medium to long term	

Table 36 Indicator Assessment per Life Cycle Phase

Legend N – Quantitative L – Qualitative A – Assessment C – Comparative E – Empiric / Measured S - Scenario		Life Cycle Phase								
		Research* (* added by thesis)	Planning** (**modified content)	Sourcing	Production	Construction	Review and Local Economy Building*	Use	End of Life	Beyond Life Cycle
Aspect	Indicator	E	A0	A1	A2- A3	A4- A5	B0	B1- B7	C1- C4	D
Safety, Risk and Resilience	Mechanical properties of raw material	NAE	NAE	NAE						
	Durability of local raw material	NAE	NAE	NAE				LAE		
	Resistance Building System, Fire, Earthquakes, Typhoons	NAE	NAE					LAE		
	Safety against Intruders and Vandalism		LAS					LAE		
	Quality and Risk Management	NAE	NAE	NAE	NAE	NAE	NAE	NAE		
	Social Vulnerability of inhabitants							NAE		
	Resilience through local value chains		LAS	LAS	LAS	LAS	LAS	LAS		
Participation	Participation, Type of it and inclusiveness	LAE	LAE	LAE	LAE	LAE	LAE	LAE		
Culture	Inclusion of heritage elements	LAE	LAE	LAE	LAE	LAE	LAE	LAE		
Acceptability	Social acceptance, Market Demand							NAE		
Capacity building & Sharing	Skill level needed		LAE	LAE	LAE	LAE				
	Number of people trained	NAE	NAE	NAE	NAE	NAE	NAE			
	Increase of future job opportunities			LAE	LAE	LAE				
	Open Technology	LAE	LAE	LAE	LAE	LAE				
	People reached through learning exchange						NAE			
Health and comfort	Thermal and Visual Comfort		NBS					NBE		
	Spatial Comfort		NBS				NBE			
	Comfort induced energy consumption		NAS					NAE		
Use Phase Services (Maintenance , Adaptability)	Technical Adaptation Potential		LAS					LAE		
	Lot space enabling expansion		NAE							
	Maintenance and Adaptation affordability		NAS					NAE		
	Maintenance (intervention, frequency)		NAS					NAE		
	Availability of service provider for expansion and maintenance						NAE			
	Acceptability to consult service provider							LAE		
Regulatory compliance	Compliance to local regulations	NBE	NBE	NBE	NBE	NBE		NBE		
	Approval for innovative technologies		NBE				NBE			
Building related cost	Costing within Social Housing Cost Seal		NBS	NAE	NAE	NAE	NBE			
	Life Cycle Costs		NBS	NAE	NAE	NAE	NBE	NAE	NAS	
Efficiency of construction	Standardization			LAE	LAE	LAE				
	Expenditure for Quality/ Risk Control	NAE	NAE	NAE	NAE	NAE	NAE	NAE		
	Pace of construction				NAE	NAE				
Equity of sites	Quality of Transport to job and school		LAE					LAE		
	Time and expense to reach job and school		LAE					LAE		
	Availability basic infrastructure/ services		LAE					LAE		
Local Economies	Investment into local economy	NAE	NAE	NAE	NAE	NAE	NAE	NAE		
	Expenditure in research on social housing	NAE								
	Partnerships to address key system barriers	LAE	LAE	LAE	LAE	LAE	LAE	LAE		
	Financial model to scale		LAS				LAE			
	Project based jobs created >6 month		NAS	NAE	NAE	NAE	NAE			
	Jobs sustained through market demand						LAE			
	Quality of jobs created		NBS	NBE	NBE	NBE	NBE			
	Percentage of local employment		NAS	NAE	NAE	NAE	NAE			
	Sourcing of Services		LAS					LAE		
GWP	Climate Change Global Warming Potential		NAS	NAE	NAE	NAE	NAE	NAE	NAS	NAS
Natural Res.	Impact2002+ Natural Resources		NAS	NAE	NAE	NAE	NAE	NAE	NAS	NAS
Health	Impact2002+ Human Health		NAS	NAE	NAE	NAE	NAE	NAE	NAS	NAS
Ecosystems	Impact2002+ Ecosystems		NAS	NAE	NAE	NAE	NAE	NAE	NAS	NAS
Waste	Waste Generation and Management		NAS	NAE	NAE	NAE	NAE		NAS	NAS
Use of renewable resource	Use of renewable resource			INA						
Biodiversity	Biodiversity			INA						
Land Use Change	Land Use			INA						