



**CHALMERS**  
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# Sustainability and Thermal Comfort of Bamboo Building Technologies in the Hot Humid Tropics

Linking Mitigation and Adaptation

Master's thesis in Industrial Ecology

DAVID AYALA LAVERDE

DEPARTMENT OF ARCHITECTURE AND CIVIL ENGINEERING  
DIVISION OF BUILDING TECHNOLOGY

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MASTER'S THESIS ACEX30

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David Ayala Laverde

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Cover:

Inside view of the case-study building: Kanya Kawayan weaving centre in Nasugbu, Philippines, where Base-Bahay foundation has implemented a combination of composite bamboo shear walls and bamboo trusses. Further details in section 4.1.1.

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**ABSTRACT**

The challenge of doubling the global building stock by 2070 has spurred interest in new building materials and technologies due to the critical environmental burdens associated with this growth. Affordable bamboo building technologies, potentially available in emerging and developing economies where most of the floor area growth is expected, emerge as an alternative. There is growing evidence that bamboo buildings outperform traditional materials in terms of global warming potential impacts. However, climate change's impact on thermal stress and the need for climate-adapted buildings require consideration of thermal comfort and energy needs. Bamboo buildings' lightweight nature prompts exploration into whether it can offer thermal comfort while eliminating or reducing cooling energy requirements in hot tropical climates. This thesis addresses the link between building technology, thermal comfort, energy demands, and overall environmental impacts in the context of bamboo structures and non-residential buildings. The aim of the study is to test whether bamboo buildings can substantially mitigate environmental impact, offer thermal comfort while minimizing cooling energy needs, and continue to mitigate impacts when energy requirements for comfort are also considered. A case study building in the Philippines implementing bamboo trusses and composite-bamboo shear walls for a 149 m<sup>2</sup> weaving centre is compared with a cradle-to-gate Life Cycle Assessment (LCA) to an equivalent building of widespread concrete and steel technologies. Adaptive comfort models are applied to on-site measurements and interviews at the case-study building to assess its thermal comfort performance. Building upon the adaptive thermal comfort statistical inference and regional climate models from different global emission pathway scenarios, an energy cooling load calculation is forecasted. The calculated potential energy needs are finally used to extend the LCA to include possible energy requirements for the case study buildings.

The study concludes that bamboo buildings in this context have a potential to mitigate 271.3 kgCO<sub>2</sub>eq/m<sup>2</sup> of cradle-to-gate GWP(100a) impacts when replacing widespread conventional technologies. A building-specific adaptive comfort temperature of  $T_C=28.0^{\circ}\text{C}$  is calculated for the case study building. And an adaptive thermal comfort performance indicator is defined to evaluate that the case study building does not deliver sufficient thermal comfort during 27.8% of its operating hours in a 16-week assessment period. The study concludes that the possible climate-adaptation of the light-weight structure might not be sufficient to guarantee thermal comfort without air conditioning. Environmental impacts from cooling energy requirement forecasts, especially under increased global emission scenarios, are shown to drive the cradle-to-use impacts of the bamboo buildings; accounting for 86% of the GWP(100a) impacts of the case study building. However, the overall performance of the bamboo buildings is shown to sustain a

mitigation potential (7.7 kgCO<sub>2</sub>eq/m<sup>2</sup>yr GWP(100a) impacts for the case study building), even when energy requirements for comfort are accounted.

Key words: Bamboo, Technology Assessments, Life Cycle Assessment, Thermal Comfort, Adaptive Thermal Comfort, Climate Adaptation, Environmental Impact Mitigation, Environmental Sustainability

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## Preface

This study is a thesis conducted as part of the Industrial Ecology master's programme at Chalmers University of Technology. The research was carried out at the Sustainable Building Group of the Division of Building Technology (Department of Architecture and Civil Engineering) under the supervision of Yutaka Goto and the examination of Holger Wallbaum. The thesis was built on a collaboration with Base-Bahay foundation in the Philippines, led by the foundation's director of technology Luis Felipe López and their external advisor for sustainability research Edwin Zea from the Swiss Federal Institute of Technology Zurich. This collaboration was also possible thanks to field studies funding from the Global Mentorship Programme from Chalmers University, counting with the external mentorship of Elin Lidén from SKF Group. I express my heartfelt appreciation to all of the above for the unwavering support, invaluable direction, and constructive input that shaped and enriched this study.

My journey to define the thesis project was strengthened and inspired by the generous guidance of Mauricio Pinilla at the Architecture Department of the University of the Andes in Colombia, Henrikke Bauman, Sverker Molander and Ulrika Palme at the Environmental Systems Analysis Division of the Technology Management and Economics Department of Chalmers University. The fieldwork component of this study was kindly supported by all the engineers and architects at Base-Bahay foundation, and its partner organizations Kanya Kawayan and Kawayan Collective. Base-Bahay foundation's research-oriented and game-changing advancement of bamboo building technologies was rendered possible by Corinna Salzer's PhD thesis at Chalmers University between 2013 and 2018, supervised by Holger Wallbaum and supported by the Hilti Foundation. To this extensive group of people committed to improve livelihoods and ecosystem health through their dedicated work, I extend my sincere gratitude.

Gothenburg, August 2023

David Ayala Laverde

## Acronyms, symbols, and abbreviations

AC	Air Conditioning
$A_{cf}$	Conditioned floor area of building
$A_{doors}$	Area of doors
$A_{ES}$	Building area exposed surface
Af	Tropical equatorial climate in the Köppen-Geiger Climate Classification
$A_{fen}$	Fenestration area
AGWP	Absolute Global Warming Potential
$A_L$	Building effective leakage area
$A_{L,flue}$	Flue effective leakage area
Am	Tropical monsoon climate in the Köppen-Geiger Climate Classification
$A_{roof}$	Roof area
$A_{shd\ walls}$	Area of shaded walls
ASHRAE	American Society of Heating, Refrigerating, and Air-Conditioning Engineers
$A_{slab}$	Area of doors
$A_{sun\ walls}$	Area of sun-exposed walls
$A_{UL}$	Unit leakage area
Aw	Tropical savanna climate in the Köppen-Geiger Climate Classification
BOM	Bill of Materials
CBSW	Composite Bamboo Shear Wall
CBSWT	Composite Bamboo Shear Wall Technology
CF	Cooling Factor
$CF_{fen}$	Cooling factor of windows
$CF_{roof}$	Cooling factor of roof
$CF_{shd\ walls}$	Cooling factor of shaded walls
$CF_{shd\ walls}$	Cooling factor of doors
$CF_{slab}$	Cooling factor of slab
$CF_{sun\ walls}$	Cooling factor of sun-exposed walls
CHB	Concrete Hollow Block
$C_l$	Air latent heat factor
COP	Coefficient of Performance of Air Conditioning Set
$C_s$	Air sensible heat factor
CSPF	Cooling Seasonal Performance Factor
$d$	Diameter of globe thermometer
$d_{bamboo}$	Thickness of bamboo mat layer (CBSW building)
$d_{bamboo}$	Thickness of bamboo mat layer (CBSW building)
$d_{mortar}$	Thickness of CHB (comparative building)
$d_{mortar1}$	Thickness of mortar layer (CBSW building)
$d_{mortar2}$	Thickness of mortar layer (comparative building)
DR	Daily Range of Outdoor Temperatures
$d_{roof\ 1}$	Thickness of roof layer 1
$d_{roof\ 2}$	Thickness of roof layer 2
$E_D$	Direct irradiance
$E_d$	Diffuse irradiance

EPD	Environmental Product Declaration
$FF_s$	Fenestration Solar Load Factor
$F_{shd}$	Fraction of fenestration shaded by permanent overhangs,
GCM	Global Climate Model
GHG	Green House Gas
GWP	Global Warming Potential
GWP(100a)	Global Warming Potential (100 years) LCIA method from IPCC 2013
$H$	Stack height
HB method	Heat Balance method
$h_{eff}$	Effective surface conductance
$IAC$	Interior shading attenuation coefficient
ICCs	Initial Construction Costs
$IDF$	Infiltration driving force
IEA	International Energy Agency
IPCC	Intergovernmental Panel on Climate Change
kg CO <sub>2</sub> eq	Kilograms of Carbon Dioxide Equivalents based on the GWP
LCA	Life Cycle Assessment
LCCs	Life Cycle Costs
LCI	Life Cycle Inventory
LCIA	Life Cycle Impact Assessment
LF method	Load Factor Method from ASHRAE
LF method	Load Factor method
NV mode	Natural Ventilation Mode
$OE$	Operational Energy
$OE_{AC}$	Air Conditioning Operational Energy
$OF_{b,doors}$	Base opaque-surface cooling factors of doors
$OF_{b,walls1}$	Base opaque-surface cooling factors of shaded walls
$OF_{b,walls2}$	Base opaque-surface cooling factors of exposed walls
$OF_{r,doors}$	Daily range opaque-surface cooling factors of doors
$OF_{r,roof}$	Daily range opaque-surface cooling factors of roof
$OF_{r,walls1}$	Daily range opaque-surface cooling factors of shaded walls
$OF_{r,walls2}$	Daily range opaque-surface cooling factors of exposed walls
$OF_{t,doors}$	Temperature opaque-surface cooling factors of doors
$OF_{t,roof}$	Temperature opaque-surface cooling factors of roof
$OF_{t,walls1}$	Temperature opaque-surface cooling factors of shaded walls
$OF_{t,walls2}$	Temperature opaque-surface cooling factors of exposed walls
PCR	Product Category Rules
PMV	Predicted Mean Vote
$POR$	Percentage of occupied hours outside of comfort range
$PXI$	Peak exterior irradiance
$Q_{bal,oth}$	Balanced ventilation flow rate via recovery ventilation equipment
$q_{fen}$	Exterior transparent surfaces cooling load
$q_{ig,l}$	Internal latent gain
$q_{ig,s}$	Occupants and appliances sensible cooling load
$q_{iv,l}$	Ventilation /infiltration latent cooling load
$q_l$	Latent cooling load

$q_{opq}$	Exterior opaque surfaces cooling load
$q_s$	Sensible cooling load
$q_t$	Cooling load
$q_{vi}$	Ventilation/infiltration cooling load
$Q_{vi}$	Combined ventilation/infiltration
RCM	Regional Climate Model
RCP	Representative Concentration Pathway
$R_{cur}$	Resistance of Slab covering material
$RF$	Radiative Forcing
$RH$	Relative Humidity
RQ	Research Question
$R_{SE}$	External roof surface resistance
$R_{SE}$	External vertical surface resistance (doors, walls)
$R_{SI}$	Internal roof surface resistance
$R_{SI}$	Internal vertical surface resistance
SDGs	Sustainable Development Goals
$SHGC$	Solar Heat Gain Coefficient
$T_a$	Indoor air temperature
$T_C$	Comfort temperature
$TCV$	Thermal Comfort Vote
$T_g$	Indoor globe temperature
$T_{OP}$	Indoor operative temperature
$T_{out}$	Outdoor temperature
$T_{out}$	Outdoor temperature
$T_r$	Mean radiant temperature
$T_x$	Transmission of exterior attachment
$U_{doors}$	U-value of doors
$U_{roof}$	U-value of roof
$U_{walls}$	U-value of walls
$U_{win}$	U-value of windows
$v$	Indoor air velocity
$\alpha_{roof}$	Roof solar absorptance
$\Delta t$	Cooling design temperature difference
$\Delta W$	Indoor-outdoor humidity ratio difference
$\lambda_{bamboo}$	Conductivity of bamboo mats layer (CBSW building)
$\lambda_{bamboo}$	Conductivity of bamboo mats layer (CBSW building)
$\lambda_{mortar}$	Conductivity of mortar layer (CBSW building)
$\lambda_{mortar}$	Conductivity of CHB (comparative building)
$\lambda_{roof1}$	Conductivity of roof, layer 1
$\lambda_{roof2}$	Conductivity of roof, layer 2



# 1 Introduction

Society faces the vast challenge of doubling its global building stock by 2070 (IEA, 2020). Paralleling this growth, resource consumption is predicted to double between 2018 and 2060, having the construction sector as its main driver (IRP, 2019). Buildings are responsible for 38% of today's global CO<sub>2</sub> emissions (IEA, 2020) and in tropical regions like the Philippines they have been a main driver of deforestation and forest degradation (GIZ, 2012). The challenge of meeting the impending building stock growth without these vast environmental burdens has boosted the quest for new materials and building technologies. As the biggest floor area growth is projected to occur in emerging and developing economies (IEA, 2022), affordability is a critical aspect of technologies to be able to mitigate environmental impacts at scale. The Sustainable Development Goals (SDGs) set up in 2015 by the United Nations General Assembly, highlighted the role of local materials in buildings as a mean of implementation of Goal 11 on sustainable cities and human settlements (UN 2030, 2015). Among the contestants is bamboo, which has been claimed to have a potential key role in in addressing six of the 17 Sustainable Development Goals (INBAR, 2017). As illustrated in Figure 1, this potential is stressed by the fact that almost all of the bamboo-growing regions of the world lie in emerging and developing economies.

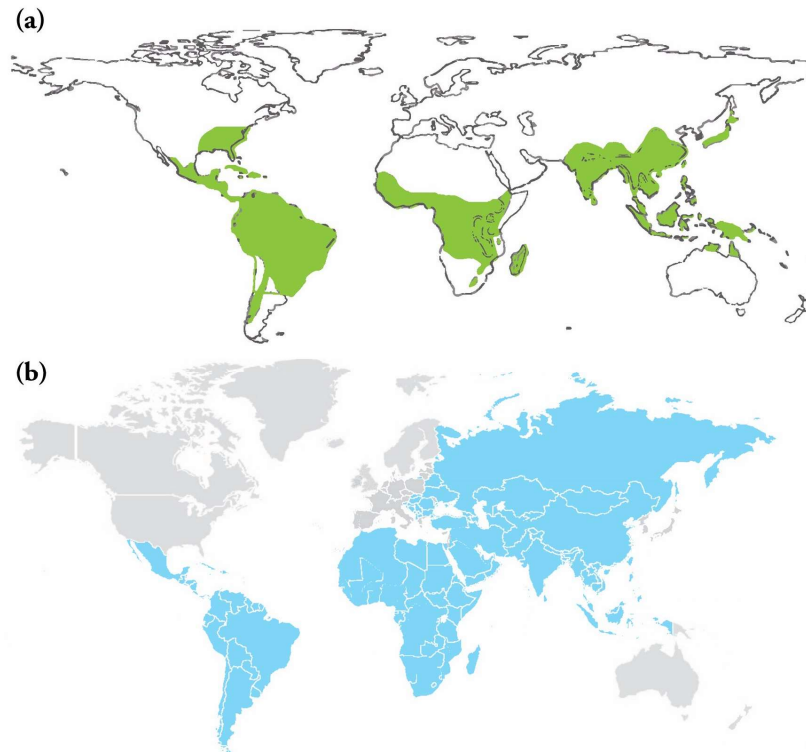


Figure 1 (a) Native geographical distribution of bamboos, highlighted in green. Adapted from Wang et al. (2020). (b) Developing and emerging economies, where the major expansion of the building stock will take place, highlighted in blue. Adapted from Steinert (2008).

Bamboo's fast-growth suggests a potential to meet part of the global south's rising building stock demand while coping with climate change mitigation (Göswein et al., 2022). It has been put forward as a renewable replacement of carbon-intensive and more land-intensive building materials (e.g. cement, steel and hardwoods), whose plantations can even perform important ecosystem services (Trujillo, 2021). Environmental performances of bamboo building technologies have been assessed through several comparative Life Cycle Assessments (LCAs) since 2004 (Acevedo, 2014; Eleftheriou et al., 2022; Murphy et al., 2004; Salzer et al., 2017; Yu et al., 2011; Zea et al., 2018). These assessments have concluded that bamboo residential buildings have better performances in global warming potential (GWP) impacts than masonry- concrete- or steel-based buildings, signalling that bamboo has a potential to mitigate environmental impacts in this context. All of these studies have reached this conclusion when comparing the building structures and envelopes from cradle-to-gate; some when including prospective assessments of the end-of-life of the buildings (Murphy et al., 2004; Salzer et al., 2017; Yu et al., 2011); Salzer *et al.* (2017) when considering the service life of the building; and Eleftheriou *et al.* (2022) through parametric variations of the buildings' dimensions.

While the construction sector is one of the main drivers of climate change, climate change in turn is creating a great challenge for the built environment. Even under scenarios of drastic greenhouse gas (GHG) emissions reductions, rising temperatures are foreseen to cause extreme thermal stress that exposes as much as 48% of the world population to deadly risks (Mora et al, 2017). This threat is most critical in the hot humid regions of the world (Mora et al, 2017). Non-lethal thermal stress also presents a detriment to human well-being, as it leads to severe health risks and compromises educational attainments and accident prevention (Ebi et al., 2021; Ormandy & Ezratty, 2012). As global temperatures rise, thermal stress in human settlements has been identified as a prominent climate impact, and safeguarding thermal comfort in buildings has been established as a category of climate adaptation pathways of its own (IPCC, 2022a, sec. 6.3.5). Cooling of buildings with air conditioning provides such adaptation, but with enormous drawbacks: creating a negative feedback loop with climate change via its energy consumption and providing comfort at a cost that most vulnerable populations cannot afford. In fact, global energy demand for cooling has already surpassed demand for heating and before 2050 it will be the biggest driver of operational impacts of buildings globally (IEA, 2018). Thus, to tackle both environmental impacts and the impacts on human well-being from thermal stress, an urgent need for *climate-adapted buildings* arises. That is, buildings that are able to provide thermal comfort by avoiding or reducing cooling energy needs. Building envelope materials have been identified as one of the factors that influence buildings' climate-adaptation potential (IPCC, 2022a). It is often claimed that in hot humid climates buildings with low thermal mass are better adapted to deliver thermal comfort (Košir, 2019; UN-Habitat, 2014). As bamboo building technologies yield lighter structures than conventional industrial technologies, the important question arises of whether bamboo structures can help to provide thermal comfort while avoiding or reducing cooling needs.

The factors described above, underline the importance to understand the relationship between building technology selection, thermal comfort, and potential energy needs. This entails a possible link between bamboo buildings and mitigation of operational environmental impacts. As buildings' impacts are spread through all of their life cycle, it is necessary to understand what influence this has on the overall environmental impacts of the building from cradle to grave. In

fact, the IPCC mitigation report (2022b) has drawn attention to this issue as a major research gap for buildings in the global south, and to the fact that the gap is even wider in for non-residential buildings. The existing literature on bamboo building technologies has not addressed the effect of considering thermal comfort levels and its potential energy requirements in the environmental assessment. This highlights the need to undertake a broader approach that studies the relationship between thermal comfort levels, potential energy needs and overall environmental impacts.

## 1.1 Aim

Based on the knowledge needs and gaps described above, the overarching goal of this thesis project is to understand and enhance the potential of bamboo building technologies to mitigate environmental impacts of affordable non-residential buildings in the hot humid tropics in an integral way. The aim is to assess the sustainability performance of these technologies and their pathways to meet thermal comfort. To fulfil this aim, bamboo buildings in this context are evaluated with regard to the following hypotheses:

- HI. Bamboo buildings can significantly mitigate embodied environmental impacts.
- HII. Bamboo buildings can help to provide thermal comfort in a way that avoids or reduces cooling energy needs.
- HIII. Bamboo building technologies, including possible energy needs to be thermally comfortable, can significantly mitigate environmental impacts.

To test these hypotheses, the following research questions, regarding affordable bamboo non-residential buildings in the hot humid tropics, are answered:

- **RQI. Cradle-to-gate assessment:** How do cradle-to-gate impacts of bamboo buildings compare to those of widespread building technologies?
- **RQII. Thermal comfort assessment:** What is the thermal comfort performance of bamboo buildings without air conditioning?
- **RQIII. Building energy assessment:** What are the energy needs for bamboo buildings to operate with air conditioning?
- **RQIV. Cradle-to-use assessment:** How do the impacts of bamboo buildings change when potential energy needs to meet thermal comfort are also considered, and how do they compare to those of widespread building technologies?

Answering these questions allows to assess environmental impacts savings of bamboo building technologies in a comprehensive way that considers their relationship to thermal comfort. This assessment aims to guide decision-makers and technology developers in the selection of technologies to be scaled up for safeguarding human well-being and the environment. This is a building block to enhance the innovation process in technologies that can contribute to meeting society's urgent and long-term needs.

## **1.2 Delimitations**

This section clarifies the scope within which the research questions are addressed in this study. First, the delimitations that are common for all the four research questions are presented, and then the limitations specific to each research question are further described.

### **1.2.1 General Delimitations**

The current state of existing bamboo and other widespread building technologies are targeted. But the issue of how the performance of the technology might change if a major scaling-up takes place is not completely addressed. Even though the assessment aims to provide important insights on how the technologies can be improved, the study does not provide a comprehensive prospective assessment of such improvements. Instead, it aims to provide a comparative baseline of the current performances.

The assessed bamboo technologies are selected considering that they are technically reliable in earthquake and typhoon-prone regions; that they are affordable; and, in the case of the bamboo building elements, that they feature social sustainability aspects along their supply chain. However, this study focuses mainly on environmental sustainability and does not cover aspects of social sustainability other than thermal comfort.

### **1.2.2 Delimitations of the cradle-to gate assessment (RQI)**

The life cycle model of the buildings is supported on several assumptions whose veracity limits the applicability of this thesis' results. However, these assumptions' validity is argued and their effect on the results is evaluated in the study. Due to time limitations, only climate-change environmental impacts are considered. And due to data availability limitations, the construction and installation process (which includes construction waste), and is referred to as module A5 in the EN 15978 standard (2011b), will not be included in the model.

### **1.2.3 Delimitations of the thermal comfort assessment and building energy assessment (RQII and RQIII)**

Establishing the precise effect of low thermal-mass in the indoor environment of the studied bamboo buildings is beyond the scope of this study. And so is the valuation of the relative effectiveness of this property compared to other factors that might lead to climate-adapted buildings in this context (e.g., building geometry, ventilation patterns, roof insulation). As these other parameters have a determining effect on the heat balance of buildings, this study cannot fully assess the potential of bamboo buildings to adapt to hot humid tropical climates. What the study does address is how big is the influence on cradle-to-use life cycle impacts of possibly having to recur to AC for meeting thermal comfort; and the effect this might have on the overall environmental performance of bamboo building technologies.

#### **1.2.4 Delimitations of the cradle-to-use assessment (RQIV)**

As with the cradle-to-gate assessment, the cradle-to-use assessment is based on a simplified model. And in the same way, several assumptions are made to be able to build such model and they are listed to understand the limitations they might bring to the interpretation of the results. And also, due to time and data availability limitations, the studied environmental impacts are restricted to those related to climate-change. Additionally, and due to the same issue, within the use-stage of the building only operational energy use is considered.

### **1.3 Thesis outline**

This report is divided in seven chapters: *1. Introduction*, *2. Background*, *3. Theoretical Framework*, *4. Methods*, *5. Results*, *6. Discussion* and *7. Conclusions*. The *Introduction* chapter states the general problem to be addressed, identifies a research gap, sets out research objectives to fill this gap, and the limitations of the study. The *Background* chapter presents the broad context and relevance of the thesis aim. The *Theoretical Framework* explains the theories, models and frameworks that define the research approach. Building on these frameworks, the *Methods* chapter describes specific techniques and procedures used to collect and analyse the data. The *Results* chapter presents the analysed data and its implications towards answering the research questions. The *Discussion* chapter delves into the extent to which the methodology and results manage to answer the research questions. And finally, the *Conclusions* chapter summarizes the main findings and how the project fulfils the research aim.

## 2 Background

This further contextualizes and shapes the topic and research aim presented in the introduction. The four sections of the chapter expand on the contexts of affordable bamboo building technologies, thermal comfort in the changing climate of the hot humid tropics, the challenges of using air conditioning to meet thermal comfort and the relationships between climate-adapted buildings and building technologies.

### 2.1 Affordable bamboo building technologies

Bamboo has been widely used as a structural material for thousands of years (Gutiérrez, 2004; Manandhar et al., 2019) but only in the last 50 years it began its evolution into a modern building technology (K. W. Liu et al., 2020). The history of how the first bamboo building code appeared exemplifies a synergy between its affordability and its structural performance. Early versions of bamboo-structure buildings steered a very rapid migration and urbanization process during the 19<sup>th</sup> century in the coffee growing region of Colombia (Castro, 1966; Robledo Castillo, 1993). Bamboo provided a virtually unlimited stock of very affordable structural materials that allowed new cities and towns to shape rapidly. These buildings employed a structural system (depicted in Figure 2) known locally as *Bahareque*; a shear-wall-based configuration consisting of bamboo frames covered with split bamboo culms and a variety mortars. Bahareque construction lived on well into the 20<sup>th</sup> century; as low-skilled self-construction characterized the rapid growth of Latin American cities, in this region of Colombia Bahareque offered the sole accessible alternative to substandard masonry and reinforced concrete structures. In 1999 a Magnitude  $M_w$  6.4 earthquake struck this area of the country and most Bahareque buildings withstood the event (Kaminski et al., 2016). This showcased the economic and social performance potential of these technologies, later evolving with other technical advances, to be included in the Colombian national building code of 2002 (Correal, 2020).



*Figure 2 Traditional "Bahareque" building in the coffee-growing region of Colombia (Castro, 2003)*

This improved version of Bahareque structures incorporated structural engineering to the traditional system, developing it into a modern structural system that has gained inclusion in numerous building codes around the world (Gatóo et al., 2014). Several names have been used to refer to the resulting structural technology and some of its variations, including *Engineered Bahareque*, *Cement-Bamboo Frame (CBF)*, *Light Cement Bamboo Frame (LCB)*, *Plaster Bamboo Wall*, and *Composite Bamboo Shear Wall (CBSW)* (Kaminski et al., 2016; Salzer et al., 2016; Tambunan et al., 2022). Throughout this thesis, the latter term will be employed. A typical implementation of this system is illustrated in Figure 3.

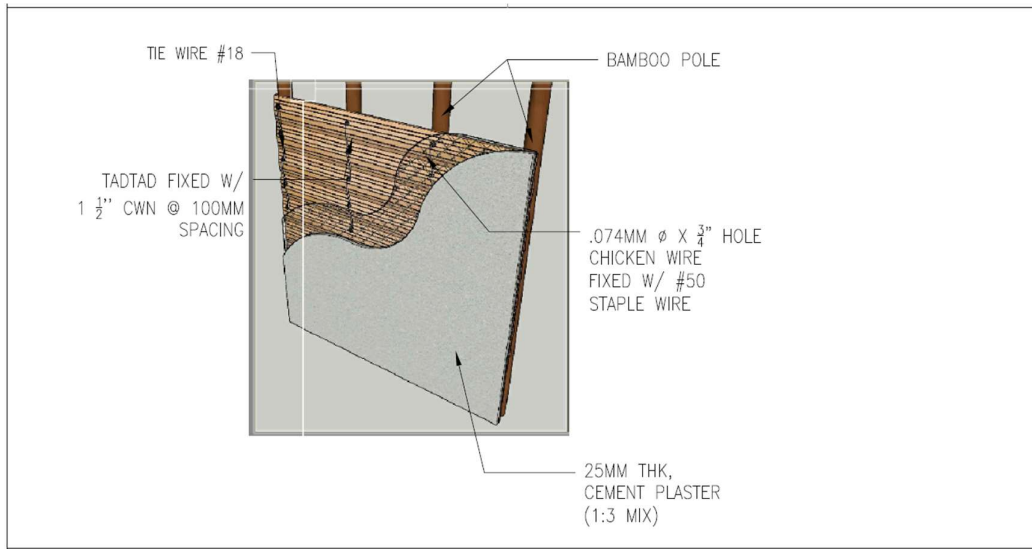


Figure 3 Example of a composite bamboo shear wall, implementing split bamboo (locally known as “tadtad” in the Philippines) to bind the cement plaster to the bamboo frame. Drawing provided by Base-Bahay foundation.

Partnering with the Colombian scientific knowledge, a further development in the Philippines of CBSW technology (hereafter CBSWT) into local *bambusa blumeana* species and technical requirements has been advanced and implemented. Furthermore, Corinna Salzer’s PhD thesis at Chalmers University of Technology has shown the potential of CBSWT’s performance across several dimensions of sustainability by developing, implementing, and assessing the technology extensively in social housing (Salzer, 2018). This thesis steered the creation of Base-Bahay Foundation (Hilti Foundation, 2017), which lived on from the PhD project and has now built over 1,000 housing units (Hilti, 2021).

Together with the early development of CBSWT, a parallel structural system was also advanced and included into several building codes and standards (Gatóo et al., 2014; ISO, 2021). This system consists of spatial trusses of treated bamboo poles joined together by modern mechanical connections such as metallic bolted joints. This structural system allows covering bigger areas and achieving taller constructions and is therefore more commonly used in non-residential applications. Bamboo trusses have also evolved into vernacular construction into modern building standards and codes like the ISO 22156 (2021) and Colombia’s national most recent building code “NSR-10” (Correal, 2020). Both CBSW and bamboo truss systems stand today as established bamboo building technologies meeting modern technical performance requirements. They have successful applications in the context of the Philippines to achieve affordable earthquake- and typhoon-resistant buildings.

The emphasis on affordability in this thesis is motivated by the fact that cost-effectiveness of building technologies is related to their potential impact on ecosystem health and human livelihoods. Cost-effective buildings can be afforded by a bigger share of prospective builders, and even more so in emerging and developing economies where the biggest floor area growth is projected to occur (IEA, 2022). And (as it is further shown in the next section) the less affluent populations at a global level are more likely to be vulnerable to thermal stress and to rely on less thermally comfortable buildings.

## 2.2 Thermal comfort and climate adaptation in the hot humid tropics

Extreme thermal stress may severely affect health and even cause death (Mora et al., 2017). It can compromise the body's ability to regulate its internal temperature, and possibly result in heat cramps, heat exhaustion, heat strokes and hyperthermia; and can also aggravate conditions like cardiovascular disease, respiratory disease, cerebrovascular disease and diabetes-related conditions (Ebi et al., 2021). Currently, around 30% of the world's population is exposed to conditions of potentially deadly thermal stress during at least 20 days a year (Mora et al 2017). Climate change is foreseen to increase this deadly risk in the coming decades. It is projected to rise to ~48% of the world's population under a scenario of drastic reductions of greenhouse gas (GHG) emissions and to ~74% under a scenario of growing emissions. As it is illustrated in Figure 4, due to the combined stress on human health of elevated temperatures and relative humidity, this risk (present and future) is more critical in tropical humid areas than in any other region of the world (Mora et al., 2017).

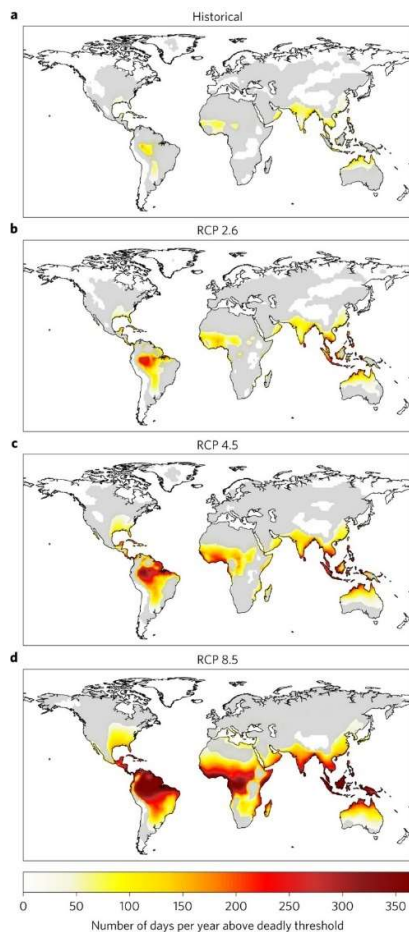


Figure 4 Number of days per year exceeding the threshold of temperature and humidity beyond which climatic conditions become deadly averaged between 1995 and 2005 (a), and between 2090 and 2100 under three different Representative Concentration Pathways RCP 2.6: low emissions (b), RCP 4.5: moderate emissions (c) and RCP 8.5 high emissions (d). Adapted from Mora et al. (2017)

Protecting people from this threat is therefore an essential function of buildings, and even more so critical in the hot humid regions of the world. Even if thermal stress does not go as far as a life-threatening risk, protection from it is also essential for human well-being. The World Health Organization has advanced decades of assessments correlating thermal discomfort with mental health problems, negative effects on educational attainments and emotional well-being, as well as an increased risk of accidents (Ormandy & Ezratty, 2012). Both the mortal and less extreme potential impacts of indoor thermal stress have been identified by the IPCC as a an escalating problem due to climate change (2022a). The observed and foreseen impacts are disproportionately concentrated amongst the economically and socially marginalized communities for whom access to thermally comfortable indoor spaces is less accessible (IPCC, 2022a; Mastrucci et al., 2019). This underlines the growing importance of understanding the ability of affordable buildings, whether they are cooled or not, to shield indoor spaces from thermal stress.

### 2.3 Air conditioning of buildings

In rapidly increasing scale around the world, a common way of shielding indoor spaces from thermal stress is the use of air conditioning systems (ACs). Even though they provide a way to keep stable indoor temperatures in hot climates, they come with major disadvantages. Most noticeably, they require a considerable supply of electricity which indirectly is likely to lead to GHG emissions for this electricity to be produced. Even though the global electricity networks are undergoing a major transformation that is reducing the carbon intensity of electricity production, the current indirect dependence of ACs on fossil fuels has led the IPCC adaptation report to consider the use of cooling as a climate maladaptation (IPCC, 2022a). That is, a measure to cope with the growing impacts of climate change that is in turn leading to more GHG emissions and thus more impacts. Furthermore, as cooling loads tend to be a decisive driver in peak electricity demand, and in many electricity grids around the world peak electricity is met with more carbon-intensive sources, the effect of widespread use of AC is even more impactful (IPCC, 2022a). Roaf *et al.* (2015) identify yet another negative feedback from the reliance on air conditioning systems: during heatwaves, soaring cooling energy demands can trigger energy shortages. These shortages have already occurred during heatwaves in Australia in 2009 and 2014, stopping ACs to deliver protection from thermal stress when it is more critically needed (Roaf et al., 2015).

Adding to the disadvantages highlighted above is the fact that ACs cannot be afforded by most of the population that requires them more critically. As climate change is foreseen to increase the need of protection from thermal stress in emerging and developing, hundreds of millions of people critically vulnerable to this stress do not have the economic means to access cooling –a situation that has been assessed and described as *cooling poverty* by Mastrucci *et al.* (2019). Adding to the environmental impacts of cooling, all of these major disadvantages highlight the importance of understanding pathways to eliminate or reduce cooling energy needs in affordable buildings in hot climates. Even more so in hot humid tropical regions where –as explained in Section 2.2– the threat of thermal stress to human health has been proven to be the biggest.

## 2.4 Climate-adapted buildings and building technologies in the hot humid tropics

Climate-adapted buildings, as defined in the introduction of this study, are those buildings that are able to deliver thermal comfort while reducing or avoiding energy needs. As the term hints, climate-adaptation depends on the local climate in which the building is located. Adaptation strategies therefore require a clear identification of the climate in which they are to be discussed. Climates that are broadly considered as hot humid ones are those identified in the Köppen-Geiger climate classification scheme, described in Table 1 as Tropical Rainforest (Af), Tropical Monsoon (Am) and Tropical Savannah (Aw). The global distribution of these climate regions is shown in Figure 5.

Table 1 Hot humid climates in the Köppen-Geiger climate classification scheme.  $T_A$ ,  $P_M$  and  $P_{an}$  denote average air temperature, monthly precipitation and annual precipitation respectively. Adapted from Košir (2019).

K-G description	K-G symbols			K-G criterion*
	1st	2nd	3rd	
Tropical	A			$T_{Amin} \geq 18 \text{ }^\circ\text{C}$
• Rainforest		f		$P_{Mmin} \geq 60 \text{ mm}$
• Monsoon		m		Not Af and $P_{Mmin} \geq 100 \text{ mm} - P_{an}/25$
• Savannah		w		Not Af and $P_{Mmin} < 100 \text{ mm} - P_{an}/25$

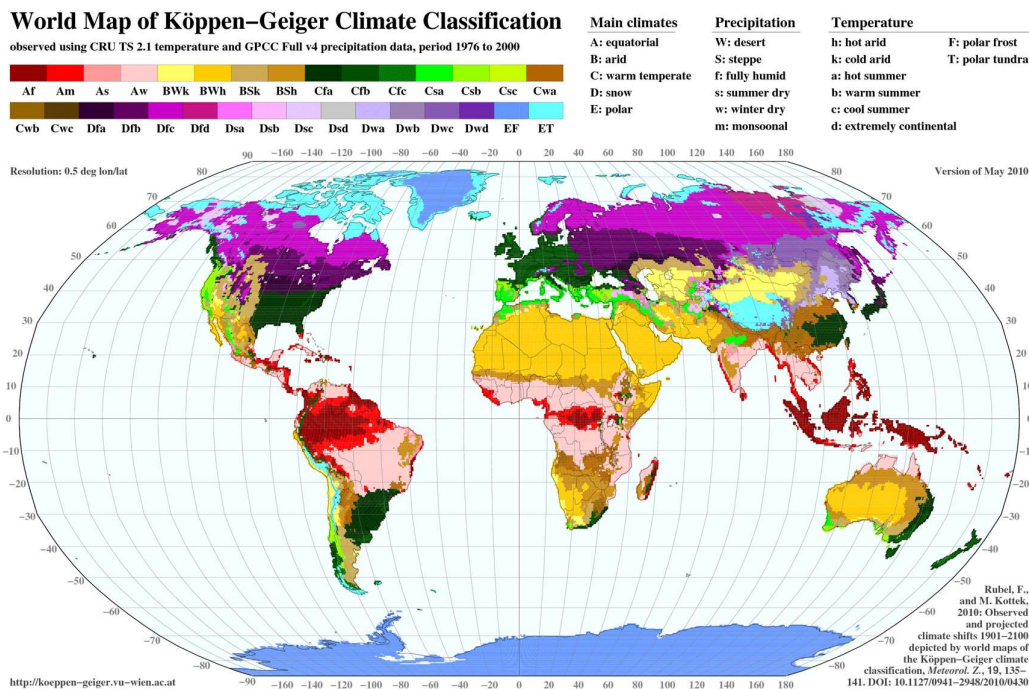


Figure 5 Global distribution of Köppen–Geiger climate regions. Figure by Rubel (2010).

Building on a broad literature review regarding climate-adaptations for hot humid climates, Košir (2019) has identified basic climate-adaptation strategies for buildings in these climates to operate

in natural ventilation mode (NV mode). These are summarized in Table 2. It should be noted that there are several other climate-adaptation strategies that have not been listed (*e.g.*, a more extensive list in Bhamare *et al.* (2019)) but that do not provide an affordable alternative. For example, insulation materials for walls and roofs is currently not economically feasible in the context of affordable buildings in the Philippines.

Table 2 Climate-adaptation strategies for buildings in Am, Af and Aw climates. Adapted from Košir (2019).

Strategy	Description
<i>Envelope Permeability</i>	Building envelopes should facilitate high air permeability.
<i>Separation</i>	Buildings should be spaced apart to ensure unobstructed wind circulation throughout the settlement and around structures.
<i>Light Envelopes</i>	Extremely light weight “no walls” envelopes are preferable.
<i>Wind Orientation and Placement</i>	Settlement placement and building orientation should be defined according to the prevailing winds.
<i>Shading</i>	Effective shading of transparent and opaque surfaces should be maximized. <i>E.g.</i> , extensive overhangs, vegetation with high treetops.
<i>Transparent Shading</i>	Avoidance of shading elements that limit ventilation considerably. <i>E.g.</i> , avoidance of roller shutters.
<i>Solar Orientation</i>	Orientation should avoid east and west-facing façades, particularly if they incorporate openings. These orientations are susceptible to overheating due to the shallow solar angles, which are challenging to shade properly.
<i>Spread geometry</i>	Compact buildings should be avoided as they make natural ventilation more difficult.
<i>Low absorptivity</i>	Materials of high absorptivity should be avoided. White or very light colours should be used in external envelope materials exposed to radiation.
<i>Stack Ventilation</i>	Enabling wind circulation induced by density differences. <i>E.g.</i> , rafter ventilations.
<i>Building Height</i>	Low-rise buildings may be preferable, as effective shading of the envelope is more feasible.

Among the strategies described above, most of them are not completely determined by the selection of structural building technology. The notable exception, and which might have a considerable synergy with bamboo construction technologies, is the light-envelope strategy: since building technologies with heavy envelopes cannot achieve this.

## **3 Theoretical framework**

This chapter presents the theories, models and frameworks that are relevant to the research objectives and that underpin the methods in the subsequent chapter. Section 3.1 addresses the use of case-studies as an approach to assess building technologies. Section 3.2. discusses the common frameworks for the assessment of the environmental sustainability of buildings. Section 3.3 discusses the assessment of thermal comfort in the context of the hot humid tropical climates. Section 3.4 presents suitable approaches to forecast energy use from air conditioning of buildings in the context of this study. Finally, Section 3.5 presents a framework through which different assessment approaches can be integrated to the systemic evaluation and development of building technologies.

### **3.1 Case-study approach**

This study aims to assess the environmental performance of a building technology. In contrast with products from other technology sectors, there are many factors that influence building properties beyond the choice of technology. Thus, the task of predicting –solely based on technology properties– how they impact their environment across their life cycles is specially challenging. To overcome this challenge, this thesis takes a case-study approach, under which the properties of the technology are approximated by those of one of some of the buildings that implements this technology. This approach assumes that the environmental and thermal comfort performance of other buildings implementing the technology will be in a similar range. To make this assumption more feasible in this context, the case study building ought to be selected considering two main issues. The first issue to be considered is that the building ought to be a representative example of the technology. A second aspect, which is especially relevant to thermal comfort assessments, is that the building technology selection (which mainly determines the properties of the envelope of the buildings) is only one of many parameters that play a significant role in the climate-adaptation potential of the building. To overcome this issue, the study can reduce its scope to those buildings within the technology that also fulfil most of the selected basic climate-adaptation strategies for hot humid climates.

Undertaking the technology assessment via the case-study approach has therefore the limitations that come with the assumption described above failing to be valid. However, it also comes with the advantage of making the research more feasible and relying on the data of a real implementation of a building technology, which encompasses data otherwise very difficultly predicted, like upstream value-chain inventories, and field-measurement capturing the complex interactions of buildings and climates.

### **3.2 Environmental sustainability assessment of building technologies**

This section introduces the common frameworks for the assessment of the environmental sustainability of buildings that are relevant for addressing RQI and RQII. The present study

addresses environmental sustainability of building technologies through the lens of industrial ecology. A widespread definition of industrial ecology describes the field as “...the study of the flows of materials and energy in technical systems, of the effects of these flows on the environment, and of the influences of economic, political, regulatory, and social factors on the flow, use, and transformation of resources” (White, 1994). An important aspect of industrial ecology is that it embraces systems thinking (Graedel, 1994), which models complex systems by prioritizing a wide scope encompassing relationships between subsystems, over a narrower scope with bigger detail.

The growing field of industrial ecology has developed a variety of tools to model and manage technical and environmental systems. Among these are Environmental Risk Assessments, Material Flow Analysis, Industrial Metabolisms, Environmental Indicators, Input-Output Analysis, Environmental Impact Assessments, and Life Cycle Assessments (LCAs). Each of these tools is suited to a specific purpose, aimed at answering particular questions about environmental sustainability. Among the industrial ecology “toolbox”, LCA is particularly useful to study buildings and building technologies, as their purpose is to assess the environmental impacts of products and services. The remainder of this section presents a general introduction to LCAs based on Tillman & Baumann (2004), ISO 14040 (2006) and ISO 14044 (2006).

### 3.2.1 Basics of Life Cycle Assessments

Life Cycle Assessment is a tool in the backbone of industrial ecology and whose purpose is to assess the environmental impacts of products and services. It has a long history going back to the 1960s when the first study containing most of their key elements was carried out (Tillman & Baumann, 2004). It has developed ever since to become a standardized framework that is widespread across the world. There are several international standards in place that guide the rationale and rules to perform these assessments, like ISO 14040 (2006) and ISO 14044 (2006). In Europe, some of these standards have been further developed for the specific assessment of buildings (EN 15978, 2011b).

LCAs owe the “Life Cycle” part of their name to the fact that they analyse products in relation to, for example:

- Processes that are necessary for them to become an operating product (*e.g.*, raw material extraction, transportation, manufacturing processes of sub-products).
- Processes that are necessary for them to function during their use-phase (*e.g.*, energy supply, sub-products for maintenance or operation).
- Processes that are necessary to handle the waste they generate or to convert them into new products (*e.g.*, landfilling, thermal treatment, recycling processes).

The set of these processes (referred to as life-cycle stages), together with the relationships between them, is what constitutes a *product system*. LCAs are based on a modelling approach that represents product systems through stocks and flows of materials and energy.

### 3.2.2 Goal and scope definition

The precise definition of the previously described product systems ought to be clearly related to the aim of an LCA. This is the content of the first step, as established by the ISO standards: 1. *Goal and Scope Definition*. The results of an LCA are not stand-alone scientific measurements of environmental impacts but are contextually related to the goal of the study. The definition of the boundaries of the product system, as well as the type of data to be collected depends on the goal of the study.

The *Scope* part of the *Goal and Scope* step of the LCA framework requires establishing the following elements of the assessment, in accordance with the goal of the study:

- *Functional unit*. The functional unit precisely establishes what is the product or service that is being assessed. It can be viewed as the final output of the product system, relative to which all the modelled flows of mass and energy are to be established.
- *Impact categories*. Step 2 of an LCA (described in Section 3.2.3) lists the environmental loads related to the product system, for step 3 (Section 3.2.4) to move on to translate these loads into environmental impacts via established methods that correspond to different environmental problems. The type of environmental problem to which those established methods correspond to, are known as *impact categories*. Since the environmental loads that should be listed in step 3 depend on which impact categories the study aims to assess, the categories should be established within step 1.
- *Type of LCA*. There are different established rationales to interpret cause-effect chains in the technosphere towards associating a product system with a set of environmental loads. Some processes cannot be easily associated to specific product systems, as they are related to possibly millions of product systems (e.g., electricity production). Most LCAs deal with this challenge by attributing environmental loads in a simplified way that linearly associates flows with environmental loads based on a physical parameter (e.g., divides all the environmental loads of electricity production into a unit of electricity outputs). Whereas other LCAs deal with this challenge by building a model that mirrors the cause effect chain between environmental loads and physical flows (e.g., matching each electricity output to the actual physical loads that enabled its production). The former type of LCAs are said to be of the *attributional* type, whereas the latter type are said to be of the *consequential* type.
- *System boundaries*. As an LCA is based on a product system model, it requires clearly defining what is included and what is excluded of such system. This boundary can be established by describing which life cycle stages are included; which components of the product are included; where and when the processes take place; and how the system processes allocate environmental loads when they have multiple inputs or outputs (some of which are not included in the product system).

### 3.2.3 Life Cycle Inventory (LCI)

Once the product system is clearly defined and related to a functional unit according to the goal and scope of the study, the next step, established by the ISO standards, is: 2. *Life Cycle Inventory (LCI)*. This step consists in gathering a precise list of all the *environmental loads* that take place in

each process in the product system. Environmental loads are the identified flows to the environment that are necessary for each process to take place: either inputs like resource extraction or outputs like emissions of substances to air, fresh water, sea water or soil. Each load is identified and listed in the inventory of each process documenting all the information that is relevant for assessing its environmental impacts in the remaining steps of the study.

### **3.2.4 Life Cycle Impact Assessment (LCIA)**

The result of the LCI step is a list of environmentally relevant flows of substances that are attributed to the product or service across its life cycle. However, at this stage the inventory of inputs and outputs is not providing a clear insight on what the environmental impacts of these flows are. This is where the third step of LCAs comes in: *3. Life Cycle Impact Assessment (LCIAs)*. LCIA methods are impact assessment methods that have been defined by a consensus in the scientific community. LCIA methods are not developed within an LCA study but are simply applied within it (usually with the help of specialized software like Open LCA, SimaPro or Gabi) to convert the long LCI lists into potential environmental impacts. Each LCIA method addresses a different environmental problem and quantifies the potential impact of the loads in the LCI to a specific environmental impact: e.g., climate change, ozone depletion, human toxicity, resource depletion.

### **3.2.5 Interpretation and iterations of LCAs**

The final step, *4. Interpretation*, consists in making sense of the LCI and LCIA results to answer the questions raised by the goal of the study. The ISO standards provide several guidelines on how this interpretation ought to be carried out. This includes procedures for identification of significant issues, data quality assessments and several techniques to conduct uncertainty analyses. LCAs are an iterative process in which all the four steps might have to be carried out several times, for the goal of the study to properly align with feasible system boundaries and data gathering.

### **3.2.6 Other aspects of LCAs**

Life Cycle Assessments are an evolving tool that constantly changes to improve some of its existing shortcomings (Finkbeiner et al., 2014). In spite of the existence of standards that guide LCA practitioners to conduct their assessments in a similar way, there are some important modelling decisions that are not fully defined there. To fill this gap, the present study draws on the recommendations from Ekvall (2020) which emphasize that LCAs are more effective at guiding environmental impact reductions when they achieve a balance between feasibility, comprehensibility and relevance for decision-making. In this context *feasibility* refers to cost and complexity limitations that influence LCA usage; *comprehensibility* refers to clarity and simplicity that attract decision-makers; *accuracy* refers to whether LCA models mirror the reality of the studied product system; and *relevance for decision making* refers to whether the assessment actually addresses its declared purpose. These aspects, Ekvall (2020) points out, often conflict with each

other and striking the right balance between them is crucial in guiding mitigation of environmental impacts.

### **3.3 Thermal comfort assessments**

Section 2.2 outlined the importance of assessing whether a building is offering thermal comfort to its users. This section presents the approaches to understand and assess thermal comfort that will underly the methodology of the thesis.

#### **3.3.1 Thermal comfort: psychophysical indicators**

A commonly accepted definition of thermal comfort is the following one proposed by the American Society of Heating , Refrigerating, and Air-Conditioning Engineers (ASHRAE, 2021a) and the ISO Standard 7730 (2005):

*That state of mind which expresses satisfaction with the thermal environment.*

It is interesting to highlight that by assessing this state of mind, the environmental conditions and the human body's reaction to them are being indirectly assessed. And thereby, for instance, whether potentially life-threatening thermal stress is occurring is also being assessed.

Psychophysics is “*the study of the relation between our sensations, the stimuli we receive from the physical world and the ways in which our brain interprets them*” (Nicol et al., 2012). And this science has been able to show that we can act as a “thermal comfort thermometer” by assigning a number to our sensations, i.e., to our level of satisfaction with the thermal environment (Nicol et al., 2012). Based on this fact, indicators of thermal comfort have been established in which a number in a descriptive scale is assigned by interviewees according to their level of thermal satisfaction. Examples of such indicators that are widely used are the ASHRAE scale and the Bedford Scale, as illustrated in Table 3:

Table 3 Two seven-point scales widely used as psychophysical indicators of thermal comfort. Adapted from Nicol et al. (2012)

ASHRAE* scale		Bedford scale	
Descriptor	Number	Descriptor	Number
Hot	+ 3	Much too warm	7
Warm	+ 2	Too warm	6
Slightly warm	+ 1	Comfortably warm	5
Neutral	0	Comfortable neither warm nor cool	4
Slightly cool	- 1	Comfortably cool	3
Cool	- 2	Too cool	2
Cold	- 3	Much too cool	1

### 3.3.2 Thermal comfort models: two approaches

The psychophysical indicators of thermal comfort cannot be applied directly to assess the level of comfort in a building, as building users cannot be endlessly interviewed to conclude how this indicator evolves even during one day. Adding to this, they do not provide any guidance on the future level of comfort of the building and even less so about buildings on the design stage. Thus, the necessity arises to have models that predict the results of psychophysical indicators based on other parameters which can be measured or predicted. Two distinct approaches have been posited for such thermal comfort attainment models. The first one relies on physics and physiology to mimic the psychophysical response of humans to environmental conditions through an analysis of heat flows in the body (Nicol et al., 2012; Yao et al., 2022). The models based on this approach are commonly referred to as “heat balance” models, but sometimes also as “rational” models (Nicol et al., 2012). A second, less widespread and more recently developed approach, is based on statistical analysis drawn from field surveys of people’s responses to the environment (Yao et al., 2022). The models based on this approach are known as “empirical” or, more commonly, “adaptive” models.

Heat balance models are the most widespread approach to predict thermal comfort in buildings. However, compilations of hundreds of studies and surveys in the last 40 years have shown that they have a major shortcoming when their predictions are tested against thermal comfort surveys (Humphreys et al., 2007, 2015; Nicol et al., 2012; Yao et al., 2022). In contrast, adaptive models are precisely built upon the results of these surveys and have identified simple parameters that have a strong correlation with comfort temperatures. Surprisingly, in the case of naturally ventilated buildings, one such parameter is the indoor temperature that building users are exposed to. When gathering data from thousands of surveys around the world, a linear correlation has been established between indoor temperatures and comfort temperatures (Humphreys et al., 2007, 2015; Nicol et al., 2012). More specifically, the relationship has often been established between comfort temperatures and indoor *operative temperatures*. Operative temperature is an index that combines indoor air temperature with mean radiant temperatures to describe their joint effect (Nicol et al., 2012). Figure 6 illustrates the linear relationship that has

been that has been found between indoor operative temperatures ( $T_{OP}$ ) and comfort temperatures for a large number of survey populations in different climates.

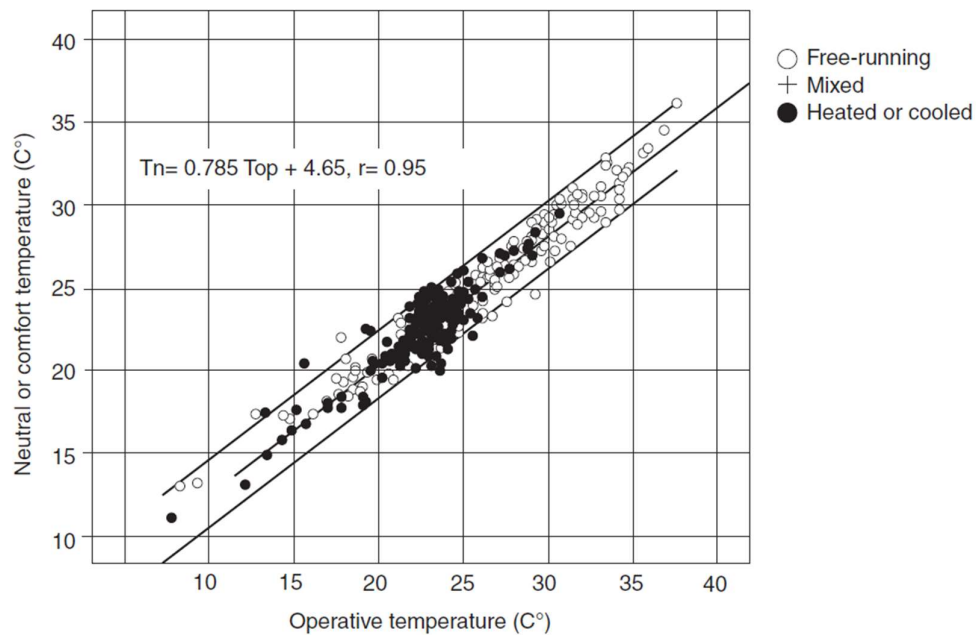


Figure 6 Scatter plot of indoor operative temperatures against comfort temperatures for a large number of survey populations in different climates. Free-running buildings are buildings operating with no heating or air conditioning. Figure from Nicol et al. (2012).

As indoor temperatures in naturally ventilated buildings are in turn correlated with outdoor temperatures, the correlation above (known as the *adaptive relationship*) can be extended to outdoor temperatures, as illustrated by Figure 7.

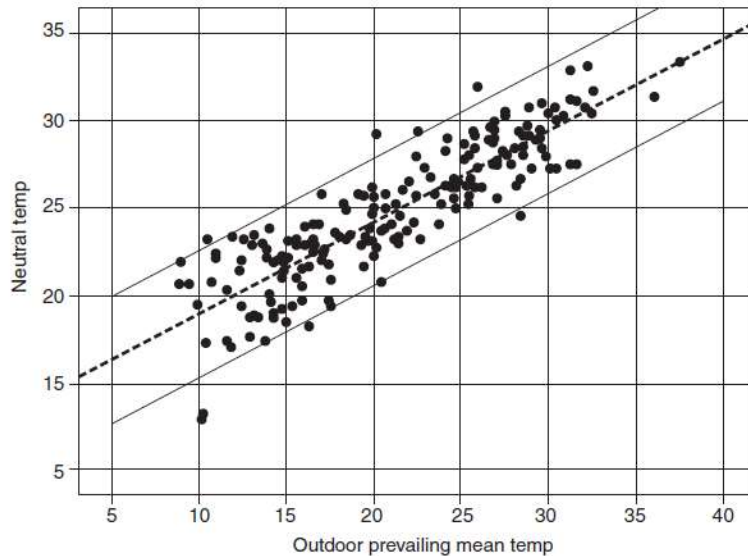


Figure 7 Scatter plot of outdoor prevailing mean temperatures against comfort temperatures (referred to as neutral temperatures in the figure) in a large number of survey populations since 1978. Figure from Nicol et al. (2012).

The reason for which the relationships described above have been named *adaptive* is that they have been explained by observing that building users adapt to the temperatures that they have to deal with to comfort. That is, as outdoor and indoor temperatures are higher, building users have several adaptation mechanisms through which they are able to reach comfort at higher temperatures. Nicol et al. (2012) suggest the following list of possible adaptation mechanisms through which higher comfort temperatures are reached, e.g., in the context of the UK:

«Some conceivable actions in response to heat:

- Vasodilation (increases blood flow to surface tissues)
- Sweating (evaporative cooling)
- Adopting an open posture (increases the area available for heat loss)
- Taking off some clothing (increases heat loss)
- Reducing the level of activity (reduces bodily heat production)
- Having a beer (induces sweating and increases heat loss)
- Drinking a cup of tea (induces sweating, more than compensating for its heat)
- Eating less (reduces body heat production)
- Adopting the siesta routine (matches the activity to the thermal environment)
- Turning on the air conditioner (lowers the air temperature)
- Switching on a fan (increases air movement, increasing heat loss)
- Opening a window (reduces indoor temperature and increases breeze)
- Finding a cool spot or visiting a friend (hoping for a cooler temperature)
- Going for a swim (selects a cooler environment)
- Building a better building (long-term way of finding a cooler spot)
- Emigrating (long-term way of finding a cooler place)
- Acclimatising (letting body and mind adjust so that heat is less stressful).» (p. 29-30)

Which Nicol et al. (2012) group in five types of adaptive actions: «i) regulating the rate of internal heat generation; ii) regulation of the rate of body heat loss; iii) regulation of the thermal environment; and iv) selection of a different thermal environment; and v) modifying the body's physiological comfort conditions.» (p. 31)

Fully demonstrating how the mechanisms above work has not been yet achieved. Regardless, the adaptive approach has the advantage when compared to heat balance models (and of special interest in the context of affordable buildings in the hot humid tropics) to reflect the fact that comfort can be achieved at higher temperatures in hotter climates. This finding is crucial for addressing climate-adaptation in buildings in a way that mitigates environmental impacts. And it is one of the reasons for which adaptive models have found their way to modern standards to assess thermal comfort like ASHRAE Standard 55 (2021b).

### 3.3.3 Thermal comfort indicators for buildings

The adaptive comfort model compares indoor operative temperatures with comfort temperatures to assess whether comfort is being met inside a building. This provides a criterion to determine if comfort is being met indoors in a specific moment, but it does not answer the question of how the building performs in delivering thermal comfort to its users. To meet this assessment need, several long-term thermal comfort performance indicators have been defined. Carlucci and Pagliano (2012) present an extensive review of such indices, their advantages and disadvantages. These range from very precise indicators based on more elaborate calculations, to less precise ones that are (in contrast) much easier to understand and communicate. As one of the goals of this study is to assess thermal comfort performance of specific buildings, such goal will be achieved by the use of one of such indicators. And as an indirect goal here is to benchmark the performance of the assessed building technologies, a key criterion for the selection of such indicator ought to be for it to be easily calculated and communicated.

## 3.4 Building energy assessments

Building energy assessments estimate the energy demand for a building to operate, which is hereafter referred to as operational energy ( $OE$ ). In cooled buildings,  $OE$  is determined by the heat flows occurring in the building, the efficiency of the cooling system, and the set-point temperature at which the system is operated. Recommended set-point temperatures are in turn based on assessments of what an ideal temperature ought to be chosen to provide thermal comfort.  $OE$  is also influenced by energy consumption from lighting and plug loads but in the context of hot humid climates it is strongly influenced by operational cooling energy ( $OE_{AC}$ ) if air conditioning is used (Duarte et al., 2018). There are different models to estimate  $OE_{AC}$  ranging from complex computer simulations up to simplified methods designed to make AC designs more available for simple buildings. This spectrum can be seen in the review of such models in Chapter 19 of ASHRAE's Fundamentals Handbook (2021a). In the present study, simpler models are more relevant due to three considerations. Firstly, only significant potential energy savings are of interest. Secondly, simpler models will allow a better understanding of the relationships between input variables, system parameters and the resulting  $OE_{AC}$  estimates. And thirdly, because (as it will be pointed out in the remainder of this section and Section 4.4) the  $OE_{AC}$  values will depend on rather uncertain variables and parameters like long-term outdoor temperatures and future AC efficiencies, that would upset the efforts of using an otherwise very accurate model. Based on criteria above, a *bin* model is selected for the  $OE_{AC}$  estimation in the present study. Bin models are based on a calculation method that partitions energy use time-series

into “bins” (i.e., intervals) according to the outdoor temperature and the corresponding cooling load and AC efficiency (ASHRAE, 2021a).

$OE_{AC}$  estimates from bin models depend on outdoor temperatures, and therefore using bin methods to estimate energy use along the building’s life cycle requires future outdoor temperatures as an input parameter for the calculations. In turn, these temperatures are likely to change during the building service life, and even more so when the effect of climate change is considered.

### **3.5 Advancing a holistic assessment of building technologies**

An important challenge to mitigate environmental impacts of building technologies, bamboo-based or not, is that they occur in complex and diverse cause-effect pathways unevenly spread in time and geography. Buildings might lead to multiple types of environmental problems: e.g., they might deplete the ozone layer, warm the planet, destroy natural habits, and even yet other environmental problems yet to be understood. These risks should be comprehensively examined to avoid addressing one environmental problem while disregarding the others. Similarly, all the environmental impacts of producing buildings ought to be understood together with those of operating and dismantling them. This highlights the importance of a systemic approach to addressing environmental assessments that doesn’t inadvertently shift environmental impacts outside of what is being assessed. This systemic awareness can be further applied beyond the environmental performance of a technology. Sub-optimisation can also take place when addressing environmental issues while disregarding other dimensions of a technology’s performance: e.g., technical, societal, and economic and the relationship between them. In fact, the impacts of a technology depend on the relationships between these dimensions (Tarr et al., 1977). For example, it might be the case that the improvement of a technical aspect leads to an improvement of economic performance (e.g., a more effective structural design); and it might be the case that the improvement of a technical aspect entails a decline in environmental performance (e.g., increased use of fire retardants). The former is a synergy between technical and economic performances, and the latter is a trade-off between technical and environmental performances. Managing the synergies and trade-offs between these different dimensions is essential for the development of sustainable building technologies.

To tackle the challenge described above, holistic approaches to technology assessments have been proposed and implemented. The advancement of composite bamboo shear-wall technologies in social housing in the Philippines took place under such a holistic approach. Salzer (2018) developed a framework for multi-dimensional assessment of building technologies that was also coupled with research-practice iterations. This theoretical framework provides a foundation to approach the integration of thermal comfort assessments with environmental sustainability assessments, and to understand the limitations of these assessments when other dimensions of sustainability are not addressed. In particular, it highlights the theoretical and practical importance of identifying synergies in thermal comfort- and environmental- performances, and of understanding these synergies in the bigger context of the technologies being assessed and advanced.

## 4 Methods

Based on the previously delimited research questions and theoretical frameworks, this chapter describes the methods that were applied to answer the project's research questions. The first section describes how the case-study buildings were selected and how their corresponding data is collected and modelled. The remaining 4 sections (4.2, 4.3, 4.4 and 4.5) present the methods to answer research questions I through IV respectively.

### 4.1 Case-study selection and data gathering

Following the case-study approach outlined in section 3.1, this thesis undertook the technology assessment through the analysis of a case-study building implementing the current state of one of these technologies. Subsections 4.1.1 and 4.1.2 describe the selection and data gathering processes of the technology and specific building respectively. And subsection 4.1.2 presents the comparative case study building that was modelled to allow a comparison with widespread affordable building technologies in the context of the Philippines.

#### 4.1.1 Case study technology: CBSW and bamboo trusses

The selected technology that was studied is a combination of CBSW and bamboo trusses, introduced in Section 2.1. The use of bamboo trusses in the context of non-residential buildings allows having open floor plans that are more flexible for non-residential buildings and likely to have a longer service life due to this flexibility. The use of CBSW allows meeting both structural and building envelope functions with the same building components. And the combination of both of these systems in the same building allows bringing both benefits together while reducing the building costs and increasing material efficiency. Both are standardized systems whose structural and typhoon resistance performances have been established (ISO, 2021).

Furthermore, this technology is being extensively applied and advanced by Base-Bahay foundation in the Philippines with which a partnership was established for this thesis. Base-bahay foundation availed all the technical information about the technology and the whole value-chain of the treated bamboo poles at the heart of it. To facilitate reference throughout the document, hereafter in the thesis CBSW will refer to the combination of composite bamboo shear walls and bamboo trusses.

#### 4.1.2 Case study building: Kanya Kawayan Weaving Centre in the Philippines

From the building technology selection outlined in the previous section, a case-study building was selected based on the compatibility with the research objectives. The selected building was a 148.8 m<sup>2</sup> weaving centre for the Kanya Kawayan social enterprise in the Batangas region of the Philippines. As shown in Figures 8 through 12 and further detailed in the blueprints in Appendix A.1, the open plan building, structured by *bambusa blumeana* trusses spanning 6.4m in the (slightly tilted) north-south direction, and by CBS walls in the (also slightly tilted) east-west

direction. The building is located in a region classified as tropical savannah climate (Aw) in the Köppen-Geiger climate classification that was presented in Section 2.4.

As highlighted in Section 1.2, this thesis focuses on affordable buildings. Previous research (Salzer, 2018) has assessed the economic performance of CBSW housing in the Philippines with indicators like Initial Construction Costs (ICCs) and Life Cycle Costs (LCCs). In that context, CBSW technologies has been shown to have potential savings of up to 40% for these indicators, and to meet the ICC ceiling established by the government of the Philippines. As benchmarks for ICCs of non-residential buildings are less available, this thesis defined a straightforward affordability criterion with ICCs below the national average ICCs per square metre. Meeting this criterion, the case study building was reported to have ICCs of 9,445 PHP per m<sup>2</sup> (Base Bahay, personal communication, June 15, 2023); whereas the national average for the third quarter of 2022, when the building was constructed, was 11,870 PHP per m<sup>2</sup>.



*Figure 8* Outside view of the case-study building: Kanya Kawayan weaving centre in Nasugbu, Philippines.



Figure 9 Inside view of the case-study building: Kanya Kawayan weaving centre in Nasugbu, Philippines.

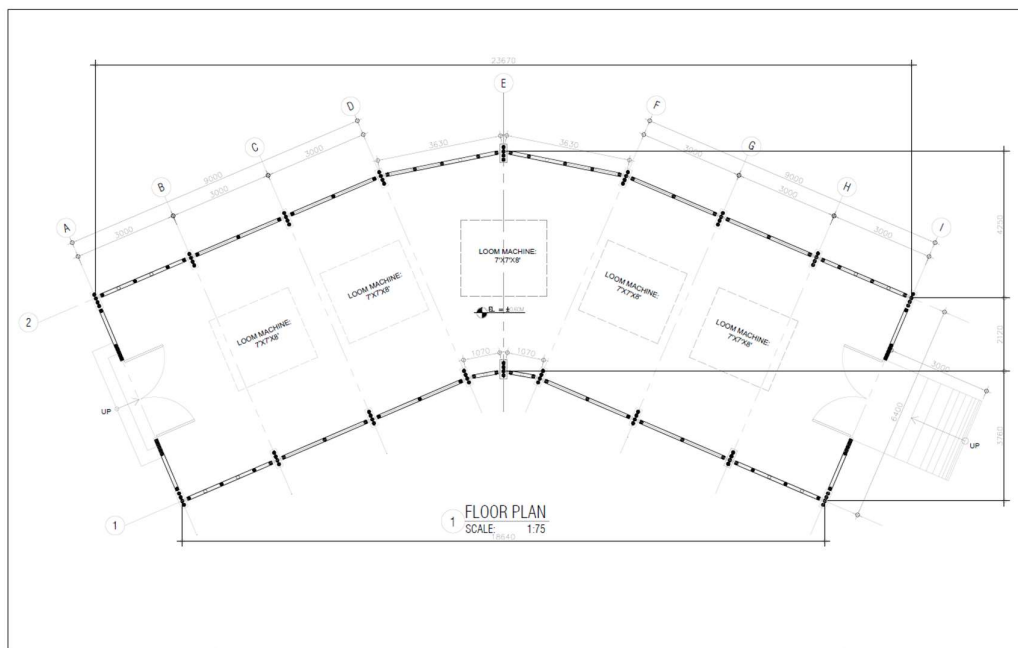


Figure 10 Floor Plan of the case-study building: Kanya Kawayan weaving centre. Northern direction upwards in the plan. Drawing not to scale. Drawings provided by Base-Bahay Foundation.

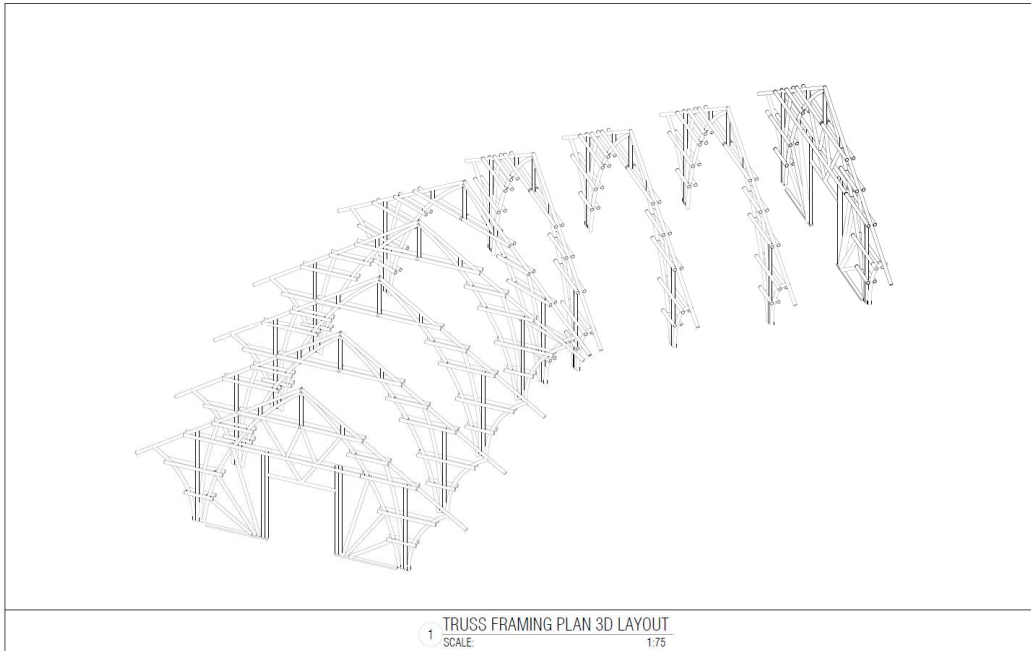


Figure 11 *Bambusa-blumeana truss framing plan 3d layout of the case-study building: Kanya Kawayan weaving centre. Drawing not to scale. Drawings provided by Base-Bahay Foundation.*

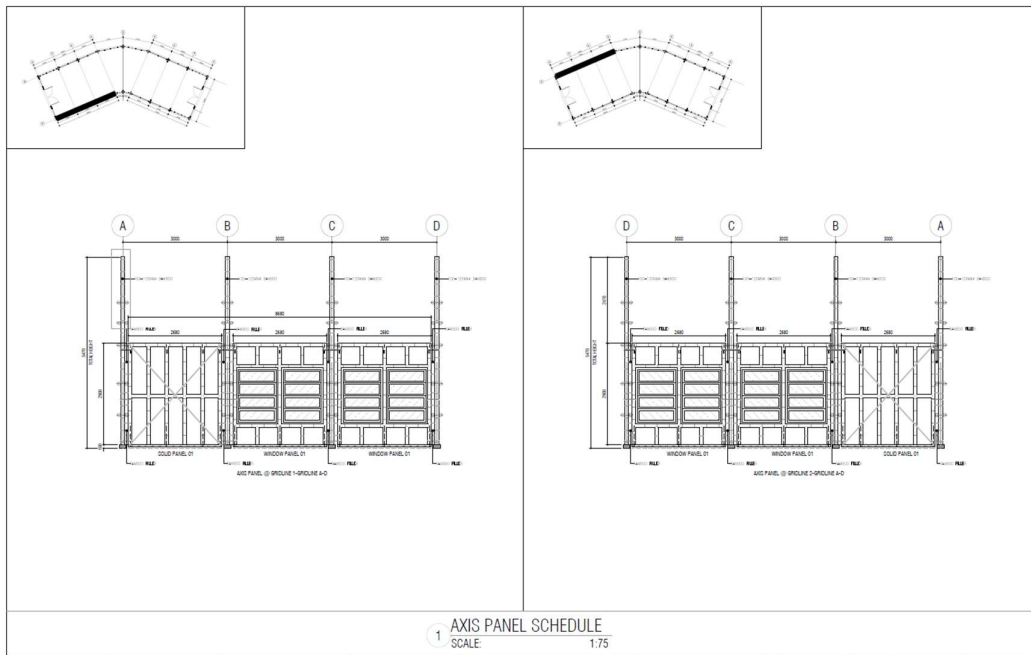


Figure 12 *Composite bamboo shear walls of the case-study building: Kanya Kawayan weaving centre. Drawing not to scale. Drawings provided by Base-Bahay Foundation.*

The selected case-study building followed most of the basic climate-adaptation strategies for hot humid climates that were identified in Section 2.4.: orientation to minimize sun exposure, overhangs extensively shading facades, high indoor space and maximized window size with cross ventilation. Some of these strategies, like including roof insulation or having air circulation underneath the floor could not be achieved within the cost limitations of this type of building project. However, the stack ventilation strategy (e.g., including a rafter ventilation) was identified as a likely affordable climate-adaptation that was not implemented in the case-study building.

As with the generalities of the building technologies, interviews with Base-Bahay foundation and Kanya Kawayan foundation provided all the information that was necessary for the study and facilitated access to the building and communication with the building users.

### 4.1.3 Equivalent concrete and steel building

To be able to compare the performance of the bamboo building technologies, a comparative case study building was considered. The comparison was made with the most widespread building technology for this building type in the Philippines: reinforced concrete with Concrete Hollow Block (CHB) walls and steel trusses for roof structure. Base-bahay foundation engineering team provided a complete building project of an equivalent building to the weaving centre but built with the widespread concrete and steel technologies. The geometry of the building, fenestration and roofing are unchanged. To ensure a thorough and fair comparison, Base-Bahay carried out a detailed structural design and building inventories for the comparative case study building, in compliance with the building code for these technologies in the Philippines. Figures 13 and 14 show a plan and 3d drawing of the comparative case study building, and the complete building plans are included in Appendix A.2.

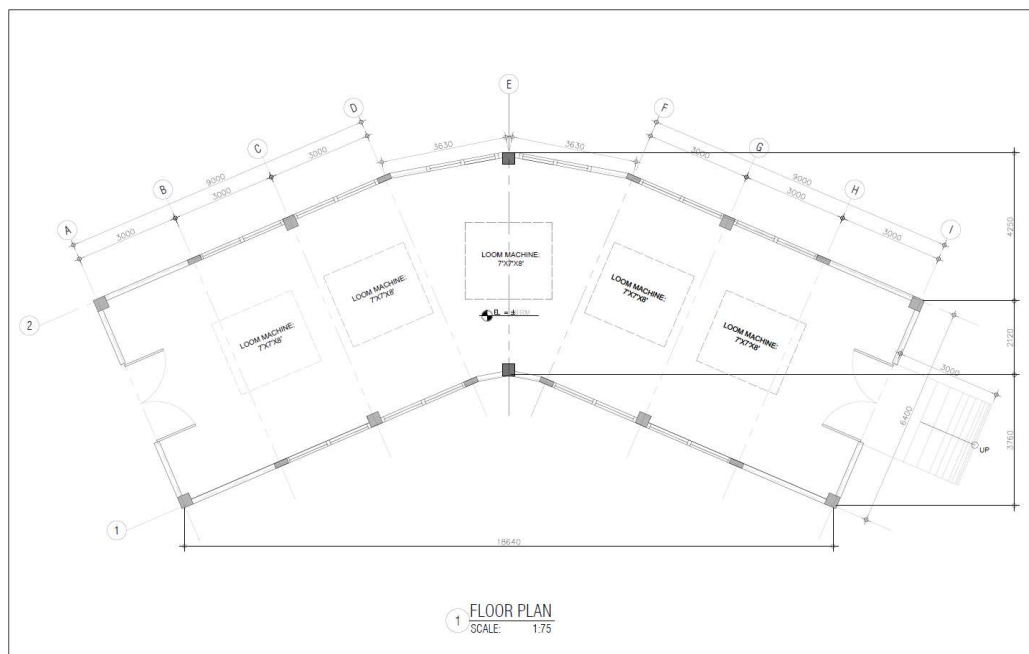
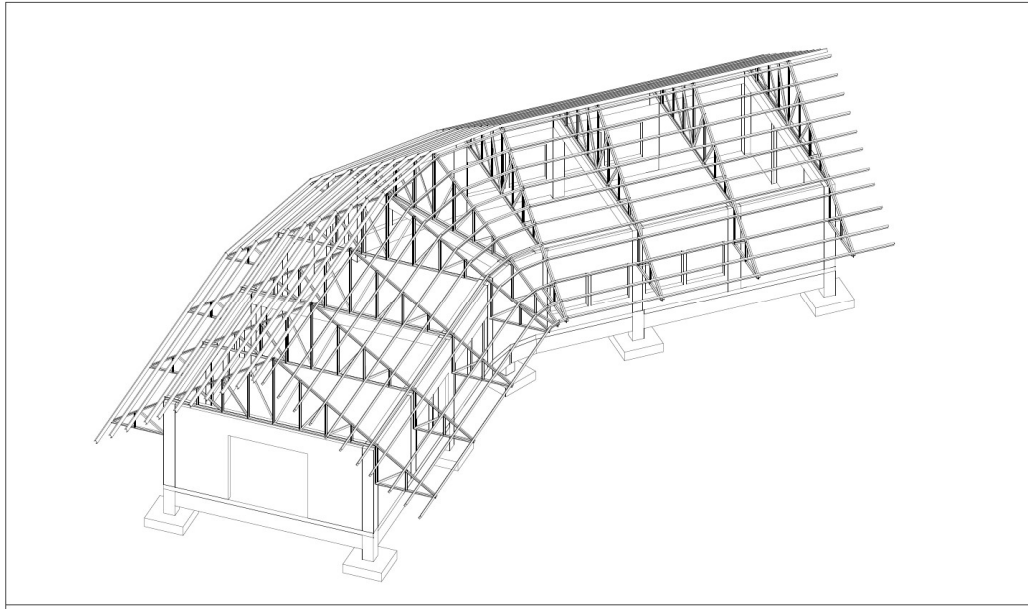


Figure 13 Floor Plan of the comparative concrete and steel case-study building. Northern direction upwards in the plan. Drawing not to scale. Drawings provided by Base-Bahay Foundation.



*Figure 14 Metallic truss framing plan 3d layout of the comparative concrete and steel case-study building. Drawing not to scale. Drawings provided by Base-Bahay Foundation.*

## 4.2 Cradle-to-gate assessment

This section presents the methods with which the cradle-to-gate environmental impacts of the buildings were modelled and measured to answer RQI regarding the life cycle impacts of bamboo- versus widespread-building-technologies:

- *RQI. How do cradle-to-gate impacts of bamboo buildings compare to those of widespread building technologies?*

Following the rationale presented in Section 3.2, the environmental performance of the building technology was approached by studying the cradle-to-gate environmental impacts of the case study buildings presented in sections 4.1.2 and 4.1.3. As highlighted in Section 3.2, LCA provides an assessment methodology to comparatively evaluate such environmental impacts and was therefore used in this study to address RQI. The following subsections describe how the assessment was carried out for the case study buildings, following the standard LCA steps that were described in Section 3.2. However, the final steps, relating to results and interpretation, are not presented in this chapter but in their corresponding sections of chapters 5 and 6.

### 4.2.1 Goal and scope definition

The goal of the LCA was to answer RQI in terms of the case study buildings: “How do the life cradle-to-gate impacts of the Kanya Kawayan Weaving Centre compare to those of the equivalent concrete and steel building?” Underlying in this goal was also the indirect goal of allowing prospective comparisons of the environmental impacts of the CBSW technology. The audience

of the assessment are technology developers at Base-Bahay foundation, and the research community interested in mitigating environmental impacts of building technologies in this context. As Base-Bahay foundation intends to share the results of this assessment for innovation purposes, the stakeholders engaged with Base-Bahay Foundation are also an indirect audience of this LCA.

The scope was determined following the corresponding elements of the assessment, as described in subsection 3.2.2. The headings in the remainder of this subsection describe how this was carried out based on the goals of the LCA.

#### Functional Unit

The functional unit was set to be built square metres of the case study buildings. In accordance with the main goal of the LCA, this allowed both a comparison between each version of the building: the original building implementing the CBSW technology (described in subsections 4.1.1 and 4.1.2.); and the equivalent one implementing widespread concrete and steel technologies (as described in subsection 4.1.3). And in accordance with the indirect goal of the assessment, the selected functional unit also fitted the purpose of allowing future comparisons of CBSW buildings.

#### Impact Categories

Following the delimitations set in subsection 1.2.2, the LCA only addressed climate-change related environmental impacts. Prioritizing this environmental impact for the assessment is motivated by the major role of the construction sector in GHG emissions and the foreseen expansion of the building stock (especially critical in emerging and developing economies) presented in the introduction of this thesis. Among the existing LCIA methods assessing climate change impacts, the selected one is IPCC's GWP-100, as presented in the IPCC AR5 WG1 report (2013). GWP(100a) stands for Global Warming Potential for 100 years. It is a metric that adds up the emissions of different gases, based on the radiative they lead to on a 100-year period, into a common scale: *CO<sub>2</sub> equivalent emissions*. The metric is based on the Absolute Global Warming Potential over 100 years: AGWP(100a); which is calculated as the integral of the radiative forcing (RF) effects of an emission pulse of a GHG (e.g., "gas X") over a 100-year period:

$$AGWP_{gas\ X}(100a) = \int_0^{100} RF_{gas\ X}(t) dt \quad (1)$$

Figure 15 illustrates how AGWP(100a) can be understood as the area of the RF (as a function of time) between year 0 and year 100.

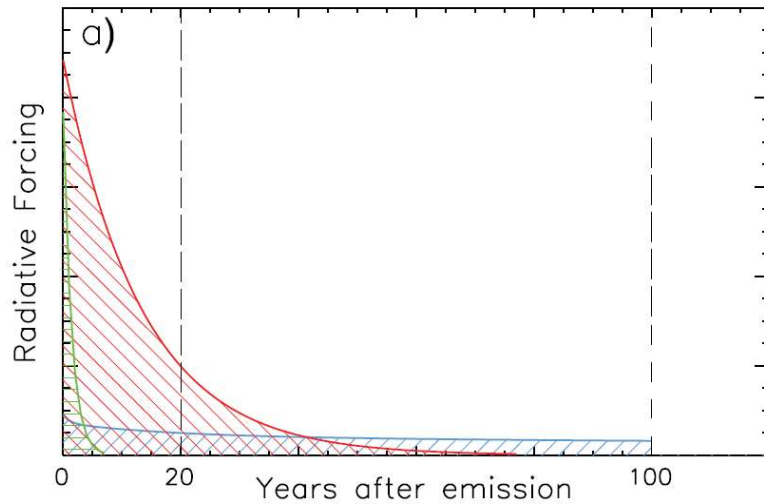


Figure 15 Illustration of AGWP(100a) as the area of RF between years 0 and 100. The blue curve and shaded area correspond to a CO<sub>2</sub> pulse; whereas the green and red curves and shaded areas correspond to gases with 1.5- and 13-years lifetimes, respectively. Adapted from IPCC AR5 WG1 report (2013).

Based on this, GWP(100a) for that GHG is defined as the ratio of AGWP(100a) of a pulse of this gas and the AGWP(100a) of 1kg of CO<sub>2</sub>:

$$GWP_{gas\ x}(100a) = \frac{AGWP_{gas\ x}(100a)}{AGWP_{CO_2}(100a)} \quad (2)$$

Consequently, GWP(100a) is a dimensionless factor, and it is commonly written as *kg CO<sub>2</sub> equivalents* or *kg CO<sub>2</sub> eq.* for short. This equivalence refers to the fact that, for example, 5 kgCO<sub>2</sub>eq., have the same RF effect over 100 years as 5 of kilograms of CO<sub>2</sub>.

The decision to use IPCC's GWP(100a) as an LCIA for this study was based on its widespread use in the context of environmental assessments of building technologies, that allows easy comparison with previous and future assessments of CBSW buildings. However, it must be noted that there is no scientific criteria to decide to use GWP-100 in place of GWP-50 or GWP-500, which are defined in the same way by the IPCC reports but considering a 50-year or 500-year horizons respectively.

### Type of LCA

The first goal of the assessment targeted a comparison of two buildings implementing a current state of two alternative technologies, and consequently an attributional LCA was more suitable. Even though the indirect goal of the LCA (targeting prospective comparisons of CBSW buildings) would have been better fulfilled with a consequential LCA approach, it would have significantly increased the complexity of the study, thereby decreasing its feasibility and comprehensibility. Considering the issues highlighted above, an attributional approach was taken for the cradle-to-gate comparative assessment.

### System Boundaries

Following the nomenclature for life cycle stages of buildings introduced by the European Norm EN 15978 (2011a) shown in Figure 16, the cradle-to-gate LCA included the stages:

- A1: Raw material supply (for building products). E.g., iron ore extraction
- A2: Transport (of raw materials to manufacturing). E.g., transportation of iron ore to steel mill.
- A3: Manufacturing (of building products). E.g., manufacturing of zinc-coated threaded rods for bamboo joints.
- A4: Transport (of building products to construction site). E.g., transportation of zinc-coated threaded rods to construction site.

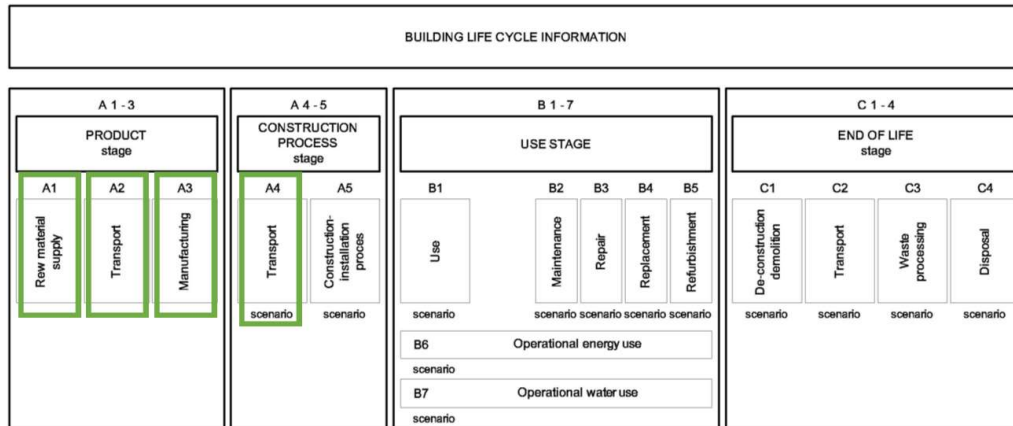


Figure 16 Life cycle phases according to EN 15978: stages within the scope of the cradle-to-gate LCA are highlighted in green. Adapted from EN 15978 (2011a).

Stage A5, which refers to construction and installation processes, was excluded from the assessment because the data relating to it was not available from the building developers.

Building elements and processes that are unchanged between both technologies being compared were excluded from the LCA model. Examples of these are the doors and windows, electrical systems and excavation works. In contrast, all the building systems that were different between the CBSW building and the concrete and steel building were included. That is, the foundations system, the structure system, and the wall envelope system.

The geographic and temporal boundaries of the product system was set by the supply chains of the building products. All of the industrial building materials implemented in both of the compared buildings are continuously produced in timescales that seldom span over 5 years. And so is the case for the *bambusa blumeana* bamboo poles used in the CBSW building; even considering its harvesting cycles which can be between 3 and 4 years (Razal, 2022).

Some of the building materials in the case study buildings have production processes with multiple outputs and therefore an allocation criterion also had to be established for the LCA model. Even though the ISO 14040 standard (2006) advises allocation to be carried out based on physical properties, it was done using economic allocation. This decision was motivated by the fact that the underlying goal of the LCA was to study the environmental impacts of the building technologies, and therefore market values can be used as a reasonable estimation criterion for attribution of upstream environmental loads.

## 4.2.2 Life Cycle Inventory

The LCI of the buildings was gathered by combining information from: the Bill of Materials (BOM) for each building provided by Base-Bahay foundation; interviews with the procurement officers and engineers of Base-Bahay foundation; field work in the Philippines; Ecoinvent 3.9.1. LCI dataset; interviews with Edwin Zea (developer of the Ecoinvent dataset for bamboo products); Environmental Product Declarations (EPDs) and several assumptions that were necessary to fill data gaps. Open LCA software was used to handle the LCI data. To facilitate calculations based on the BOMs, the LCI was first carried out relative to the complete building, and then scaled to the functional unit considering the total area of the buildings.

The headings in the remainder of this subsection describe how the LCI model was carried out for each life cycle stage.

### A1-A3: Building Product Stage

The starting point of the inventory was the BOM of the case-study buildings provided by Base-Bahay foundation. These BOMs are documented in Table C1 and Table C2 in Appendix C, highlighting in grey all the building materials that were excluded from the assessment. Most of these items were excluded based on the system boundary (set in subsection 4.1.1) according to which building elements that were common to both buildings were not to be assessed. Others were excluded due to the fact that the corresponding information was not available for the comparative case-study building, e.g., items 11.1 through 11.19. And only Solignum (a permethrin-based wood preservation chemical listed in items 3.15, 4.2, 6.24, and 4.2') was excluded due to insufficient data. This product and its main components were not found in Ecoinvent or in EPD databases, and an inquiry was made to the product manufacturer without any replies.

The next step was to model the product system for each of these products in stages A1, A2 and A3. To do this, four different approaches listed in Table 4 were taken, depending on whether the building material's product system model was available in the Ecoinvent 3.9.1 database or not.

Table 4 List of building product (stages A1-A3) LCI modelling approaches and their description.

LCI modelling approach	Description of modelling approach
<b>Approach (i)</b>	The product was modelled directly with an Ecoinvent process.
<b>Approach (ii)</b>	A product system was modelled by combining different Ecoinvent processes based on assumptions to fill data gaps or uncertainties.
<b>Approach (iii)</b>	The product was modelled by collecting data on site and interviewing Ecoinvent data-base developers to adjust the model to the context of the case-study building.
<b>Approach (iv)</b>	The product was modelled via an approximation with the EPD of a similar product.

The last column in Table C1 and Table C2 in Appendix C indicates which modelling approach was taken for each building product.

The first approach was taken for building products that appeared directly in the Ecoinvent database. Interviews with Base-Bahay were carried out to trace the most likely provenance of the materials in the markets of the Philippines. Ecoinvent processes represent the average production conditions within a geographical region (Ecoinvent, 2021). For virtually all products in the case-study buildings, there were no processes to represent the specific required geographic region. In those cases, processes representing world averages or “rest of the world” averages (i.e., production outside of Europe) were chosen. The only exception were wood products (items 3.1 and 6.23 from Table C1 in Appendix C); for which processes representing Canadian production averages were chosen, which is the most likely provenance for timber products used in Base-Bahay buildings.

As a consequence to the discussion above, for each building material modelled taking approach (i), an underlying assumption was made:

*Assumption i.1:* The production conditions have cradle-to-gate production conditions that closely approximate the average production conditions of a specific geographic region.

In this context, the specific geographic region refers to the closest matching dataset in Ecoinvent, based on the matching criteria just discussed above. Tables 5 and 6 below, show the filtered list of building materials modelled with approach (i) for each of the case study buildings, together with the Ecoinvent processes they were matched to. Because the units in the BOM did not coincide with the reference flow unit of the Ecoinvent processes, a conversion factor was needed; and it is shown in the last column in these two tables. The calculation of this conversion factor is discussed later on.

**Table 5** *Building materials for the CBSW building that were modelled with approach (i) (i.e., directly with an Ecoinvent process). The item codes correspond to those in the complete BOM of the building presented in Table C1. The required conversion factor translates the quantities from the BOM to the reference flows of Ecoinvent activities.*

Item Code	Item	Quantity	Units	Ecoinvent		Provider	Required Conversion Factor
				Process Folder	Ecoinvent Processes		
2.1	2B.1. G1 Gravel 1"	18	m3	810	gravel and sand quarry operation   gravel, round   Cutoff, U	RoW	kg/m3
2.3	Portland Cement Premium Type 1P	50	bg	2394	cement production, blast furnace slag 21-35%   cement, blast furnace slag 21-35%   Cutoff, U	RoW	kg/bg
2.4	Coarse Washed Sand	2.73	m3	810	market for sand   sand   Cutoff, U	RoW	kg/m3
2.5	Gravel 3/4 (crushed/selected)	5.46	m3	810	gravel and sand quarry operation   gravel, round   Cutoff, U	RoW	kg/m3
2.6	10mmØ x 6.00m RSB Grade 40	55	pc	2410	reinforcing steel production   reinforcing steel   Cutoff, U	RoW	kg/pc
2.7	8mmØ x 6.00m RSB Grade 33	32	pc	2410	reinforcing steel production   reinforcing steel   Cutoff, U	RoW	kg/pc
2.9.	Portland Cement Premium Type 1P	68	bg	2394	cement production, blast furnace slag 21-35%   cement, blast furnace slag 21-35%   Cutoff, U	RoW	kg/bg
2.10.	Coarse Washed Sand	3.75	m3	810	market for sand   sand   Cutoff, U	RoW	kg/m3
2.11.	Gravel 3/4 (crushed/selected)	7.51	m3	810	gravel and sand quarry operation   gravel, round   Cutoff, U	RoW	kg/m3
2.12.	12mmØ x 6.00m RSB Grade 40	39	pc	2410	reinforcing steel production   reinforcing steel   Cutoff, U	RoW	kg/pc
2.13.	10mmØ x 6.00m RSB Grade 40	112	pc	2410	reinforcing steel production   reinforcing steel   Cutoff, U	RoW	kg/pc
2.14.	8mmØ x 6.00m RSB Grade 33	42	pc	2410	reinforcing steel production   reinforcing steel   Cutoff, U	RoW	kg/pc
2.22.	Portland Cement Premium Type 1P	144	bg	2394	cement production, blast furnace slag 21-35%   cement, blast furnace slag 21-35%   Cutoff, U	RoW	kg/bg
2.23.	Coarse Washed Sand	7.99	m3	810	market for sand   sand   Cutoff, U	RoW	kg/m3
2.24.	Gravel 3/4 (crushed/selected)	15.98	m3	810	gravel and sand quarry operation   gravel, round   Cutoff, U	RoW	kg/m3
2.25.	8mmØ x 6.00m RSB Grade 33	227	pc	2410	reinforcing steel production   reinforcing steel   Cutoff, U	RoW	kg/pc
3.1.	2x4x8' S4SKD Lumber (lower plate)	102.47	bd.ft	1610	planing, beam, softwood, u=20%   sawnwood, beam, softwood, dried (u=20%), planed   Cutoff, U	CA-QC	m3/bd.ft
3.5.	1/8 x 1 x 6m Flat Bar (3mm thick)	16	pc	2410	steel production, low-alloyed, hot rolled   steel, low-alloyed, hot rolled   Cutoff, U	RoW	kg/pc
3.14.	Paint Thinner	2.23	bottle	2022	market for solvent for paint   solvent for paint   Cutoff, U	GLO	kg/pc
3.16.	wood glue/ stikwel (connecting wood frames)	0.63	ltr	2029	market for polyurethane adhesive   polyurethane adhesive   Cutoff, U	GLO	kg/ltr
5.6.	Paint Thinner	0.28	bottle	2022	market for solvent for paint   solvent for paint   Cutoff, U	GLO	kg/pc
5.9.	Portland Cement Premium Type 1P	17.10	bag	2394	cement production, blast furnace slag 21-35%   cement, blast furnace slag 21-35%   Cutoff, U	RoW	kg/bg
5.10.	washed fine sand	1.50	cu.m.	810	market for sand   sand   Cutoff, U - RoW	RoW	kg/m3
6.10.	paint thinner	1.46	bot	2022	market for solvent for paint   solvent for paint   Cutoff, U	GLO	kg/pc
6.11.	portland cement type1p	34.35	bags	2394	cement production, blast furnace slag 21-35%   cement, blast furnace slag 21-35%   Cutoff, U	RoW	kg/bg
6.12.	washed sand	3.01	m3	810	market for sand   sand   Cutoff, U - RoW	RoW	kg/m3
6.22.	paint thinner	0.82	bottle	2022	market for solvent for paint   solvent for paint   Cutoff, U	GLO	kg/pc
6.23.	1"x2"x8ft long KD wood	223.61	bdft	1610	planing, beam, softwood, u=20%   sawnwood, beam, softwood, dried (u=20%), planed   Cutoff, U	CA-QC	m3/bd.ft
6.26.	portland cement type1p	10.08	bag	2394	cement production, blast furnace slag 21-35%   cement, blast furnace slag 21-35%   Cutoff, U	RoW	kg/bg
6.27.	washed sand	0.88	cu.m.	810	market for sand   sand   Cutoff, U - RoW	RoW	kg/m3
7.1.	Masonry Cement	91.23	bag	2394	cement production, blast furnace slag 21-35%   cement, blast furnace slag 21-35%   Cutoff, U	RoW	kg/bg
7.2.	washed fine sand	7.98	cu.m.	810	market for sand   sand   Cutoff, U - RoW	RoW	kg/m3

**Table 6** *Building materials for the concrete and steel building that were modelled with approach (i) (i.e., directly with an Ecoinvent process). The item codes correspond to those in the complete BOM of the building presented in Table C2. The required conversion factor translates the quantities from the BOM to the reference flows of Ecoinvent activities.*

Item Code	Item	Quantity	Units	Ecoinvent Process		Provider	Required Conversion Factor
				Folder	Ecoinvent Processes		
2.1'. 2B.1. G1	Gravel 1"	18	m3		810 gravel and sand quarry operation   gravel, round   Cutoff, U	RoW	kg/m3
2.3'	Portland Cement Premium Type 1P	78.44	bg		2394 cement production, blast furnace slag 21-35%   cement, blast furnace slag 21-35%   Cutoff, U	RoW	kg/bg
2.4'	Coarse Washed Sand	4.28	m3		810 market for sand   sand   Cutoff, U - RoW	RoW	kg/m3
2.5'	Gravel 3/4 (crushed/selected)	8.57	m3		810 gravel and sand quarry operation   gravel, round   Cutoff, U	RoW	kg/m3
2.6'	RSB	1751.12	kg		2410 reinforcing steel production   reinforcing steel   Cutoff, U	RoW	kg/kg
2.8'	Portland Cement Premium Type 1P	101.81	bg		2394 cement production, blast furnace slag 21-35%   cement, blast furnace slag 21-35%   Cutoff, U	RoW	kg/bg
2.9'	Coarse Washed Sand	5.61	m3		810 market for sand   sand   Cutoff, U - RoW	RoW	kg/m3
2.10'	Gravel 3/4 (crushed/selected)	11.24	m3		810 gravel and sand quarry operation   gravel, round   Cutoff, U	RoW	kg/m3
2.11'	RSB	39.00	pc		2410 reinforcing steel production   reinforcing steel   Cutoff, U	RoW	kg/pc
2.19'	Portland Cement Premium Type 1P	144	bg		2394 cement production, blast furnace slag 21-35%   cement, blast furnace slag 21-35%   Cutoff, U	RoW	kg/bg
2.20'	Coarse Washed Sand	7.99	m3		810 market for sand   sand   Cutoff, U - RoW	RoW	kg/m3
2.21'	Gravel 3/4 (crushed/selected)	15.98	m3		810 gravel and sand quarry operation   gravel, round   Cutoff, U	RoW	kg/m3
2.22'	8mmØ x 6.00m RSB Grade 33	227	pc		2410 reinforcing steel production   reinforcing steel   Cutoff, U	RoW	kg/pc
3.1'	Portland Cement Premium Type 1P	156.40	bg		2394 cement production, blast furnace slag 21-35%   cement, blast furnace slag 21-35%   Cutoff, U	RoW	kg/bg
3.2'	Coarse Washed Sand	8.68	m3		810 market for sand   sand   Cutoff, U - RoW	RoW	kg/m3
3.3'	Gravel 3/4 (crushed/selected)	17.36	m3		810 gravel and sand quarry operation   gravel, round   Cutoff, U	RoW	kg/m3
3.4'	RSB	5423.08	kg		2410 reinforcing steel production   reinforcing steel   Cutoff, U	RoW	kg/kg
3.7'	Cement for mortar	2275.92	kg		2394 cement production, blast furnace slag 21-35%   cement, blast furnace slag 21-35%   Cutoff, U	RoW	kg/kg
3.8'	Sand for Mortar	4.74	m3		810 market for sand   sand   Cutoff, U - RoW	RoW	kg/m3
3.9'	Cement for plaster	349.89	kg		2394 cement production, blast furnace slag 21-35%   cement, blast furnace slag 21-35%   Cutoff, U	RoW	kg/kg
3.10'	Sand for plaster	1.45	m3		810 market for sand   sand   Cutoff, U - RoW	RoW	kg/m3
6.1'	Steel Trusses	8439	kg		2410 steel production, low-alloyed, hot rolled   steel, low-alloyed, hot rolled   Cutoff, U	RoW	kg/kg
6.2'	Steel Purlins	2736	kg		2410 steel production, low-alloyed, hot rolled   steel, low-alloyed, hot rolled   Cutoff, U	RoW	kg/kg

A second assumption was made when applying modelling approach (i). The cement that was used in the case-study building (items 2.3, 2.9, 2.22, 5.9, 6.11, 6.26, 7.1) was not the regular Portland cement which dominates the market of the Philippines. But rather another type of cement that is branded as an ecologically friendly alternative and was donated by a manufacturer who sponsored the building to showcase their product. Upon inquiry with the manufacturers and guidance from the cement type classification defined in the European standard EN 197-1:2011 (CEN, 2011), the cement type was found to be CEM II/B-S. In typical Portland cement (CEM I in the EN 197-1 classification system) 95 to 100 percent of the mass content comes from clinker. But in CEM II/B-S, only 65 to 79 percent is clinker, which is partially replaced by blast-furnace slag (a by-product of steel production). Thus, the cement used in the building had 21 to 35 percent of

the mass content coming from a lower embodied carbon by-product of another industry. Even though this is not a widespread cement type in the context of the Philippines, a decision was made to assume in this LCA that CEM II/B-S was used both in the CBSW building, and in the comparative case-study building (in items 2.3', 2.8', 2.19', 3.1', 3.7', 3.9'):

*Assumption i.2:* CEM II/B-S type building is used in both case-study buildings

Keeping in mind the goal of the LCA, this can be compared to assuming that the assessed building technologies are to some extent defined by the use of this type of cement. CEM II/B-S is alleged to have a lower environmental impact due to the partial replacement of clinker with a by-product from another industry.

The last step to be able to complete the LCI for the products modelled using approach (i) was to relate the BOM units to the corresponding Ecoinvent reference flow. That is, to find the value of the conversion factor in the last column of tables 5 and 6. The calculation of these factors together with the approximations and minor assumptions that are necessary are reported in Table C3 in Appendix C.

Approach (ii) described in Table 4 was taken for industrial building products that do not appear directly in Ecoinvent. Except for the CHB blocks in the comparative case study building, all of the materials modelled using this approach were metallic products used in the structure or the foundations. Tables 7 and 8 show the list of all the building products modelled with Approach (ii). Similarly to Tables 5 and 6, the last column of tables 7 and 8 shows the conversion factor that was necessary to link the modelled product system to the original BOMs. Table 9 lists the main assumptions that were necessary to model each material in Table 7 and Table 8.

Table 10 lists the Ecoinvent processes inputs that were used to model each of these materials (based on the assumptions from Table 9). And finally, Table C4 in the appendix shows the calculations and minor assumptions that were used in computing the corresponding inflows and the necessary conversion factors (as listed in the last columns of Table 7 and Table 8).

*Table 7 Building materials for the CBSW building that were modelled with approach (ii). The item codes correspond to those in the complete BOM of the building presented in Table C2. The required conversion factor translates the quantities from the BOM to the reference flows of Ecoinvent activities.*

<i>Item Code</i>	<i>Item</i>	<i>Quantity</i>	<i>Units</i>	<i>Modelling Approach</i>	<i>Ecoinvent Composite Processes</i>	<i>Required Conversion Factor</i>
2.8	#16 Tie wire	58.2	kg	(ii)	(n) tie wire	kg/kg
2.15.	#16 Tie wire	9.77	kg	(ii)	(n) tie wire	kg/kg
2.18.	1 1/2" CWN	0.7	kg	(ii)	(n) nails	kg/kg
2.19.	2 1/2" CWN	0.7	kg	(ii)	(n) nails	kg/kg
2.26.	#16 Tie wire	6.01	kg	(ii)	(n) tie wire	kg/kg
3.6.	1/2" Ø x 3.00m Threaded Rod	9.33	pc	(ii)	(n) threaded rods	kg/pc
3.7.	1/2" Ø Nut	210	pc	(ii)	(n) nuts	kg/pc
3.8.	1/2" Ø Washer	210	pc	(ii)	(n) washers	kg/pc
3.9.	CWN 2 1/2"	6.42	kg	(ii)	(n) nails	kg/kg
3.10.	3/8" Ø x 3.00m Threaded Rod (on flat bar)	3.7	pc	(ii)	(n) threaded rods	kg/pc
3.11.	3/8" Ø Nut	148	pc	(ii)	(n) nuts	kg/pc
3.12.	3/8" Ø Washer	148	pc	(ii)	(n) washers	kg/pc
3.17.	1 1/2" CWN (connecting wood frames)	0.23	kg	(ii)	(n) nails	kg/kg
5.2.	3/8" Ø x 3.00m Threaded Rod	8.73	pc	(ii)	(n) threaded rods	kg/pc
5.3.	3/8" Ø Nut	120	pc	(ii)	(n) nuts	kg/pc
5.4.	3/8" Ø Washer	120	pc	(ii)	(n) washers	kg/pc
5.7.	CWN 2 1/2"	1	kg	(ii)	(n) nails	kg/kg
5.8.	4" concrete nail	0.73	kg	(ii)	(n) nails	kg/kg
6.6.	1/2" Ø x 3m full threaded rod	36	pc	(ii)	(n) threaded rods	kg/pc
6.7.	1/2" nuts	630	pc	(ii)	(n) nuts	kg/pc
6.8.	1/2" washers	630	pc	(ii)	(n) washers	kg/pc
6.18.	3/8" Ø x 3m full threaded rod	36	pc	(ii)	(n) threaded rods	kg/pc
6.19.	3/8" nuts	352	pc	(ii)	(n) nuts	kg/pc
6.20.	3/8" washers	352	pc	(ii)	(n) washers	kg/pc
7.4.	CWN 1 1/2"	11.05	Kg	(ii)	(n) nails	kg/kg
7.5.	#18 Tie Wire	2.60	Kg	(ii)	(n) tie wire	kg/kg
7.6.	3/4" hole chicken wire #20 (4ft width)	6.56	roll	(ii)	(n) chicken wire	kg/roll
7.8.	1 1/2" concrete nail	0.8	Kg	(ii)	(n) nails	kg/kg

Table 8 Building materials for the case-study comparative concrete and steel building that were modelled with approach (ii). The item codes correspond to those in the complete BOM of the building presented in Table C2. The required conversion factor translates the quantities from the BOM to the reference flows of Ecoinvent activities.

Item Code Item	Quantity	Units	Modelling		Conversion Factor
			Approach	Ecoinvent Composite Processes	
2.7'. #16 Tie wire	91.30	kg	(ii)	(n) tie wire	kg/kg
2.12'. #16 Tie wire	14.63	kg	(ii)	(n) tie wire	kg/kg
2.15'. 1 1/2" CWN	1.05	kg	(ii)	(n) nails	kg/kg
2.16'. 2 1/2" CWN	1.05	kg	(ii)	(n) nails	kg/kg
2.23'. #16 Tie wire	6.01	kg	(ii)	(n) tie wire	kg/kg
3.5'. #16 Tie wire	6.01	kg	(ii)	(n) tie wire	kg/kg
3.6'. CHB Blocks	109	m2	(ii)	(n) CHB (150mm wall)	m2/m2

Table 9 Assumptions for building materials modelled using approach (ii)

Assumption	Building materials modelled with the assumption	Description of modelling assumption
Assumption ii.1	(n) chicken wire (n) nuts (n) threaded rods (n) washers	Based on the mass and surface area of the metal product, its production inputs can be approximated by Ecoinvent processes: <ul style="list-style-type: none"> <li>metal working, average for steel product manufacturing</li> <li>market for steel, low-alloyed, hot rolled</li> <li>zinc coating, pieces</li> </ul>
Assumption ii.2	(n) CHB (150mm wall)	Based on the volume and mass of the blocks, its production inputs can be approximated by the Ecoinvent processes: <ul style="list-style-type: none"> <li>cement production, Portland</li> <li>market for sand</li> <li>market for transport, freight, lorry, all sizes, EURO4</li> </ul>
Assumption ii.3	(n) nails (n) tie wire	Based on the mass of the product, its production inputs can be approximated by Ecoinvent processes: <ul style="list-style-type: none"> <li>metal working, average for steel product manufacturing</li> <li>market for steel, low-alloyed, hot rolled</li> </ul>

Table 10 Building materials modelled using Approach (ii): list of inputs modelled using Ecoinvent Processes.

Ecoinvent Composite Process	Reference Output		Input	Input min	Input Max	Unit	Ecoinvent Process Folder	Ecoinvent Input Process	Origin
	Flow Size	Unit							
(n) chicken wire	1	kg	zink coating	0.039	0.042	m2	2592 zinc coating, pieces   zinc coat, pieces   Cutoff, U	RoW	
			metal working	1	1	kg	259 metal working, average for steel product manufacturing   metal working, average for steel product manufacturing   Cutoff, U	RoW	
			steel	1	1	kg	241 market for steel, low-alloyed, hot rolled   steel, low-alloyed, hot rolled   Cutoff, U	GLO	
(n) CHB	1	m2	cement	11.7	11.7	kg	2394 cement production, Portland   cement, Portland   Cutoff, U	RoW	
			aggregate	128.1	128.1	kg	810 market for sand   sand   Cutoff, U	RoW	
			transport to factory	18.7	18.7	t*km	4923 transport, freight, lorry, all sizes, EURO4 to generic market for transport, freight, lorry, unspecified   transport, freight, lorry,	RoW	
(n) nails	1	kg	metal working	1	1	kg	259 metal working, average for steel product manufacturing   metal working, average for steel product manufacturing   Cutoff, U	RoW	
			steel	1	1	kg	241 market for steel, low-alloyed, hot rolled   steel, low-alloyed, hot rolled   Cutoff, U	GLO	
(n) nuts	1	kg	zink coating	0.0364	0.0364	m2	2592 zinc coating, pieces   zinc coat, pieces   Cutoff, U	RoW	
			metal working	1	1	kg	259 metal working, average for steel product manufacturing   metal working, average for steel product manufacturing   Cutoff, U	RoW	
			steel	1	1	kg	241 market for steel, low-alloyed, hot rolled   steel, low-alloyed, hot rolled   Cutoff, U	GLO	

Table 10 (Continued)

Ecoinvent Composite Process	Reference Output		Input	Input min	Input Max	Unit	Ecoinvent Process Folder	Ecoinvent Input Process	Origin
	Flow Size	Unit							
(n) threaded rods	1 kg	zinc coating	0.039	0.042	m2	2592	zinc coating, pieces   zinc coat, pieces   Cutoff, U	RoW	
		metal working	1	1	kg	259	metal working, average for steel product manufacturing   metal working, average for steel product manufacturing   Cutoff, U	RoW	
		steel	1	1	kg	241	market for steel, low-alloyed, hot rolled   steel, low-alloyed, hot rolled   Cutoff, U	GLO	
(n) tie wire	1 kg	metal working	1	1	kg	259	metal working, average for steel product manufacturing   metal working, average for steel product manufacturing   Cutoff, U	RoW	
		steel	1	1	kg	241	market for steel, low-alloyed, hot rolled   steel, low-alloyed, hot rolled   Cutoff, U	GLO	
(n) washers	1 kg	zinc coating	0.071	0.071	m2	2592	zinc coating, pieces   zinc coat, pieces   Cutoff, U	RoW	
		metal working	1	1	kg	259	metal working, average for steel product manufacturing   metal working, average for steel product manufacturing   Cutoff, U	RoW	
		steel	1	1	kg	241	market for steel, low-alloyed, hot rolled   steel, low-alloyed, hot rolled   Cutoff, U	GLO	

Approach (iii) described in Table 4 was taken for the bamboo products. These materials are: bamboo poles (of different sizes, as listed in the BOM in Table C1); and bamboo mats, which are known as tad-tad in the Philippines (item 7.3 in the BOM in Table C1). Production of bamboo poles and bamboo mats in the Philippines are included in Ecoinvent 3.8.1, but these processes were not used as they appear in the database due to two considerations. First, because upon interviews with the developer of the Ecoinvent dataset for bamboo products (Zea Escamilla, 2023), who acted as an external advisor to Base-Bahay foundation in this project, it was established that the datasets have included fertilizer inputs, which is a very rare practice in the context of bamboo stands in the Philippines. And second, because field observations that supported this project verified differences in production conditions when compared to the Ecoinvent product systems. An example of these differences lied in the machinery to harvest and process bamboo culms and poles. However, there was one difference that was detected but could not be corrected in the bamboo LCI model due to insufficient data. The chemical that was used to treat bamboo poles in the construction site (and in virtually all bamboo treatment facilities in the Philippines, following Base-Bahay supply chain guidance) is a permethrin-based preservative. Whereas production in the Ecoinvent dataset features preservation with boric acid. As discussed above regarding the wood preservation agent, it was not possible to gather LCI data for permethrin-based chemicals, and therefore this variation was not featured in the LCI model.

Finally, Approach (iv) described in Table 4 was taken for a building material that was not found in Ecoinvent database, but did have very similar products with public Environmental Product Declarations (EPDs). This material was the metal primer (listed in items 3.13, 5.5, 6.9 and 6.21 in the BOM in Appendix C), used in the reinforcement of the bamboo structure to prevent rusting of steel elements. EPDs are standardized LCAs that, instead of being goal-oriented

assessments, are guided by a set of rules known as Product Category Rules (PCRs). An existing EPD of a commercial metal primer (Gloria, 2018) was found, which includes the LCIA results for the A1-A3 stages. Even though these impact assessment results were calculated using a different method than IPCC's GWP(100), they were approximated via a conversion factor developed by Dong *et al.* (2021). The details of the conversion calculation is included in Table C5 in Appendix C.

#### A4: Transportation to Construction Site

As introduced in subsection 4.2.1, stage A4 is the life-cycle stage where the building materials are transported from their manufacturing site to the construction site.

For each building material, the LCI of transportation stage was gathered by following three steps:

1. Calculating the mass of the material.
2. Calculating the transportation distance(s) of the material for each transportation step.
3. Assessing the most likely transportation technology for each transportation step and matching it to the closest Ecoinvent dataset.

In this way, for each building product, step 1 yields the mass to be transported; step 2 yields the distances and transportation modes it is to be transported (e.g.,  $x$  tonne\*km of land freight,  $y$  tonne\*km of sea freight); and step three converts these parameters into LCI values (e.g.,  $z$  kg of CO<sub>2</sub> emissions to air).

The calculation of the mass of the material is not necessary for those products that were already listed in the BOM having mass as their reference quantity. For the other materials, the procedures and assumptions for the calculations are included in Tables C3, C4 and C5 in Appendix C.

The calculation of transportation distances of the building materials is determined by the sourcing of the materials. From a narrow perspective, the direct goal of the LCA (building level) would have required the exact sourcing of the materials for the specific buildings. But the indirect goal (technology level) aligns better with “the most likely” sourcing for each building material in the context of affordable buildings the Philippines. Based on interviews with Base Bahay foundation and their suppliers, both the specific sourcing (when known) and the feasible sourcing (when unknown) of each building material were considered. Based on this rationale, the calculations of the transportation distances for each transportation mode were calculated, as shown in Table C6 in Appendix C.

Finally, for step 3, once the transported mass and distance are known for each building material, the conversion of the transportation service into an inventory of environmental loads is done by matching each transportation step to the closest Ecoinvent process. This assignment is shown in Table 11 below.

Table 11 Modelling of transportation steps of building materials (A4 module) with selected Ecoinvent processes. Materials that are not included in the table are transported from a manufacturing site in Manila and therefore have the same A4 distance as cement in the first entry of the table.

Process Name	Reference Output Flow Size	Unit	Transportation step	Unit	Input min	Input Max	Ecoinvent Process Folder	Ecoinvent Process	Origin
(n) cement A4	1 kg		factory to site	t*km	0.113	0.113	4923	transport, freight, lorry, all sizes, EURO4 to generic market for transport, freight, lorry, unspecified   Cutoff, U	Glo
(n) gravel A4	1 kg		factory to site	t*km	0.019	0.019	4923	transport, freight, lorry, all sizes, EURO4 to generic market for transport, freight, lorry, unspecified   Cutoff, U	Glo
(n) nails A4	1 kg		factory to site	t*km	0.113	0.113	4923	transport, freight, lorry, all sizes, EURO4 to generic market for transport, freight, lorry, unspecified   Cutoff, U	Glo
(n) reinforcing steel A4	1 kg		factory to port	t*km	0.898	0.898	4912	market for transport, freight train   transport, freight train   Cutoff, U	RoW
			port to port	t*km	2.268	2.268		market for transport, freight, sea, container ship   Cutoff, U	Glo
			port to site	t*km	0.113	0.113	4923	transport, freight, lorry, all sizes, EURO4 to generic market for transport, freight, lorry, unspecified   Cutoff, U	Glo
(n) sand A4	1 kg		factory to site	t*km	0.0274	0.0274	4923	transport, freight, lorry, all sizes, EURO4 to generic market for transport, freight, lorry, unspecified   Cutoff, U	Glo
(n) sawnwood A4	1 kg		sawmill to port	t*km	0.898	0.898	4912	market for transport, freight train   transport, freight train   Cutoff, U	RoW
			port to port	t*km	36.071	36.071		market for transport, freight, sea, container ship   transport, freight, sea, container ship   Cutoff, U	Glo
			port to site	t*km	0.113	0.113	4923	transport, freight, lorry, all sizes, EURO4 to generic market for transport, freight, lorry, unspecified   Cutoff, U	Glo

### 4.3 Thermal comfort assessment

This section describes the methods with which the thermal comfort assessment of the case study building was carried out, and how they answer RQII regarding thermal comfort performance of bamboo buildings without air conditioning:

- RQII. What is the thermal comfort performance of bamboo buildings without air conditioning?

As proposed by adaptive thermal comfort models discussed in subsection 3.3.2, the criteria to assess comfort was to use indoor operative temperature as a thermal comfort index and to calculate the ideal value for this index based on site measurements and surveys. The methods presented in this section were structured and systematized in the book *Adaptive thermal comfort: Principles and Practice* by Nicol, Humphreys and Roaf (2012); and provide a more general

applicability to adaptive thermal comfort assessments than ASHRAE standard 55 (ASHRAE, 2021b)<sup>1</sup>.

The present study approached RQII by assessing the thermal comfort performance of the case-study building. This was done in four steps. The first step, presented in the first subsection of this section, was gathering the data in the building. The second step (subsection 4.3.2) was the calculation of operative temperatures. The third step (subsection 4.3.3) was calculating the comfort temperature ( $T_c$ ). And the final step (subsection 4.3.4) was to use the comfort temperature and environmental data collected in the building to calculate a thermal comfort indicator that gauged how good is the building at maintaining this comfort condition.

### 4.3.1 Environmental data gathering in the case-study building

With the aid of sensors and data loggers listed in Appendix B and shown in Figures 17 and 18, the following indoor and outdoor environmental data were measured:

- Indoor air temperature ( $T_a$ )
- Globe Temperature ( $T_g$ )
- Air velocity ( $v$ )
- Relative Humidity ( $RH$ )
- Outdoor temperature ( $T_{out}$ )



Figure 17 Outdoor measuring equipment in the case-study building. Technical details in Appendix B.

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<sup>1</sup> ASHRAE standard 55 (2020) presents a simplified version of the adaptive model in section 5.4 which does not assess thermal comfort when metabolic rates are above 1.5met, which renders it unapplicable for a wide range of non-residential buildings. For example, in the case-study building looming and warping activities might have higher metabolic rates than 1.5met.



*Figure 18 Indoor measuring equipment in the case-study building. Technical details included in Appendix B.*

Measurements were taken every 10 minutes during the period of March 24<sup>th</sup> of 2023 to July 22<sup>nd</sup> of 2023. Historic meteorological from the region of Nasugbu, collected from Meteonorm8 software, showed that typical years have a hot season between the first days of April and the last days of May; and a wetter season between the last days of May and the first days of November. The measurement period was chosen attempting to cover both seasons in which thermal comfort assessment is most critical. During this same period, 144 interviews among 8 regular users of the building were carried out, using the questionnaire shown in Figure 19 and Figure 20. The questionnaire was developed by adapting the template proposed by Nicol et al. (2012) to the specific goals and context of this study.

Base Bahay & Chalmers University of Technology  
 Thermal Comfort Study of Kanya Kawayan Weaving Centre, Nasugbu

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WHO ANSWERS THIS QUESTIONNAIRE AND WHEN:  
 Name:..... Date:..... Time: .....

---

AT PRESENT I FEEL:

Very Cold	Cold	A bit cold	OK	A bit hot	Hot	Very Hot
<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>

---

I WOULD PREFER TO BE:

Much cooler	A bit cooler	No change	A bit warmer	Much warmer
<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>

---

CLOTHING:

Shirt with no sleeves <input type="checkbox"/>	Boots <input type="checkbox"/>
Shirt with short sleeves <input type="checkbox"/>	Shoes <input type="checkbox"/>
Shirt with long sleeves <input type="checkbox"/>	Sandals <input type="checkbox"/>
Pants or sweat pants <input type="checkbox"/>	Other (specify) .....
Shorts <input type="checkbox"/>	.....

---

ACTIVITY IN THE LAST 15 MINUTES:

Sitting and sewing <input type="checkbox"/>	Other (specify) .....
Sitting and weaving <input type="checkbox"/>	
Only Sitting <input type="checkbox"/>	

---

CONTROLS :

Door open <input type="checkbox"/>	Fan on <input type="checkbox"/>
Window open <input type="checkbox"/>	

---

Who filled out this questionnaire? .....

Figure 19 Questionnaire for the adaptive thermal comfort assessment: first week of the study.

Thermal Comfort Study of Kanya Kawayan Weaving Centre, Nasugbu

Pangalan:..... Petsa: .....

PANAMAMIT

Sando <input type="checkbox"/>	Bota <input type="checkbox"/>	Pantalon <input type="checkbox"/>
T-shirt <input type="checkbox"/>	Sapatos <input type="checkbox"/>	Shorts <input type="checkbox"/>
Shirt with long sleeves <input type="checkbox"/>	Sandalyas o Tsinelas <input type="checkbox"/>	Iba pa .....

SA NGAYON NAKAKARAMDAM AKO NG:

Time:.....am .....am .....pm .....

Sobrang malamig				
Malamig				
Medyo malamig				
Sakto lang				
Medyo Mainit				
Mainit				
Sobrang init				

MAS GUSTO KO KUNG:

Masmalamig				
Medyomalamig				
Walang pagbabago				
Medyomainit				
Masmainit				

GINAWA MO SA NAKARAANG 15 MINUTO:

Sitting and sewing				
Sitting and weaving				
Sitting and winding				
Sitting and spinning				
Sitting and inserting				
Standing up and beaming				
Standing up and warping				
Standing up and inserting				
Ipa ba	.....	.....	.....	.....

CONTROLS

Fan above on				
Nearby window open				

Comments or observations

.....	.....	.....	.....
-------	-------	-------	-------

Questionnaire na pinunan ni:.....

Figure 20 Questionnaire for the adaptive thermal comfort assessment: from week 2 to the end of the study. The questions are the same as in the first questionnaire (Figure 19) but translating some of them to Tagalog (national language of the Philippines) and fitting three interview times in a single sheet to facilitate data collection.

### 4.3.2 Operative temperatures calculation

As mentioned in Section 3.3, adaptive models are commonly carried out by using indoor operative temperatures to assess comfort. This section presents the procedure that was used to calculate operative temperatures based on the collected data described in the previous section. First off, the mean radiant temperature ( $T_r$ ) was calculated as a function of the globe temperature ( $T_g$ ), the diameter of the globe thermometer that was used ( $d$ ), indoor air speed ( $v$ ) and indoor air temperature ( $T_a$ ) according to the formula:

$$T_r = [(T_g + 273)^4 + (1.2 \times 10^8 d^{0.4})v^{0.6}(T_g - T_a)]^{0.25} - 273 \quad (3)$$

And then  $T_{op}$ , which is an indicator to describe the combined effect of mean radiant temperature and indoor air temperature, was computed as the average of these two values:

$$T_{op} \approx (T_a + T_r) / 2 \quad (4)$$

### 4.3.3 Comfort temperature calculation

The data gathered following the procedures in the two previous sections, yielded a dataset of thermal comfort votes (TCVs) in the ASHRAE scale (ranging from -3 to 3), each associated to a corresponding  $T_{op}$  value that was registered at the time when that interview took place. That is, comfort votes inside the building together with the operative temperature in the building at the time of the vote. These values were then fitted with a linear regression and the comfort temperature was estimated by the  $T_{OP}$  value at which the linear regression equalled 0 (i.e., the neutral comfort vote). Figure 21 shows conceptually (without actual measurements from the study) how the calculation of the comfort temperature is made out of the scatter plot of comfort votes and  $T_{OP}$  values via the intersection of a regression line at the neutral comfort vote.

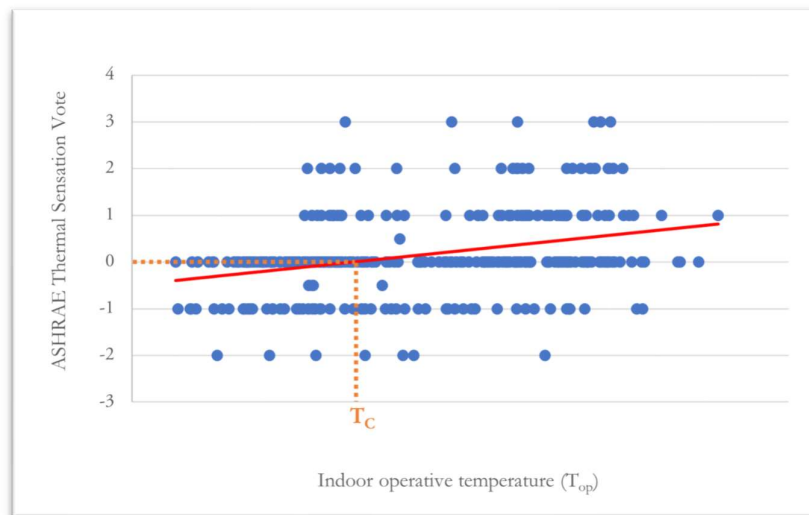


Figure 21 Conceptual example of a scatter plot of thermal comfort votes (referred to in the figure as thermal sensation votes) against indoor operative values.

### 4.3.4 Indicator to assess thermal comfort performance of a building

Among the many different indicators that build upon comfort temperatures to assess thermal comfort performance of a building, the *POR* (percentage of occupied hours outside of comfort range) was implemented. This indicator was selected by giving precedence to the fact that it is easily computed and communicated. The latter feature is critical in the context of this study, as an indirect goal is to enable technology improvements based on the communicating a metering of thermal comfort performance. As it can be inferred from the name of the indicator, *POR* is the percentage of hours during which the building is occupied and does not meet thermal comfort.

That is:

$$POR \text{ (Bamboo Building)} = 100\% \times \frac{\text{Hours with } T_{Op} \text{ outside comfort range}}{\text{Occupied hours}} \quad (5)$$

The comfort range is defined as a range of temperatures centred at the comfort temperature ( $T_C$ ), as described in the previous section. The size of this interval depends on how the expectation of comfort level is set for the building. ASHRAE 55 standard (2021b) sets out a framework to define *acceptability levels* of thermal comfort. Based on global datasets of surveys a 90% acceptability level is defined so that the difference between the indoor temperature and the adaptive comfort temperature is not bigger than 2.5°C; and a 80% acceptability level is defined so that this difference is not bigger than 3.5°C (Carlucci & Pagliano, 2012). ASHRAE (2021b) recommends meeting the 80% level for “typical applications”, and the 90% level only when a higher level of thermal comfort is desired. For the present study, it was decided to implement the former level (*i.e.*, handling the broader  $T_C - 3.5^\circ\text{C}$  to  $T_C + 3.5^\circ\text{C}$  comfort range). The decision was motivated by the fact that the adaptive comfort assessment for buildings hosting activities with metabolic rates higher than those of office buildings is very rare (Yao et al., 2022), and it would only make sense to increase the expectation of comfort levels after a lower level of comfort are known to be met. Finally, based on the fact that ASHRAE Standard 55 defines a thermally acceptable environment to be that which at least 80% of the occupants find thermally comfortable, this study sets the criteria for thermally comfortable building to be that in which *POR* is smaller than 20%.

## 4.4 Building energy assessment

This section explains the method with which building energy assessment was carried out and how it allows answering RQIII regarding the energy needs for the case study buildings to operate with AC. As it was discussed in Section 3.4, the present study estimated  $OE_{AC}$  by adopting a bin method, which is based on a partition of energy time-series into “bins” (*i.e.*, intervals) according to the outdoor temperature, the corresponding cooling load and AC efficiency. Subsection 4.4.1 presents the way in which the time series of outdoor temperatures was gathered for the case study buildings. Subsection 4.4.2. introduces the method with which the cooling loads were calculated for each given outdoor temperature and set-point temperature; that is, for each “bin” in the model. Finally, subsection 4.4.3 describes how the energy use was calculated for each bin and summed up to yield the desired  $OE_{AC}$  calculation.

### 4.4.1 Outdoor temperature time series based on climate change scenarios

Regional Climate Models (RCMs) allow having reliable estimates of outdoor temperatures for different GHGs emission scenarios (Flato et al., 2013). Meteororm V8 software (2020) generates RCM models by downscaling Global Climate Models (GCMs) from the IPCC scenarios and combining them with stochastic generation (Remund et al., 2020). IPCC climate change scenarios are based on emissions scenarios known as Representative Concentration Pathways

(RCPs) developed by the IPCC (Flato et al., 2013). RCP4.5 and RCP8.5 scenarios consider, respectively, a scenario of considerable emission reductions, and scenario of business-as-usual increasing of emissions (Flato et al., 2013).

To meet the need of this study regarding  $OE_{AC}$  calculations, Meteonorm V8 software (2020) was used to generate time series of outdoor temperatures at the case study buildings' site. Time series for the years 2020, 2030, 2040 and 2050, with a 10-minute resolution, and for both the RCP4.5 and RCP8.5 scenarios were gathered in this way. Time series beyond 2060 were not generated because, as it will be discussed in Section 4.5, the expected lifetime for the building will be of 30 years.

#### 4.4.2 Calculation of cooling loads

This subsection presents the method with which the cooling loads were calculated. This was done with the Load Factor (LF) method, outlined in ASHRAE's Fundamentals Handbook (2021a). This method is a simplified procedure derived from more accurate and comprehensive Heat Balance (HB) method for cooling load calculations, which is based on a detailed modelling of space temperatures and heat flows. The results of using the LF method have been shown to be within a 10% range (ASHRAE, 2021a) of those calculated with the HB method. Implementing this simpler (although less accurate) LF method in this study is motivated by the same arguments with which simpler  $OE_{AC}$  calculations were justified in Section 3.4.

The Load Factor method owes its name to the fact that it estimates some major components of the cooling load through the use of Cooling Factors ( $CFs$ ), which enable calculations to rely on hand-tractable arithmetic. LF method models cooling load based on the AC set-point temperature and parameters related to outdoor climate, building systems properties, building geometry and materials. The set-point temperature was determined from the adaptive comfort temperature, whose calculation was described in Section 4.3. The following heading, the parameters and how they were calculated is described; and the final heading of this subsection describes how these parameters are used by the LF method to calculate the case study buildings' cooling load.

##### Parameters for cooling load calculation with the LF method

Table 12 includes all the outdoor climate parameters required by the LF method, as well as a description of how their values were retrieved or calculated.

Table 12 Outdoor climate parameters for cooling load calculation

Parameter	Symbol	Description of value for the case-study buildings	Value	Units
Air sensible heat factor	$C_s$	Value for sites close to sea level is given in ASHRAE Fundamentals Handbook (2021a, p. 17.3)	1.23	W/(L·s·K)
Daily range of outdoor temperatures	$DR$	Difference between maximum and minimum temperatures in the day. Directly calculated from the time series in subsection 4.4.1	<i>Varies daily</i>	°C
Outdoor temperature	$T_{out}$	From the time series in subsection 4.4.1	<i>Varies in each bin</i>	°C
Indoor-outdoor humidity ratio difference	$\Delta W$	ASHRAE Fundamentals Handbook (2021a, p. 17.14)	0.0050	<i>Unitless</i>
Air latent heat factor	$C_l$	ASHRAE Fundamentals Handbook (2021a, p. 17.3)	3010	W/(L·s)
Direct irradiance	$E_D$	Table 10 of ASHRAE Fundamentals Handbook (2021a, p. 17.9)	106	W/m <sup>2</sup>
Diffuse irradiance	$E_d$	Table 10 of ASHRAE Fundamentals Handbook (2021a, p. 17.9)	97	W/m <sup>2</sup>

Table 13 includes all the parameters related to building systems that were required by the LF method, as well as a description of how their values were retrieved or calculated. As it can be seen in detail in this table, one of these values was calculated based on an assumption that compensated uncertainty regarding the way in which the buildings would have been adapted for an AC system.

Table 13 Building systems parameters for cooling load calculation

Parameter	Symbol	Description of value for the case-study buildings	Value	Units
Balanced ventilation flow rate via recovery ventilation equipment	$Q_{bal,oth}$	Equals zero because there is no indoor/outdoor mechanical ventilation systems in the buildings	0	L/s
Flue effective leakage area	$A_{L,flue}$	Equals zero because the buildings don't have flues	0	m <sup>2</sup>
Unit leakage area	$A_{UL}$	Table 3 of ASHRAE Fundamentals Handbook (2021a, p. 17.6) gives an $A_{UL}=5.6$ cm <sup>2</sup> /m <sup>2</sup> value to leaky buildings. An assumption is made that this would be a plausible scenario for the case study buildings.	5.6	cm <sup>2</sup> /m <sup>2</sup>
Transmission of exterior attachment (screen or shades)	$T_x$	Table 11 of ASHRAE Fundamentals Handbook (2021a, p. 17.10) gives an $T_x=1$ value to buildings with no exterior attachments in windows.	1	<i>Unitless</i>

Table 14 includes all the parameters related to building geometry and materials that were required by the LF method, as well as a description of how their values were retrieved or calculated.

Table 14 Building geometry and materials parameters for cooling load calculation

Parameter	Symbol	Description of value for the case-study buildings	Value	Units
Conditioned floor area of building,	$A_{cf}$	Calculated from the plans of the case study buildings (Appendix A)	147.5	m <sup>2</sup>
Stack height	$H$	Calculated from the plans of the case study buildings (Appendix A)	4.19	m <sup>2</sup>
Building area exposed surface	$A_{ES}$	Calculated from the plans of the case study buildings (Appendix A)	435.19	m <sup>2</sup>
Fraction of fenestration shaded by permanent overhangs,	$F_{shd}$	Calculated from the plans of the case study buildings (Appendix A)	1	Unitless
Fenestration Solar Load Factor	$FF_s$	Table 13 of ASHRAE Fundamentals Handbook (2021a, p. 17.10) gives $FF_s=0.44$ and $0.47$ values to buildings with fenestration oriented northwards and southward respectively. The weighted factor is the average between both factors.	0.455	Unitless
Interior shading attenuation coefficient	$IAC$	This coefficient is set to zero in buildings (like the case study buildings) because the windows don't have any type of shades.	0	Unitless
Solar Heat Gain Coefficient	$SHGC$	Table 2 of ASHRAE Fundamentals Handbook (2021a, p. 17.5) gives $SHGC=0.75$ for windows with 1 layer of clear glazing and operable frames, matching the window types of the case study buildings (plans in Appendix A)	0.75	Unitless
U-value of windows	$U_{win}$	Table 2 of ASHRAE Fundamentals Handbook (2021a, p. 17.5) gives $U=7.24$ for windows with 1 layer of clear glazing and operable frames (plans in Appendix A)	7.24	W/(m <sup>2</sup> K)
Fenestration area	$A_{fen}$	Calculated from the plans of the case study buildings (Appendix A)	18.83	m <sup>2</sup>
Roof solar absorptance	$\alpha_{roof}$	Table 8 of ASHRAE Fundamentals Handbook (2021a, p. 17.8) gives $\alpha_{roof}=0.45$ .	0.45	Unitless
Resistance of Slab covering material	$R_{cov}$	Value for bare concrete slab with no covering. Table 3, HVAC systems and equipment (2020, p. 6.7)	0	m <sup>2</sup> K/W
Daily range opaque-surface cooling factors of doors	$OF_{r,doors}$	Table 7 of ASHRAE Fundamentals Handbook (2021a, p. 17.8) gives $OF_r=-0.36$ for doors with solar exposure	-0.36	Unitless

Table 14 (Continued)

Base opaque-surface cooling factors of doors	$OF_{b,doors}$	Table 7 of ASHRAE Fundamentals Handbook (2021a, p. 17.8) gives $OF_b=8.2$ for doors with solar exposure	8.2	Unitless
Temperature opaque-surface cooling factors of doors	$OF_{t,doors}$	Table 7 of ASHRAE Fundamentals Handbook (2021a, p. 17.8) gives $OF_t=1$ for doors with solar exposure	1	Unitless
U-value of doors	$U_{doors}$	See Table 15 and equation (6).	2.50	W/(m <sup>2</sup> K)
Daily range opaque-surface cooling factors of exposed walls	$OF_{r,walls2}$	Table 7 of ASHRAE Fundamentals Handbook (2021a, p. 17.8) gives $OF_r=-0.36$ for walls with solar exposure	-0.36	Unitless
Base opaque-surface cooling factors of exposed walls	$OF_{b,walls2}$	Table 7 of ASHRAE Fundamentals Handbook (2021a, p. 17.8) gives $OF_b=8.2$ for walls with solar exposure	8.2	Unitless
Temperature opaque-surface cooling factors of exposed walls	$OF_{t,walls2}$	Table 7 of ASHRAE Fundamentals Handbook (2021a, p. 17.8) gives $OF_t=1$ for walls with solar exposure	1	Unitless
Daily range opaque-surface cooling factors of shaded walls	$OF_{r,walls1}$	Table 7 of ASHRAE Fundamentals Handbook (2021a, p. 17.8) gives $OF_r=-0.36$ for shaded walls	-0.36	Unitless
Base opaque-surface cooling factors of shaded walls	$OF_{b,walls1}$	Table 7 of ASHRAE Fundamentals Handbook (2021a, p. 17.8) gives $OF_b=0$ for shaded walls	0	Unitless
Temperature opaque-surface cooling factors of shaded walls	$OF_{t,walls1}$	Table 7 of ASHRAE Fundamentals Handbook (2021a, p. 17.8) gives $OF_t=1$ for shaded walls	1	Unitless
U-value of walls	$U_{walls}$	See Table 15 and equation (6)	Varies between buildings	W/(m <sup>2</sup> K)
Daily range opaque-surface cooling factors of roof	$OF_{r,roof}$	Table 7 of ASHRAE Fundamentals Handbook (2021a, p. 17.8) gives $OF_r=-0.36$ for roofs	-0.36	Unitless
Temperature opaque-surface cooling factors of roof	$OF_{t,roof}$	Table 7 of ASHRAE Fundamentals Handbook (2021a, p. 17.8) gives $OF_t=1$ for roofs	1	Unitless
U-value of roof	$U_{roof}$	See Table 15 and equation (6)	2.02	W/(m <sup>2</sup> K)
Area of doors	$A_{stab}$	Calculated from the plans of the case study buildings (Appendix A)	147.5	m <sup>2</sup>

Table 14 (Continued)

Area of doors	$A_{doors}$	Calculated from the plans of the case study buildings (Appendix A)	11.5	m <sup>2</sup>
Area of shaded walls	$A_{shd\ walls}$	Calculated from the plans of the case study buildings (Appendix A)	132.5	m <sup>2</sup>
Area of sun-exposed walls	$A_{sun\ walls}$	Calculated from the plans of the case study buildings (Appendix A)	26.6	m <sup>2</sup>
Roof area	$A_{roof}$	Calculated from the plans of the case study buildings (Appendix A)	246.1	m <sup>2</sup>

Some of the parameters in Table 14 are the U-values of the different building materials. These parameters are, in turn, dependent on the parameters in Table 15, and are calculated using the standard equation:

$$U = \frac{1}{R_{SE} + \sum \frac{d_i}{\lambda_i} + R_{SI}} \quad (6)$$

Where  $R_{SE}$  is the external surface resistance;  $R_{SI}$  is the internal surface resistance; the  $d_i$ 's are the thicknesses of the different layers of the material; and the  $\lambda_i$ 's are the conductivities of the corresponding layers of the material.

Table 15 Parameters for the U-value calculation of the different building materials

Parameter	Symbol	Description of value for the case-study buildings	Value	Units
Internal roof surface resistance	$R_{SI}$	Common values, table 3.1 in Pinteric (2017)	0.17	m <sup>2</sup> K/W
External roof surface resistance	$R_{SE}$	Common values, table 3.1 in Pinteric (2017)	0.04	m <sup>2</sup> K/W
Conductivity of roof, layer 1	$\lambda_{roof1}$	Conductivity of steel metal sheets gathered from Pinteric (2017, p247)	50	W/(mK)
Thickness of roof layer 1	$d_{roof2}$	Thickness of steel metal sheets. Gathered from interviews with Base Bahay (personal communication, June 15, 2023)	0.006	m
Conductivity of roof, layer 2	$\lambda_{roof2}$	Conductivity of thatched roof gathered from CIBSE Guide A- Environmental design (2006, p3-40)	0.07	W/(mK)
Thickness of roof layer 2	$d_{roof2}$	Thickness of thatched roof. Gathered from interviews with building contractors (personal communication, May 3, 2023)	0.02	m
Internal vertical surface resistance	$R_{SI}$	Common values, table 3.1 in Pinteric (2017)	0.13	m <sup>2</sup> K/W
External vertical surface resistance	$R_{SE}$	Common values, table 3.1 in Pinteric (2017)	0.04	m <sup>2</sup> K/W

Table 15 (Continued)

Conductivity of mortar layer (CBSW building)	$\lambda_{mortar}$	Conductivity of mortar, gathered from Pinteric (2017)	0.07	W/(mK)
Thickness of mortar layer (CBSW building)	$d_{mortar1}$	Average thickness of mortar. Gathered from interviews with building contractors (personal communication, May 3, 2023)	0.025	m
Thickness of mortar layer (comparative building)	$d_{mortar2}$	Typical thickness of mortar is 1.5cm; equivalent to 3cm for two layers of mortar. Assumption based on typical CHB buildings	0.03	m
Conductivity of bamboo mats layer (CBSW building)	$\lambda_{bamboo}$	Conductivity of bamboo (Huang & Sun, 2021)	0.15	W/(mK)
Thickness of bamboo mat layer (CBSW building)	$d_{bamboo}$	Average thickness of bamboo. Gathered from interviews with building contractors (personal communication, May 3, 2023)	0.01	m
Conductivity of bamboo mats layer (CBSW building)	$\lambda_{bamboo}$	Conductivity of bamboo (Huang & Sun, 2021)	0.15	W/(mK)
Thickness of bamboo mat layer (CBSW building)	$d_{bamboo}$	Average thickness of bamboo. Gathered from interviews with building contractors (personal communication, May 3, 2023)	0.01	m
Conductivity of CHB (comparative building)	$\lambda_{mortar}$	Conductivity of concrete without gravel, gathered from Pinteric (2017)	0.07	W/(mK)
Thickness of CHB (comparative building)	$d_{mortar}$	Typical thickness of each wall of the block is 1.5cm; equivalent to 3cm for two layers. Assumption based on typical CHB buildings in the Philippines.	0.03	m

Additionally, there is one parameter that depends on the way in which the building is used. This is the number of occupants of the building ( $N_{OC}$ ) whose value was estimated based on an interview with the building operator (Kanya Kawayan, personal communication, April 1<sup>st</sup>, 2023). Finally, and as mentioned before, the indoor set-point temperature ( $T_{set}$ ) is another parameter that determines the cooling load calculation. The value of  $T_{set}$  was determined with  $T_C$ , the adaptive comfort temperature of the case study buildings, whose calculation was outlined in Section 4.3.

#### Calculation of cooling load with the LF method

The LF method was used to calculate the cooling load ( $q_t$ ) for each 10-minute interval bin, following the method's equations which yield  $q_t$  as a hand-traceable function of the parameters that were presented in the previous tables. Table 16 below shows how  $q_t$  is calculated. The table presents a new variable in each row, and how this variable depends on variables in the following rows, until all of the variables are shown to be straightforward function of the parameters.

Table 16 Equations for the calculation of cooling loads based on the LF method.

Eq. no.	Variable that is calculated by the equation and its units	Equation	How each term is defined and calculated	The variable enables calculating:
(7)	Cooling load ( $q_t$ ), W	$q_t = q_s + q_l$	$q_s$ is defined in eq. (8) $q_l$ is defined in eq.(9)	
(8)	Sensible cooling load ( $q_s$ ), W	$q_s = q_{opq} + q_{fen} + q_{vi} + q_{ig,s}$	$q_{opq}$ is defined in eq. (10) $q_{fen}$ is defined in eq. (11) $q_{vi}$ is defined in eq. (12) $q_{ig,s}$ is defined in eq. (13)	Cooling load ( $q_t$ )
(9)	Latent cooling load ( $q_l$ ), W	$q_l = q_{iv,l} + q_{ig,l}$	$q_{iv,l}$ is defined in eq. (14) $q_{ig,l}$ is defined in eq. (15)	
(10)	Exterior opaque surfaces cooling load ( $q_{opq}$ ), W	$q_{opq} = \sum_{i=r}^{sun\ walls, shd\ walls, doors, slab} A_i \times CF_i$	$A_i$ 's are parameters in Table 14 $CF_{roof}$ is defined in eq. (16) $CF_{sun\ walls}$ is defined in eq. (17) $CF_{shd\ walls}$ is defined in eq. (18) $CF_{doors}$ is defined in eq. (19) $CF_{slab}$ is defined in eq. (20)	Sensible cooling load ( $q_s$ )
(11)	Exterior transparent surfaces cooling load ( $q_{fen}$ ), W	$q_{fen} = A_{fen} \times CF_{fen}$	$A_{fen}$ is a parameter in Table 14 $CF_{fen}$ is defined in eq. (21)	
(12)	Ventilation/ infiltration cooling load ( $q_{vi}$ ), W	$q_{vi} = C_i Q_{vi} \Delta t$	$C_i$ is a parameter in Table 12 $\Delta t$ is defined in eq. (22) $Q_{vi}$ is defined in eq. (23) $\Delta t$ is a parameter in Table 12	
(13)	Occupants and appliances sensible cooling load ( $q_{ig,s}$ ), W	$q_{ig,s} = 136 + 2.2A_{cf} + 22N_{OC}$	$A_{cf}$ is a parameter in Table 14 $N_{OC}$ is the number of occupants in the building.	
(14)	Ventilation /infiltration latent cooling load ( $q_{iv,l}$ ), W	$q_{iv,l} = C_i (Q_{vi} + Q_{bal,oth}) \Delta W$	$C_i$ is a parameter in Table 12 $Q_{vi}$ is defined in eq. (23) $Q_{bal,oth}$ is a parameter in Table 13 $\Delta W$ is a parameter in Table 12	Latent cooling load ( $q_l$ )
(15)	Internal latent gain ( $q_{ig,l}$ ), W	$q_{ig,l} = 20 + 0.22A_{cf} + 22N_{OC}$	$A_{cf}$ is a parameter in Table 14 $N_{OC}$ is the number of occupants in the building.	
(16)	Cooling factor of roof ( $CF_{roof}$ ), W/m <sup>2</sup>	$CF_{roof} = \frac{U_{roof} (OF_{r,roof} \Delta t + OF_{b,roof} + OF_{r,roof} DR)}{DR}$	$U_{roof}$ is a parameter in Table 14 $OF_i$ 's are parameters in Table 14 $\Delta t$ is a parameter in Table 12 $DR$ is a parameter in Table 12	Exterior opaque surfaces cooling load ( $q_{opq}$ )
(17)	Cooling factor of sun-exposed walls ( $CF_{sun\ walls}$ ), W/m <sup>2</sup>	$CF_{sun\ walls} = \frac{U_{walls} (OF_{walls1} \Delta t + OF_{b,walls1} + OF_{walls1} DR)}{DR}$	$U_{walls}$ is a parameter in Table 14 $OF_i$ 's are parameters in Table 14 $\Delta t$ is a parameter in Table 12 $DR$ is a parameter in Table 12	
(18)	Cooling factor of shaded walls ( $CF_{shd\ walls}$ ), W/m <sup>2</sup>	$CF_{shd\ walls} = \frac{U_{walls} (OF_{walls2} \Delta t + OF_{b,walls2} + OF_{walls2} DR)}{DR}$	$U_{walls}$ is a parameter in Table 14 $OF_i$ 's are parameters in Table 14 $\Delta t$ is a parameter in Table 12 $DR$ is a parameter in Table 12	

Table 16 (Continued)

(19)	Cooling factor of doors ( $CF_{abd, walls}$ ), $W/m^2$	$CF_{doors} = U_{doors} (OF_{t, doors} \Delta t + OF_{b, doors} + OF_{r, doors} DR)$	$U_{doors}$ is a parameter in Table 14 $OF_i$ 's are parameters in Table 14 $\Delta t$ is a parameter in Table 12 $DR$ is a parameter in Table 12	
(20)	Cooling factor of slab ( $CF_{slab}$ ), $W/m^2$	$CF_{slab} = 1.9 - 1.4 h_{srf}$	$h_{srf}$ is defined in eq. (24)	
(21)	Cooling factor of windows ( $CF_{fen}$ ), $W/m^2$	$CF_{fen} = U(\Delta t - 0.46DR) + PXI \times SHGC \times IAC \times FF_s$	$U_{win}$ is a parameter in Table 14 $\Delta t$ is a parameter in Table 12 $DR$ is a parameter in Table 12 $PXI$ is defined in eq. (25) $SHGC$ is a parameter in Table 14 $IAC$ is a parameter in Table 14 $FF_s$ is a parameter in Table 14	Exterior transparent surfaces cooling load ( $q_{fen}$ )
(22)	Cooling design temperature difference ( $\Delta t$ ), K	$\Delta t = 0$ if $T_{set} \geq T_{out}$ $= T_{out} - T_{set}$ if $T_{set} < T_{out}$	$T_{set}$ is the set-point temperature parameter. $T_{out}$ is a parameter in Table 12	Ventilation/infiltration cooling load ( $q_{vi}$ ); Cooling factors ( $CF_i$ 's); and Infiltration driving force ( $IDF$ );
(23)	Combined ventilation/infiltration ( $Q_{vi}$ ), L/s	$Q_{vi} = A_L IDF$	$A_L$ is defined in eq.(26) $PXI$ is defined in eq. (27)	Ventilation/infiltration cooling load ( $q_{vi}$ ) and Ventilation/infiltration latent cooling load ( $q_{vi,l}$ ),
(24)	Effective surface conductance ( $h_{srf}$ ), $W/(m^2K)$	$h_{srf} = \frac{1}{R_{cvr} + 0.12}$	$R_{cvr}$ is a parameter in Table 14	Cooling factor of slab ( $CF_{slab}$ )
(25)	Peak exterior irradiance, including shading modifications, for shaded windows (PXI), $W/m^2$	$T_x [E_d + (1 - F_{shd}) E_D]$	$T_x$ is a parameter in Table 13 $E_d$ is a parameter in Table 12 $F_{shd}$ is a parameter in Table 14 $E_D$ is a parameter in Table 12	Cooling factor of windows ( $CF_{fen}$ )
(26)	building effective leakage area (including flue) at reference pressure difference = 4 Pa, (assuming discharge coefficient CD = 1, $cm^2$ ), ( $A_L$ ), $cm^2$	$A_L = A_{ES} A_{UL}$	$A_{ES}$ is a parameter in Table 14 $A_{UL}$ is a parameter in Table 13	Combined ventilation/infiltration ( $Q_{vi}$ ) and Infiltration driving force ( $IDF$ )
(27)	Infiltration driving force ( $IDF$ ), $L/(s \cdot cm^2)$	$IDF = \frac{25 + H \Delta t  [0.8 + 0.12 \frac{A_{L, flue}}{A_L}]}{1000}$	$H$ is a parameter in Table 14 $\Delta t$ is a parameter in Table 12 $A_{L, flue}$ is a parameter in Table 13 $A_L$ is defined in eq. (26)	Combined ventilation/infiltration ( $Q_{vi}$ )

### 4.4.3 Calculation of air conditioning operational energy

The LF method outlined in the previous section yielded, a procedure to calculate  $q_t$  as for each 10-minute bin (*i.e.*, interval), based on the daily range variation  $DR$  and the specific value of  $T_{out}$  in that bin. Since the other parameters can be considered to be fixed for the building, and  $T_{out}$  is known (from subsection 4.4.1) for each 10-minute interval  $i$  during the year, this accounts for having a function  $q_t(T_{out}(i), DR(i))$ , which can be used to calculate the cooling load during each interval  $i$ . Defining the 10-minute intervals during which the building is occupied as “10-minute bins”, the following formula can be used to estimate  $OE_{AC}$  for any given year:

$$OE_{AC,year\ X} = \sum_{i \in \{10\text{-min. bin in year } X\}} q_t(T_{out}(i), DR(i)) \times \frac{1}{6} \text{h} \times COP \quad (28)$$

Where  $COP$  is the coefficient of performance of the AC unit installed in the building. The  $\frac{1}{6}$  h term converts the cooling load (which is a rate of heat removal) into a cooling output (which is an amount of heat removed during the 10-minute bin).  $COP$  is an efficiency rating of the AC unit, defined as the ratio of the cooling output and the electrical energy input. Now,  $COP$  is not a fixed rate, but it depends on the specific environmental conditions like  $T_{out}$  and  $RH$ . Ideally, the  $COP$  values of the AC unit should be known to calculate the precise  $OE_{AC}$ . But even if these values were at hand for a given AC unit, the uncertainty would remain of whether that actual technology would be implemented in the case study buildings. Thus, using  $COP$  to estimate  $OE_{AC}$  would require a very specific set of assumptions regarding the AC unit. In contrast, another indicator that assesses AC energy performance, the Cooling Seasonal Performance Factor ( $CSPF$ ) allows a calculation based on a simpler assumption.  $CSPF$  measures the efficiency of a cooling equipment taking into account changes in operating conditions, and thus allows simplifying equation (28) to:

$$OE_{AC,year\ X} = CSPF \sum_{i \in \{10\text{ min. bin in year } X\}} q_t(T_{out}(i), DR(i)) \times \frac{1}{6} \text{h} \quad (29)$$

This rewriting of the equation is possible because, in contrast to  $COP$ ,  $CSPF$  is not a function of  $T_{out}$ .  $CSPF$  has been recommended as a cooling efficiency metric for the context of South East Asia (IEA, 2019). In the Philippines the International Energy Agency (IEA) has assessed that the maximum  $CSPF$  that be achieved with an AC unit below the average price is  $4.0 \text{ W}_{cooling}/\text{W}_{electricity}$  (2019). Based on this fact, the present study assumed that an AC unit with a  $CSPF$  value of  $4.0 \text{ W}_{cooling}/\text{W}_{electricity}$  would be used in the case study buildings. Consequently, the calculation of  $OE_{AC}$  was set out with the formula:

$$OE_{AC,year\ X} = \frac{2}{3} \frac{\text{h} \cdot \text{W}_{cooling}}{\text{W}_{electricity}} \sum_{i \in \{10\text{ min. bin in year } X\}} q_t(T_{out}(i), DR(i)) \quad (30)$$

Section 4.4.1 outlined how the  $T_{out}$  time series values were estimated for years 2030, 2040 and 2050 in each selected RCP scenario. Thus, the formula in equation (30) allowed calculating  $OE_{AC, 2020}$ ,  $OE_{AC, 2030}$ ,  $OE_{AC, 2040}$  and  $OE_{AC, 2050}$  for each RCP scenario.

## 4.5 Cradle-to-use assessment

This section presents the methods with which the cradle-to-use environmental impacts of the buildings were modelled and measured to answer RQII regarding the life cycle impacts of bamboo- versus widespread-building-technologies:

- *RQIV. How do the impacts of bamboo buildings change when potential energy needs to meet thermal comfort are also considered, and how do they compare to those of widespread building technologies?*

Again following the rationale presented in Section 4.1, the environmental performance of the building technology was approached by studying the environmental impacts of the case study building. But here the focus was on the use-stage, and consequently the approach is to extend the LCA presented in Section 4.2 to include the use-stage of the building. To avoid unnecessary repetitions with Section 4.2, the following subsections will cover mostly the LCA steps that differ from the cradle-to-gate assessment. And, as before, the final steps, relating to results and interpretation, are not presented in this chapter but in their corresponding sections of chapters 5 and 6.

### 4.5.1 Goal and scope definition

The goal of the LCA was to answer RQIV in terms of the case study buildings: “How do the life cradle-to-use impacts (including potential energy needs to meet thermal comfort) of the Kanya Kawayan Weaving Centre compare to those of the equivalent concrete and steel building?” Underlying in this goal was also the indirect goal of allowing prospective comparisons of the environmental impacts of the CBSW technology. The audience of the assessment are technology developers at Base-Bahay foundation, and the research community interested in mitigating environmental impacts of building technologies in this context. As Base-Bahay foundation intends to share the results of this assessment for innovation purposes, the stakeholders engaged with Base-Bahay Foundation were also an indirect audience of this LCA.

#### Functional Unit

The functional unit was set to be a year of service of built (and thermally comfortable) square metre of the case study buildings. The criterion to determine thermal comfort was set to be a minimum *POR* value (as defined in subsection 4.3.4) of less than 20%. In accordance with the main goal of the LCA, this functional unit allowed assessing the environmental impacts of the two compared technologies, now including the comfort requirement in each version of the technology. And, also in accordance with the indirect goal of the LCA, the selected f.u. also allows future comparison with CBSW buildings meeting the thermal comfort functional requirement.

#### System Boundaries

Following the EN 15978 (2011a) nomenclature shown again in Figure 22, the cradle-to-use LCA included the stages:

- A1-A5: as in the cradle-to-gate LCA.
- B6: Operational energy use.

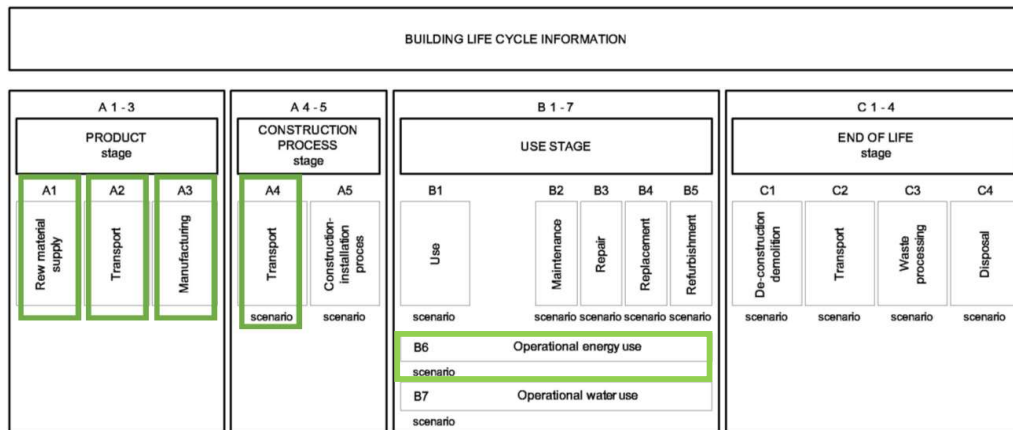


Figure 22 Life cycle phases according to EN 15978: stages within the scope of the cradle-to-use LCA are highlighted in green. Adapted from EN 15978 (2011a).

Stages B1-B5 and B7, were excluded from the assessment, following the delimitations set in Section 1.2.

The functional unit of this LCA required the comfort criteria defined in Section 4.3 to be met by the case study buildings. To ensure this, it was assumed that if the buildings failed to meet this criterion in NV mode, they would have compensated this shortcoming by implementing an AC unit whose efficiency, in accordance with the feasibility for this issue outlined in subsection 4.4.3, would meet a *CSPF* value of 4.0.

The system boundaries of for the A-module of the buildings, as well as the LCA type and allocation approach, were set in the same way as in the cradle-to-gate LCA. In particular, the cradle-to-gate stages of the AC unit itself, as well as possible minor adaptations of the buildings for cooling were not included in the system boundaries. This was justified by the same criteria outlined before of not including building systems that would be the same for both of the compared building technologies.

The temporal boundaries were extended from the cradle-to-gate LCA assuming a 30-year service life for both of the buildings. Such assumption was necessary to compensate for the prospective service-life uncertainty; but was justified to be a feasible time period based on interviews with Base Bahay foundation regarding the durability of the building systems; and with the building owner, regarding the likely maximum use period for the building.

#### 4.5.2 Life Cycle Inventory (use-stage)

The first step to build the LCI model for the B6-module of the building was to estimate the operational energy needs for the case study buildings. For the NV mode scenario, *OE* was calculated from data gathered on-site for the lighting and fans in the building, their operation hours and power consumption. For the AC mode scenario, to estimate the value of  $OE_{AC, year X}$  for the in-between years ( $X = 2023, 2024, \text{etc.}$ ) in the service life of the building, the values of  $OE_{AC}$  were linearly extrapolated based the values of  $OE_{AC, 2020}$ ,  $OE_{AC, 2030}$ ,  $OE_{AC, 2040}$  and  $OE_{AC, 2050}$  whose calculation was described in subsection 4.4.3.

After calculating *OE* needs for the 2023 to 2053 period, the second step was to convert this electrical energy flow into LCI data. This was done with the help of OpenLCA software by linking the *OE* values to the Ecoinvent dataset for the electricity in the Philippines. Implicit in this modelling approach, was the assumption that the carbon intensity of the electricity mix in the Philippines would not have a major change in the coming 30 years.

## 5 Results

This chapter presents the analysed data that results from applying the methods above to the case study buildings. The implications of these findings towards answering the research questions are highlighted. Sections 5.1 through 5.4 present the results yielded by the corresponding sections in Chapter 4 (Sections 4.2 through 4.5).

### 5.1 Cradle-to-gate assessment

Table 17 and Figure 23 show the results of the cradle-to-gate LCIA, comparing the case-study bamboo and comparative buildings and grouping impacts by life-cycle stage. The bamboo building allows mitigating, 271.3 kgCO<sub>2</sub>eq/m<sup>2</sup> of GWP(100a) impacts by replacing a concrete and steel building. That is, the bamboo building entails a 67.7% GWP impacts reduction when compared to the impacts of the equivalent concrete and steel building.

Table 17 LCIA results of the bamboo building and the concrete and steel building, each partitioned into life cycle stages A1-A3 and A4. The mitigation potential refers to the GWP impacts that would be reduced by implementing one technology against the other.

	A1-A3 GWP (100a) [kgCO <sub>2</sub> eq/m <sup>2</sup> ]	A4 GWP (100a) [kgCO <sub>2</sub> eq/m <sup>2</sup> ]	A1-A4 GWP (100a) [kgCO <sub>2</sub> eq/m <sup>2</sup> ]	Mitigation Potential GWP (100a) [kgCO <sub>2</sub> eq/m <sup>2</sup> ]
Bamboo building	123.5 (31%)	5.7 (1%)	<b>129.1</b> (32%)	271.3 (68%)
Concrete & steel building	383.4 (96%)	16.9 (4%)	<b>400.4</b> (100%)	–

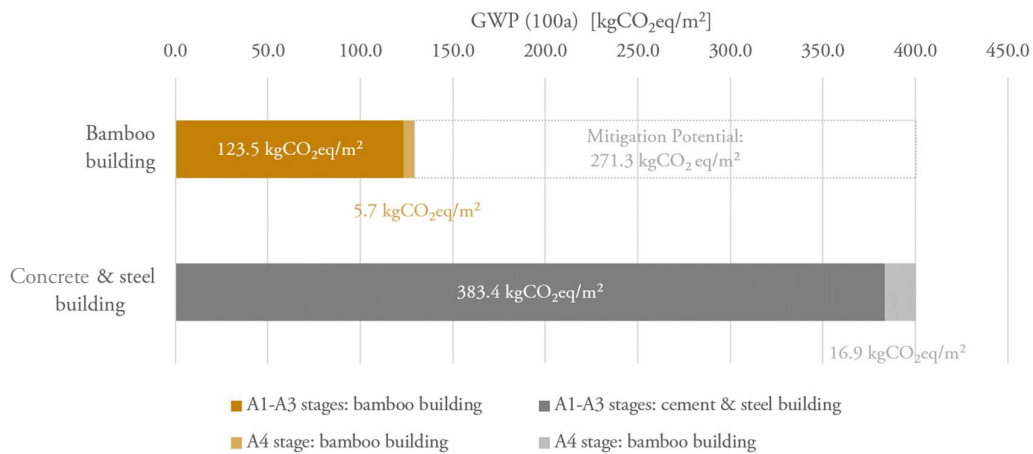


Figure 23 LCIA results of the bamboo building and the concrete and steel building, each partitioned into life cycle stages A1-A3 and A4. The mitigation potential refers to the GWP impacts that would be reduced by implementing one technology against the other.

It must be highlighted, however, that these are the impacts of the diverging building components across the two building and in this assessment the impacts of the common building components are unknown. Table 17 and Figure 23 also show that, for both building technologies, transportation from material production-site to construction site (module A4) bears a minor share of the impacts when compared to the embodied emissions of the building materials from extraction and production (modules A1-A3)

Figure 24 shows the LCIA results with a different partition: classifying the impacts of each building according to the building systems. Even though the foundations of the bamboo building are also made with reinforced concrete, the load they bear is lower and therefore require less materials and have less GWP impacts. This partition of the impacts also illustrates that the biggest impact mitigation across building systems comes at the truss & purlin system, as those of the bamboo building emit 25.9 kg CO<sub>2</sub>eq/m<sup>2</sup>; which is 144.5 kg CO<sub>2</sub>eq/m<sup>2</sup> less than the 170.4 kg CO<sub>2</sub>eq/m<sup>2</sup> of the metallic trusses and purlins of the concrete and steel building. This mitigation is even bigger considering that the trusses in the bamboo building not only provide the roof structure, but most the horizontal load structure for the north-south direction of the building; whereas in the comparative building these loads are also taken by the concrete frame structure below the trusses (compare Figure 11 and Figure 14 in Section 4.1) .

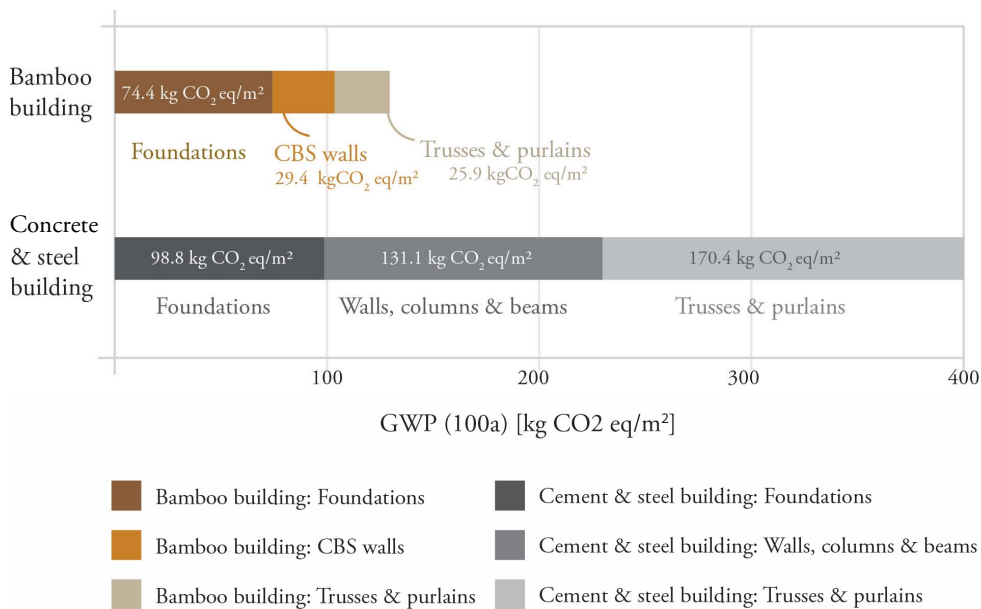


Figure 24 LCIA results of the bamboo building and the concrete and steel building, partitioned into building systems.

Finally, Figure 25 shows the LCIA results partitioning impacts into the different building components. The bamboo production in the case study building emits only 17.4 kg CO<sub>2</sub>eq/m<sup>2</sup>, which is 13.5% of the GWP impacts of all the assessed components in the bamboo building and 4.3% of the GWP impacts of all the assessed components in the concrete and steel building.

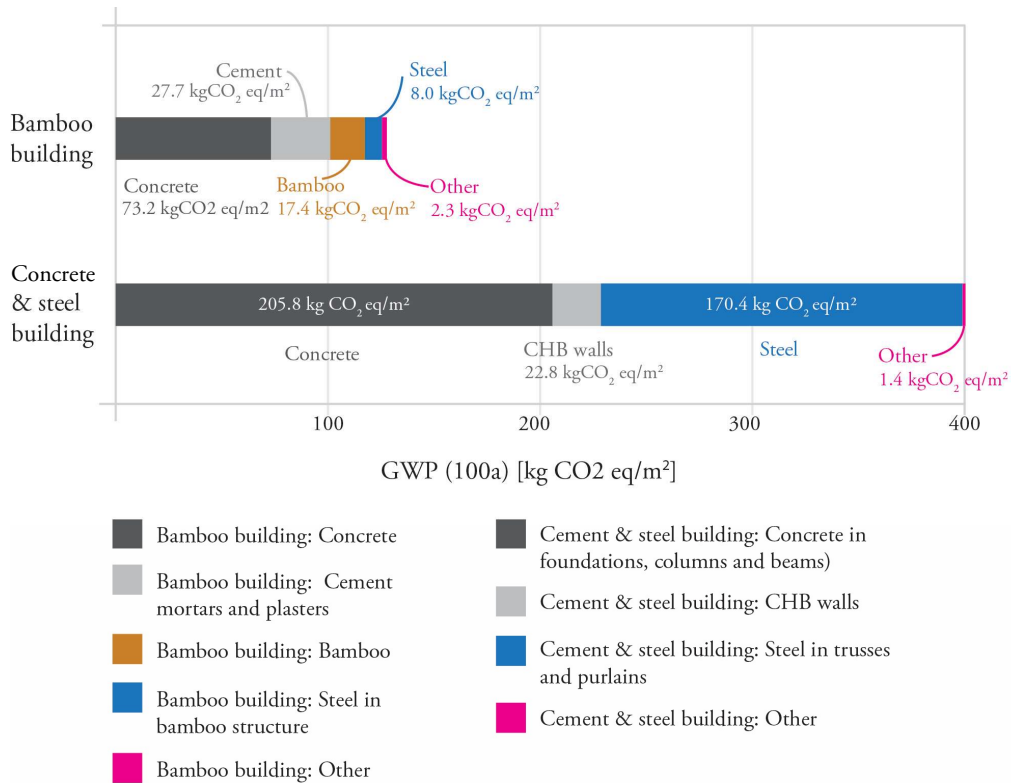


Figure 25 LCIA results of the bamboo building and the concrete and steel building, partitioned into building materials.

## 5.2 Thermal comfort assessment

Following the method presented in the Section 4.3, this section presents the results of the thermal comfort assessment of the built bamboo case-study building. Figure 26 shows the scatter of the comfort votes measured against the indoor operative temperature during the assessed period. Following the adaptive thermal comfort statistical inference methods described in the methodology, the relationship that links TCV and T<sub>OP</sub> is modelled with a linear regression as:

$$TCV = -5.775 + 0.200 T_{OP}$$

From the equation of the regression line, the comfort temperature for the building is estimated by setting TCV=0 (the neutral or comfortable vote) and solving for T<sub>OP</sub>:

$$T_C = (0 + 5.775) / 0.200 = 28.00 \text{ } ^\circ\text{C}$$

It ought to be clarified that this comfort temperature is specific to the case-study building and the ways in which its users inhabit it: including all possible adaptations that are not fully deciphered by the adaptive model of thermal comfort. Furthermore, this comfort temperature is specific to the period during which the interviews were carried out (March 24<sup>th</sup> of 2023 to July 22<sup>nd</sup> of 2023).

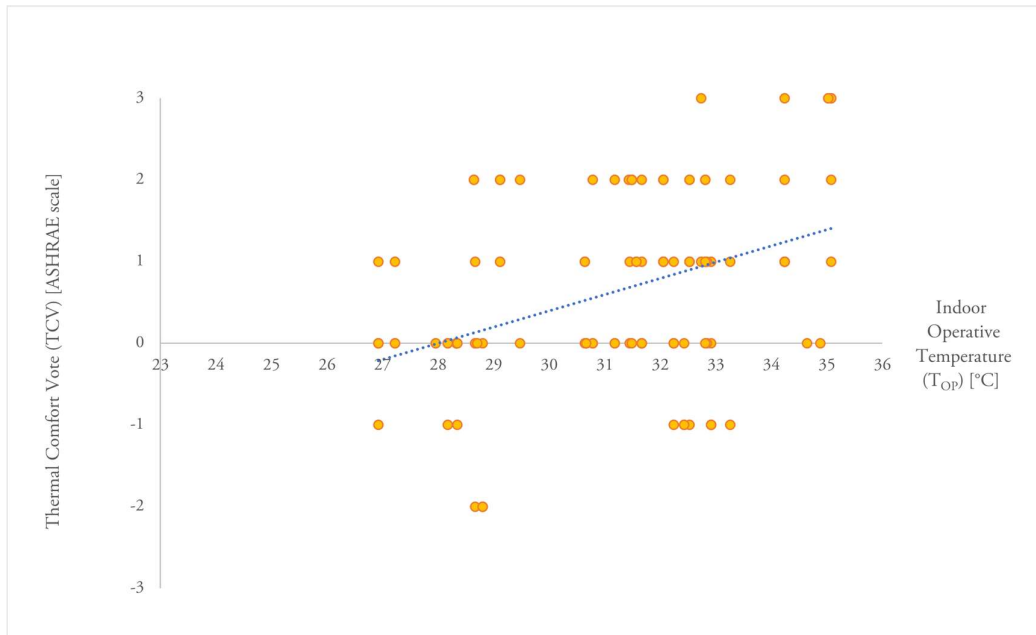


Figure 26 Scatter of thermal comfort vote and indoor operative temperature with linear regression for TCV on  $T_{OP}$  included.

Comparing the comfort temperature calculated above to the gathered data for  $T_{OP}$  during the occupied hours, the occupied hours within the comfort range [ $T_C - 3.50^\circ\text{C}$ ,  $T_C + 3.50^\circ\text{C}$ ] = [ $24.5^\circ\text{C}$ ,  $31.5^\circ\text{C}$ ] can be computed:

Hours with  $T_{OP}$  inside comfort range: 419h

Hours with  $T_{OP}$  outside comfort range: 161h

The percentage of occupied hours outside of comfort range ( $POR$ ) is therefore:

$$\begin{aligned}
 POR \text{ (Bamboo Building)} &= 100\% \times \frac{\text{Hours with } T_{OP} \text{ outside comfort range}}{\text{Occupied hours}} \\
 &= 100\% \times \frac{161 \text{ h}}{161 \text{ h} + 420 \text{ h}} \\
 &= 27.8\%
 \end{aligned}$$

Thus, the assessment with the  $POR$  indicator yields that the building is failing to protect its users during a significant amount of operation time.

Contrasting the results of the  $POR$  indicator results, field observations during the interviews and data-gathering period, showed that during all of the operation hours of the building, its users did not open all of the available windows in the building. This situation is captured in the daytime picture in Figure 9. Upon inquiry with the building users, they explained their behaviour by expressing the inconvenience of having to open all the numerous (fragmented) windows in the building. The interviews metadata also showed that some of the fans in the building had malfunctions that might have affected some of the thermal comfort votes.

### 5.3 Building energy assessment

This section shows the results of the building energy assessment of the case study buildings, based on the methods and assumptions outlined in the corresponding section in Chapter 4.

#### 5.3.1 Cooling load function with the LF method

Based on the fixed parameters in subsection 4.4.2, the cooling load function  $q_c(T_{out}, DR)$  estimates the cooling load of each case study building. Table 18 and Table 19 give the values of this functions for the bamboo building and the concrete and steel building. As would be expected, the bigger  $T_{out}$  or  $DR$ , the bigger  $q_c$ . For reasons that will be discussed in Section 6.3, the cooling loads are only slightly lower for the concrete and steel building.

Table 18 Total cooling load,  $q_c$  [W] of the bamboo building for different outdoor temperatures ( $T_{out}$ ) and daily range variations (DR). Colour scale described below the table. Values of  $T_{out}$  in the forecasts have a maximum value of 38.4°C and DR forecasts vary between 2.2°C and 11.4°C.

Outdoor Temperature ( $T_{out}$ ) [°C]	$(\Delta t)$ [°C]	Cooling Daily Range (DR) [°C]										
		2	3	4	5	6	7	8	9	10	11	12
28.8	1	10,473	10,024	9,575	9,126	8,677	8,228	7,779	7,329	6,880	6,431	5,982
29.8	2	11,830	11,381	10,932	10,483	10,034	9,585	9,136	8,687	8,238	7,789	7,339
30.8	3	13,197	12,748	12,299	11,850	11,401	10,951	10,502	10,053	9,604	9,155	8,706
31.8	4	14,573	14,124	13,675	13,226	12,777	12,328	11,879	11,430	10,981	10,532	10,082
32.8	5	15,959	15,510	15,061	14,612	14,163	13,714	13,265	12,815	12,366	11,917	11,468
33.8	6	17,354	16,905	16,456	16,007	15,558	15,109	14,660	14,211	13,762	13,313	12,864
34.8	7	18,759	18,310	17,861	17,412	16,963	16,514	16,065	15,616	15,167	14,718	14,269
35.8	8	20,174	19,725	19,276	18,826	18,377	17,928	17,479	17,030	16,581	16,132	15,683
36.8	9	21,598	21,149	20,700	20,250	19,801	19,352	18,903	18,454	18,005	17,556	17,107
37.8	10	23,031	22,582	22,133	21,684	21,235	20,786	20,337	19,888	19,439	18,990	18,541
38.8	11	24,474	24,025	23,576	23,127	22,678	22,229	21,780	21,331	20,882	20,433	19,984

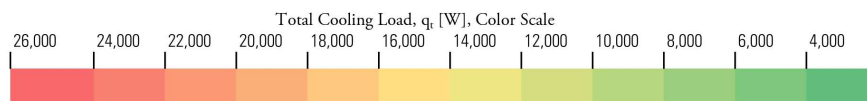
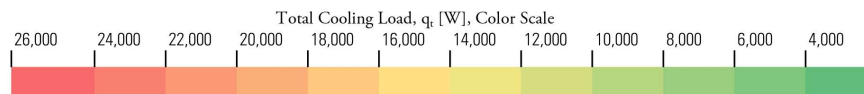


Table 19 Total cooling load,  $q_t$  [W] of the concrete and steel building for different outdoor temperatures ( $T_{out}$ ) and daily range variations (DR). Colour scale described below the table. Values of  $T_{out}$  in the forecasts have a maximum value of 38.4°C and DR forecasts vary between 2.2°C and 11.4°C.

Outdoor Temperature ( $T_{out}$ ) [°C]	Cooling Daily Range (DR) [°C]	Cooling Daily Range (DR) [°C]										
		2	3	4	5	6	7	8	9	10	11	12
28.8	1	9,821	9,405	8,989	8,573	8,157	7,741	7,325	6,909	6,493	6,077	5,661
29.8	2	11,079	10,663	10,246	9,830	9,414	8,998	8,582	8,166	7,750	7,334	6,918
30.8	3	12,345	11,929	11,513	11,097	10,681	10,265	9,849	9,432	9,016	8,600	8,184
31.8	4	13,620	13,204	12,788	12,372	11,956	11,540	11,124	10,708	10,292	9,875	9,459
32.8	5	14,904	14,488	14,072	13,656	13,240	12,824	12,408	11,992	11,576	11,159	10,743
33.8	6	16,197	15,781	15,365	14,949	14,533	14,116	13,700	13,284	12,868	12,452	12,036
34.8	7	17,498	17,082	16,666	16,250	15,834	15,418	15,002	14,586	14,170	13,754	13,338
35.8	8	18,809	18,393	17,977	17,561	17,145	16,729	16,313	15,897	15,480	15,064	14,648
36.8	9	20,128	19,712	19,296	18,880	18,464	18,048	17,632	17,216	16,800	16,384	15,968
37.8	10	21,456	21,040	20,624	20,208	19,792	19,376	18,960	18,544	18,128	17,712	17,296
38.8	11	22,793	22,377	21,961	21,545	21,129	20,713	20,297	19,881	19,465	19,049	18,633



Because the LF method finds the total cooling load as the sum of different cooling loads, the calculation of the values of  $q_t$  included the calculation of the partial loads conveying the different pathways of heat gain in the building. The size and share of each of these loads in the total load when  $T_{out} = 29.8^\circ\text{C}$  (*i.e.*,  $\Delta t = 1^\circ\text{C}$ ) and  $DR = 7^\circ\text{C}$  for the bamboo case study building is shown in Table 20, Table 21 and Table 22. Table 20 partitions the loads into sensible and latent loads; showing that the sensible cooling load is dominating the cooling needs. Table 21 further partitions the loads including all of the components of both the sensible and latent loads, and thus showing that the opaque surfaces cooling loads holds the biggest share of the load (72.8%). To better understand, in turn, what dominates the opaque surfaces load, Table 22 partitions it into the cooling loads of floors, shaded and exposed walls, roofs and slab. This last partition shows that the roof has a major effect on the cooling needs of the building, as the roof cooling load accounts for 52.6% of the cooling load. And that, according to the LF model, the slab is significantly helping to cool down the building, as it yields a negative cooling load of 1,441 W.

Table 20 Partion of cooling load ( $q_t$ ) into sensible cooling load ( $q_s$ ) and latent cooling load ( $q_l$ ) for the bamboo case study building with  $\Delta t=1^\circ\text{C}$  and  $DR=7^\circ\text{C}$ .

Description of cooling load	Formula	Load (W)	Share of total load
Total Cooling Load ( $q_t$ )	$q_s + q_l$	8,228	100.00%
Sensible cooling Load ( $q_s$ )	$q_{\text{opq}} + q_{\text{fen}} + q_s + q_{\text{ig},s}$	7,024	85.37%
Latent cooling Load ( $q_l$ )	$q_{\text{vi},l} + q_{\text{ig},l}$	1,204	14.63%

Table 21 Partion of cooling load ( $q_t$ ) into the partial loads that constitute the sensible cooling load ( $q_s$ ) and latent cooling load ( $q_l$ ) for the bamboo case study building with  $\Delta t=1^\circ\text{C}$  and  $DR=7^\circ\text{C}$ .

Description of cooling load	Formula	Load (W)	Share of total load
Total Cooling Load ( $q_t$ )	$q_s + q_l$	8,228	100.0%
Exterior opaque surfaces cooling load ( $q_{\text{opq}}$ )	$\Sigma[A \times CF]$	5,987	72.8%
Exterior transparent surfaces cooling load ( $q_{\text{fen}}$ )	$A \times CF_{\text{fen}}$	321	3.9%
Ventilation/infiltration cooling load ( $q_{\text{vi}}$ )	$C_s Q_{\text{vi}} \Delta t$	80	1.0%
Occupants and appliances sensible cooling load ( $q_{\text{ig},s}$ )	$136 + 2.2A_{\text{cf}} + 22N_{\text{OC}}$	637	7.7%
Ventilation/infiltration latent cooling load ( $q_{\text{vi},l}$ )	$C_l(Q_{\text{vi}} + Q_{\text{bal,oth}}) \Delta W$	975	11.9%
Internal lateng gain ( $q_{\text{ig},l}$ )	$20 + 0.22A_{\text{cf}} + 22N_{\text{OC}}$	228	2.8%

Table 22 Partion of cooling load ( $q_t$ ) into the partial loads that constitute the opaque surfaces cooling load ( $q_{\text{opq}}$ ) and latent cooling load ( $q_l$ ) for the bamboo case study building with  $\Delta t=1^\circ\text{C}$  and  $DR=7^\circ\text{C}$ .

Description of cooling load	Formula	Load (W)	Share of total load
Total Cooling Load ( $q_t$ )	$q_s + q_l$	8,228	100.0%
Roof cooling load	$A_{\text{roof}} \times CF_{\text{roof}}$	4,326	52.6%
Sun-exposed cooling load	$A_{\text{sun walls}} \times CF_{\text{sun walls}}$	-139	-1.7%
Shaded walls cooling load	$A_{\text{shd walls}} \times CF_{\text{shd walls}}$	3,050	37.1%
Doors cooling load	$A_{\text{doors}} \times CF_{\text{doors}}$	192	2.3%
Slab cooling load	$A_{\text{slab}} \times CF_{\text{slab}}$	-1,441	-17.5%
Exterior transparent surfaces cooling load ( $q_{\text{fen}}$ )	$A_{\text{fen}} \times CF_{\text{fen}}$	321	3.9%
Ventilation/infiltration cooling load ( $q_{\text{vi}}$ )	$C_s Q_{\text{vi}} \Delta t$	80	1.0%
Occupants and appliances sensible cooling load ( $q_{\text{ig},s}$ )	$136 + 2.2A_{\text{cf}} + 22N_{\text{OC}}$	637	7.7%
Ventilation/infiltration latent cooling load ( $q_{\text{vi},l}$ )	$C_l(Q_{\text{vi}} + Q_{\text{bal,oth}}) \Delta W$	975	11.9%
Internal lateng gain ( $q_{\text{ig},l}$ )	$20 + 0.22A_{\text{cf}} + 22N_{\text{OC}}$	228	2.8%

### 5.3.2 Air conditioning operational energy

Table 23 and Table 24 below show the results of the  $OE_{AC}$  data for the case study bamboo and conventional building respectively. The results show that the  $OE_{AC}$  is just slightly bigger for the bamboo case study building, which corresponds to what was discussed in Section 4.4 due to the limitations of the LF method for cooling load calculations. The trends in Table 23 and Table 24 also show that the  $OE_{AC}$  increases substantially with the warming outdoor temperatures predicted by the RCMs from 2020 through 2030: 17% increase for RCP4.5 and 19% for RCP8.5.

Table 23 Estimation of AC operational energy for the bamboo case study building for different RCPs and different years from 2020 through 2050.

Emissions Pathway	Year	AC Operational Energy (Whole Building) [kWh/yr]	AC Operational Energy [kWh/m <sup>2</sup> *yr]
RCP4.5	2020	5,385	36.2
	2030	5,696	38.3
	2040	6,154	41.4
	2050	6,305	42.4
RCP8.5	2020	5,486	36.9
	2030	5,747	38.6
	2040	6,312	42.4
	2050	6,511	43.8

Table 24 Estimation of AC operational energy for the concrete and steel case study building for different RCPs and different years from 2020 through 2050.

Emissions Pathway	Year	AC Operational Energy (Whole Building) [kWh/yr]	AC Operational Energy [kWh/m <sup>2</sup> *yr]
RCP4.5	2020	5,240	35.2
	2030	5,545	37.3
	2040	5,994	40.3
	2050	6,142	41.3
RCP8.5	2020	5,339	35.9
	2030	5,595	37.6
	2040	6,149	41.3
	2050	6,344	42.6

Finally, the results of the energy assessment including the remaining operational energy demand stemming from illumination and plugin devices is shown in Table 25 and Table 26. Clearly,  $OE$  is dominated by  $OE_{AC}$  regardless of the scenario, and as  $OE_{AC}$  increases the dominance is further accentuated.

Table 25 Estimation of overall operational energy for the bamboo case study building for different RCPs and different years from 2020 through 2050.

Emissions Pathway	Year	AC Operational Energy (Whole Building) [kWh/yr]	AC Operational Energy [kWh/m <sup>2</sup> *yr]	Remaining Operational Energy [kWh/m <sup>2</sup> *yr]
RCP4.5	2020	5,385	36.2	5.6
	2030	5,696	38.3	5.6
	2040	6,154	41.4	5.6
	2050	6,305	42.4	5.6
RCP8.5	2020	5,486	36.9	5.6
	2030	5,747	38.6	5.6
	2040	6,312	42.4	5.6
	2050	6,511	43.8	5.6

Table 26 Estimation of overall operational energy for the concrete and steel case study building for different RCPs and different years from 2020 through 2050.

Emissions Pathway	Year	AC Operational Energy (Whole Building) [kWh/yr]	AC Operational Energy [kWh/m <sup>2</sup> *yr]	Remaining Operational Energy [kWh/m <sup>2</sup> *yr]
RCP4.5	2020	5,240	35.2	5.6
	2030	5,545	37.3	5.6
	2040	5,994	40.3	5.6
	2050	6,142	41.3	5.6
RCP8.5	2020	5,339	35.9	5.6
	2030	5,595	37.6	5.6
	2040	6,149	41.3	5.6
	2050	6,344	42.6	5.6

## 5.4 Cradle-to-use assessment

Following the methodology presented in Section 4.5, the results from the AC operational energy forecasts, LCI results for module B for each RCP scenario, as included in Appendix X. These LCI results allow extending the LCIA results to the use-stage of the life cycle of each of these buildings. Table 27 and Figure 27 show the results of the cradle-to-use LCIA results, comparing the case-study bamboo and comparative buildings and grouping impacts by life-cycle stage. Noteworthy is that, in contrast to the results of Section 5.1, these results are given for the functional unit m<sup>2</sup>yr and are based on the assumption, motivated in subsection 4.5.1, that the building will have a 30-year service life.

Table 27 LCIA results of the bamboo building and the concrete and steel building, each partitioned into life cycle stages A1-A4 and B6. The mitigation potential refers to the GWP impacts that would be reduced by implementing one technology against the other, and it is computed for both the m<sup>2</sup> and m<sup>2</sup>yr functional units.

	A1-A4 GWP (100a) [kgCO <sub>2</sub> eq/m <sup>2</sup> yr]	B6 GWP (100a) [kgCO <sub>2</sub> eq/m <sup>2</sup> yr]	A1-14 & B6 GWP (100a) [kgCO <sub>2</sub> eq/m <sup>2</sup> yr]	Mitigation Potential GWP (100a) [kgCO <sub>2</sub> eq/m <sup>2</sup> yr]	Mitigation Potent GWP (100a) [kgCO <sub>2</sub> eq/m <sup>2</sup> ]
Concrete & steel building	13.3 ( 3% )	24.8 ( 6% )	<b>38.1</b> ( 10% )	7.7 ( 2% )	230.6 ( 58% )
Bamboo building	4.3 ( 1% )	26.2 ( 7% )	<b>30.5</b> ( 8% )		

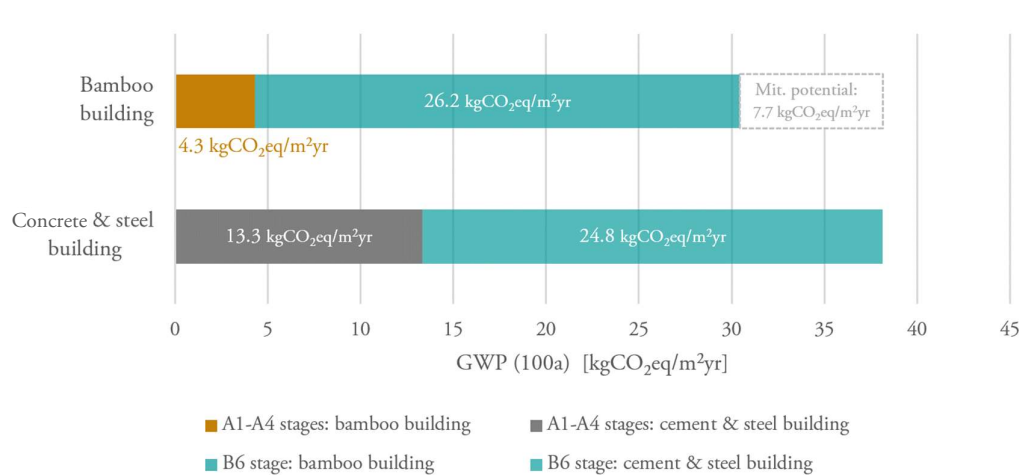


Figure 27 LCIA results of the bamboo building and the concrete and steel building, each partitioned into life cycle stages A1-A4 and B6. The mitigation potential refers to the GWP impacts that would be reduced by implementing one technology against the other. The mitigation potential refers to the GWP impacts that would be reduced by implementing one technology against the other

## 6 Discussion

This chapter discusses how the methodology and results deal with answering the research questions. The four sections deal with the results of the corresponding four research questions for the case study building.

### 6.1 Cradle-to-gate assessment

This section discusses the results of the cradle-to-gate assessment of the case-study buildings, how they were obtained, and the extent to which they manage to answer RQ1.

The LCA study is based on a set of assumptions that are documented in Section 4.2. Thus, the validity of the calculated mitigation potential depends on the likelihood of these assumptions. However, as the share of impacts stemming from some LCI results is much lower, the assumptions that are made to build these inventory items are poised to have much less influence on the aggregated results. For example, the assumptions made about the transportation A4 module are under 5% of the overall impacts for the bamboo and conventional buildings respectively, and thus if the assumptions made regarding transportation technologies and distances fail to be true, this ought not to affect the calculated mitigation potential considerably.

In contrast, assumptions and modelling decisions regarding LCI results that have big share of the total impacts should be more critically discussed. A straightforward hotspot analysis from the LCIA results shows that the material with the biggest embodied impact in the building is cement. Thus, the assumption regarding the type of cement implemented in the concrete and steel building ought to be revised. As documented in Section 4.2, because the case-study building was actually built using CEMII/B-S type cement, it was assumed that the comparative case-study building would also use this cement. To revise the effect of this assumption (and of the decision to use CEMII/B-S in the original bamboo building), a variation analysis is carried out in which the LCI and LCIA results are recalculated considering each building implementing each type of cement. Figure 28 shows the result of this analysis. As would be expected, because CEMII/B-S type cement replaces approximately 30% of its clinker dry mass with blast-furnace slag (CEN, 2011), a by-product of steel production, GWP impacts are increased when CEMI is used instead. What type of cement is used does affect the size of the mitigation potential of replacing the conventional technology with bamboo to 278.4 kgCO<sub>2</sub>eq/m<sup>2</sup>; compared to the 217.3 kgCO<sub>2</sub>eq/m<sup>2</sup> mitigation potential assessed in the first place (Section 5.1). When the CEMII/B-S type is only used in the bamboo building, the mitigation potential rises to 300 kgCO<sub>2</sub>eq/m<sup>2</sup>. This is a rather plausible scenario, as the market of CEMII/B-S in the Philippines is small, seldom used in buildings in the countryside, and it is more likely to be used with a technology that requires considerably lower volumes.

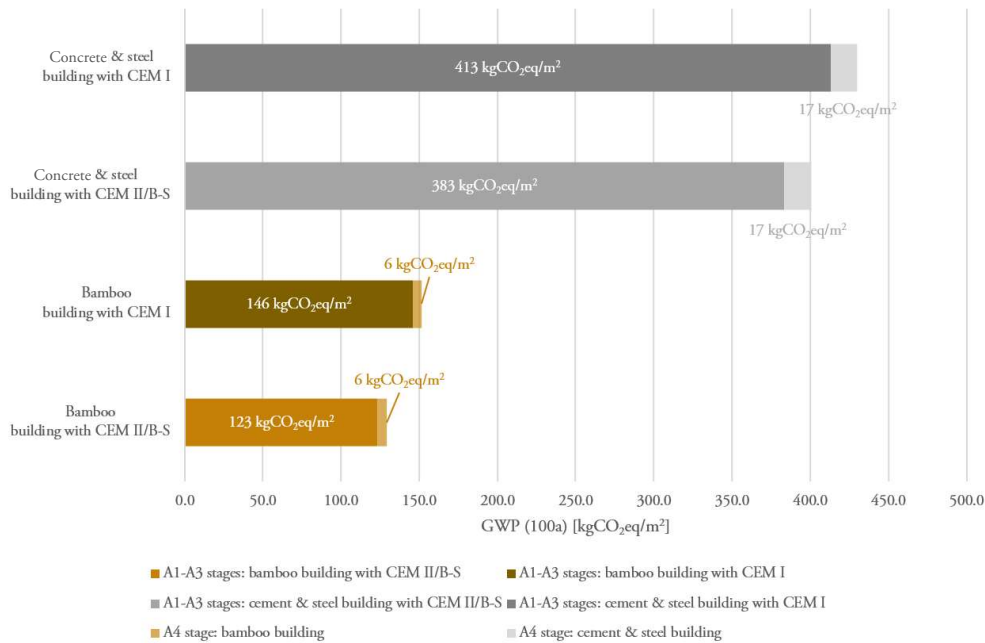


Figure 28 Variation analysis of the cradle-to-gate assessment of the case study buildings, considering both CEM I-type cement and CEM II/B-S cement.

The results of this LCA are based on a static approach to account GWP impacts in a 100-year horizon. Therefore, they fail to capture the potential of biobased materials to delay GHG emissions as they store the harvested biomass along their service life. A simplified approach to account for the potential impact reduction of biogenic CO<sub>2</sub> (GWP<sub>bio</sub>) can be applied without the complications of a more complex dynamic LCIA calculation (Bundi, 2022; W. Liu et al., 2017). With this accounting approach the possible mitigation potential of bamboo building technologies can be calculated to be even bigger.

## 6.2 Thermal comfort assessment

This section discusses the limitations of the results of the thermal comfort assessment of the case-study bamboo building and the extent to which they manage to answer RQII.

The method with which the bamboo building's thermal comfort was assessed has two main limitations. The first one lies in the fact that the building was not studied for a whole year and thus the calculated *POR* indicator only describes the performance during the period between March 24<sup>th</sup> of 2023 and July 22<sup>nd</sup> of 2023. However, the data-gathering period did include both the hot and rainy season that characterize the local climate (Tropical Savanna Climate (Aw) according to the Köppen climate classification). Thus, it is qualitatively likely that the *POR* values for the whole year cycle are similar, but this was not assessed quantitatively in this study. Regardless of this limitation, even if the *POR* values were considerably different for the whole year, those values obtained in the studied period (27.8%) do indicate that there is considerable thermal stress that entails all the risks that were discussed in Section 2.2.

The second possible limitation regarding the applied assessment method is that, even though a dry and a rainy season were assessed, a single comfort temperature was calculated. However, as documented in a comprehensive study from Yao *et al.* reviewing all the existing studies that implement adaptive comfort models (2022), there is no standardization or regularity on the number of comfort temperatures corresponding to different seasons that ought to be assessed. The disadvantage of having a single  $T_C$  in this study is that the resulting *POR* might fail to capture the fact that, as proven by Nicol (2004), elevated relative humidities in tropical hot humid regions tend to require lower adaptive comfort temperatures.

Finally, the matter of how the obtained results allow answering RQII is addressed. The results evidence that the case study building does not deliver thermal comfort, as the obtained 27.8% *POR* value is higher than the established acceptable 20% value. Thus, the study shows that the use of light-weight bamboo structures, in combination with basic climate-adaptation strategies, does not improve thermal comfort performance to an extent that a thermally acceptable environment is guaranteed (i.e. a *POR* value lower than 20% is not reached). These results show that the use of a bamboo system is not improving comfort performance enough to ensure thermal comfort, but this does not discard that this system might be improving comfort performance to some extent. It could be possible that the bamboo structure is partially improving thermal comfort performance (e.g., it could be the case that with a heavier structure and envelope the *POR* value would be even higher than 27.8%). However, verifying this latter possibility falls outside the limitations of the results of this thesis.

## 6.3 Building energy assessment

This section discusses the results of the building energy assessment of the case-study buildings, how they were obtained, and the extent to which they manage to answer RQIII.

As pointed out in sections 3.4 and 4.4., the LF method used in this study is an accessible way to calculate cooling loads that is less precise than more complex (but less accessible) heat-balance models and simulations. In particular, as it is clarified by the ASHRAE Handbook where the method is presented (ASHRAE, 2021a) the method does not consider the effect of heat capacities on moderating and delaying building heat gains. Consequently, the resulting cooling loads and energy calculations in this study are not portraying the possible effect of thermal mass on building energy requirements. It remains uncertain whether accounting for the effects of thermal mass would have increased or decreased the cooling requirements for each building.

### 6.3.1 Cooling loads

The partitioning of cooling loads modelled by the LF method shows that the roof entailed more than half of the cooling load needed to run the AC unit. This provides an insight regarding the possible variations of the building that would most effectively contribute to reduce cooling needs. Table 28 shows the calculation of the cooling loads that would result from different variations regarding the section of the roof. Adding even a low-end insulation layer would drastically reduce the overall cooling needs. And even an increase of the thatched roof layer would entail a major reduction. These scenarios also show that the existing thatched roof layer is enormously contributing to reduce the cooling loads.

Table 28 Total cooling load ( $q_c$ ) and roof cooling load for the bamboo case study building with  $\Delta t=1^\circ\text{C}$  and  $DR=7^\circ\text{C}$ , resulting from different roof section variations.

Roof section scenario	Total Cooling Load ( $q_c$ ) [W]	Roof cooling load [W]
As built	8,228	4,326
Removing thatched roof layer	14,109	10,207
Increasing thatched roof layer to 5cm	8,228	4,326
Adding a 30mm, 0.03W/mK, insulation	5,017	1,115

Since the LF method model approximately models the principal heat flows in the buildings, it also provides insights on the behaviour of the buildings in NV mode. Thus, the discussion above is also a strong indicator of the fact that (even slight) improvements in the roof insulation could be a critical factor in improving the thermal comfort performance of the case study buildings in NV mode.

### 6.3.2 Operational energy

As the method to calculate  $OE_{AC}$  values for the case-study buildings (the LF method described in Section 4.4) yields less precise predictions than building simulations, their limitations can be approached by comparing them with  $OE$  values of buildings in similar settings. Studies in the hot humid neighbouring climate of Singapore (Am in the Köppen-Geiger classification scheme) showcase values of energy-efficient office buildings to be in the  $OE_{AC}$  range of 58 to 62 kWh/m<sup>2</sup>yr (Duarte et al., 2018). This is much higher than the obtained  $OE_{AC}$  value range of 35 to 44kWh/m<sup>2</sup>yr obtained in the results in subsection 5.3.2. However, this difference could be explained with the fact that those office buildings are modelled based on the assumption of a set-point temperature of 24°C. This is 4°C below the adaptive 27.8°C set-point temperature proposed in this study, and which was based on the thermal comfort assessment. To analyse the effect of this approach in the building energy assessment, the LF method is applied to the case-study building changing this parameter and accordingly recalculating the  $\Delta t$  values. The results for these scenarios are shown in Table 29 and Table 30. Reassuringly, in this scenario,  $OE_{AC}$  now result in values between 51 and 65 kWh/m<sup>2</sup>yr, which are closer to the reference range described above.

The 24°C set-point temperature also illustrates that as lower set-point temperatures are assumed, the effect of increasing energy demand during the lifetime of the building due to increasing outdoor temperatures is further amplified.

Table 29 24°C set-point temperature scenario. Estimation of AC operational energy for the bamboo case study building for different RCPs and different years from 2020 through 2050.

Emissions Pathway	Year	AC Operational Energy (Whole Building) [kWh/yr]	AC Operational Energy [kWh/m <sup>2</sup> *yr]
RCP4.5	2020	8,176	54.9
	2030	8,587	57.7
	2040	9,200	61.8
	2050	9,406	63.2
RCP8.5	2020	8,311	55.9
	2030	8,649	58.1
	2040	9,419	63.3
	2050	9,650	64.8

Table 30 24°C set-point temperature scenario. Estimation of AC operational energy for the concrete and steel case study building for different RCPs and different years from 2020 through 2050.

Emissions Pathway	Year	AC Operational Energy (Whole Building) [kWh/yr]	AC Operational Energy [kWh/m <sup>2</sup> *yr]
RCP4.5	2020	7,592	51.0
	2030	7,900	53.1
	2040	8,359	56.2
	2050	8,513	57.2
RCP8.5	2020	7,693	51.7
	2030	7,946	53.4
	2040	8,523	57.3
	2050	8,696	58.4

## 6.4 Cradle-to-use assessment

The carbon-intensity of the electricity mix in the Philippines (average values of 0.58 kgCO<sub>2</sub>eq/kWh) is very high when it is compared to those of most countries in the world. Furthermore, it is in the range of the carbon emissions of generating electricity directly from fossil fuels (Edenhofer et al., 2011). Thus, it is of interest to see what would be the effect on the assessment of having a different carbon intensity supplying the energy to meet OE<sub>AC</sub> demands. This variation analysis was carried by multiplying the OE values by the carbon intensities (i.e., GWP impacts necessary to deliver a fixed amount of electrical energy) available in IPCC special reports (Edenhofer et al., 2011). Table 31 illustrates the results of such analysis, when considering carbon intensities within likely ranges of photovoltaic cells. The resulting GWP impacts are noticeably reduced from a range of 24 to 28 kgCO<sub>2</sub>eq/m<sup>2</sup>yr to a range of 3 to 4 kgCO<sub>2</sub>eq/m<sup>2</sup>yr. Thus, scenarios in which the electricity supplied to the building from renewable sources have the effect of restoring the mitigation potential that was shown to be hindered by OE needs in the cradle-to-use LCA results in Section 6.3.

Table 31 Variation analysis for the bamboo case study building showing the yearly GWP impacts of  $OE_{AC}$  demands being met with low-carbon intensity electricity sources:  $0.08\text{kgCO}_2\text{eq/kWh}$  (Edenhofer et al., 2011).

Emissions Pathway	Year	AC Operational Energy	Remaining Operational Energy	Carbon Intensity Scenario	Emissions	Emissions	Low-Carbon Intensity Scenario	Emissions	Emissions
		[kWh/m <sup>2</sup> yr]	[kWh/m <sup>2</sup> yr]	[kgCO <sub>2</sub> eq/kWh]	[kgCO <sub>2</sub> eq/yr]	[kgCO <sub>2</sub> eq/m <sup>2</sup> yr]	[kgCO <sub>2</sub> eq/kWh]	[kgCO <sub>2</sub> eq/yr]	[kgCO <sub>2</sub> eq/m <sup>2</sup> yr]
RCP4.5	2020	36.2	5.6	0.6	3,135.2	21.1	0.08	454.1	3.05
	2030	38.3	5.6	0.6	3,316.5	22.3	0.08	480.3	3.23
	2040	41.4	5.6	0.6	3,583.0	24.1	0.08	518.9	3.49
	2050	42.4	5.6	0.6	3,670.9	24.7	0.08	531.7	3.57
RCP8.5	2020	36.9	5.6	0.6	3,194.1	21.5	0.08	462.6	3.11
	2030	38.6	5.6	0.6	3,345.9	22.5	0.08	484.6	3.26
	2040	42.4	5.6	0.6	3,675.0	24.7	0.08	532.2	3.58
	2050	43.8	5.6	0.6	3,790.6	25.5	0.08	549.0	3.69

## 7 Conclusions

Existing bamboo building technologies for affordable non-residential buildings in the hot humid tropics have a potential to mitigate cradle-to-gate climate impacts when they replace widespread conventional technologies. The extent of this mitigation potential is further increased when more carbon-intensive cements are implemented in conventional building technologies, and when delayed emissions of carbon stored in bamboo building materials is considered.

Bamboo technologies' light-weight nature, in combination with standard climate-adaptation strategies in this context, might not be sufficient to guarantee thermal comfort without air conditioning. Further climate adaptation strategies ought to be considered within the limits of affordable building technologies.

Air conditioning to bridge the thermal comfort performance shortcomings is expected to dominate the energy needs of both bamboo and conventional buildings in this context. This holds true even when an adaptive approach is taken to define air conditioning set-temperatures to deliver thermal comfort in bamboo buildings. The dominance is poised to increase further during the service life of the building, as increasing outdoor temperatures further drive AC energy needs. This trend is expected both in climate change scenarios for considerable emission reductions (RCP4.5), and for scenarios business-as-usual increasing of emissions (RCP8.5).

If air conditioning is implemented to meet thermal comfort in either bamboo or concrete and steel buildings, it is expected to take over the cradle-to-use impacts of both bamboo and conventional buildings in this context. This continues to be the case even when an adaptive approach is taken to define air conditioning set-temperatures for meeting thermal comfort in the buildings. In parallel to the dominance of operational energy, its resulting climate impacts are poised to increase dominance of the cradle-to-use impacts during the service life of the building. And the dominance trend is further stressed with climate change scenarios resulting from business-as-usual increasing of emissions. However, the dominance trend is hindered if the carbon intensity of the electricity-mix that powers cooling is sourced with photovoltaic cells or a less carbon intensive electricity mix than the current carbon-intensive mix of the Philippines.

In spite of the above, the cradle-to-use environmental performance of the bamboo buildings is shown to continue to have a mitigation potential, even when energy requirements for comfort are accounted. As the use-stage is included in the assessment, potential operational energy needs from cooling to deliver thermal comfort are likely to reduce bamboo building's mitigation potential. Consequently, because delivering protection from increasing thermal stress in buildings is a critical function of buildings in the hot humid tropics, improvements of alternative climate-adaptations should be addressed to preserve bamboo's mitigation potential from a life-cycle perspective.

This study identifies some of these affordable adaptation measures for technology development and building operation, such as facilitating the operability of windows and fans and adding rafter ventilations to the roofs. This research also finds strong indications that even slight improvements in roof insulation are critical to improve thermal comfort performance. Further research is recommended regarding the effect of reducing the thermal mass in hot humid climates, comparing the comparative thermal- and cost-effectiveness of a bigger spectrum of affordable

climate-adaptations, and integrating thermal comfort studies with increasingly comprehensive sustainability assessments.

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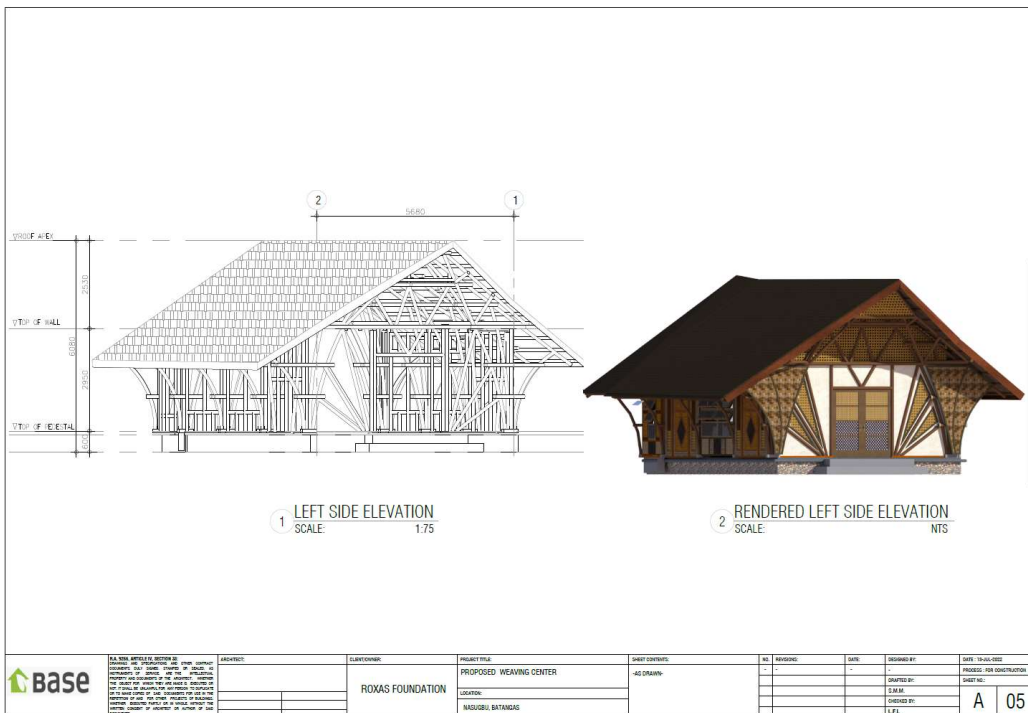
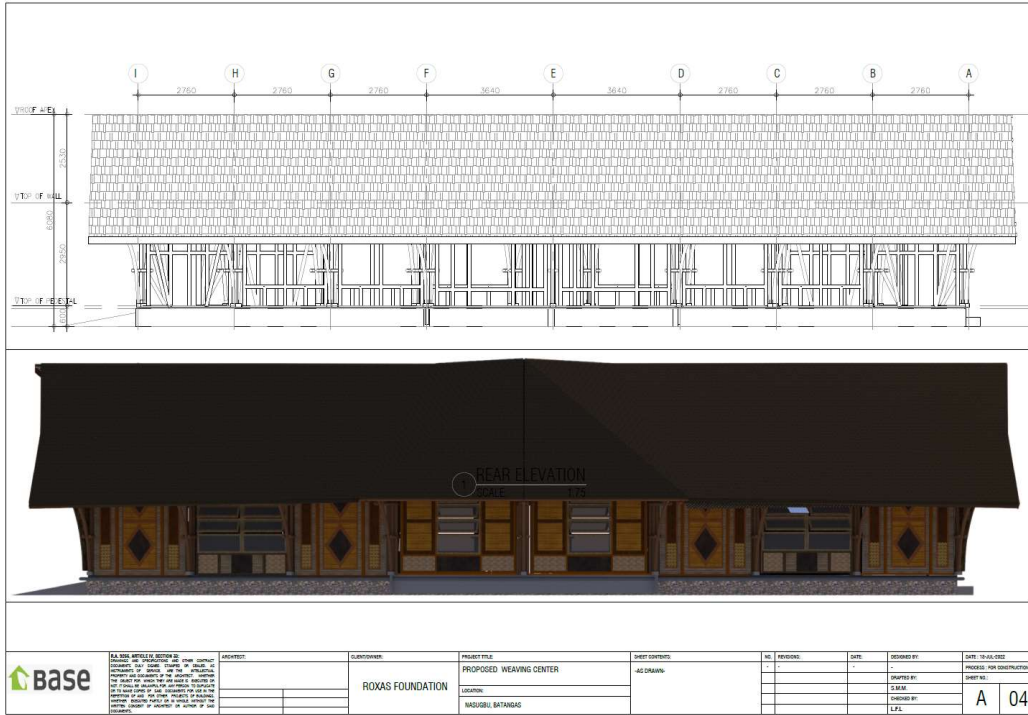
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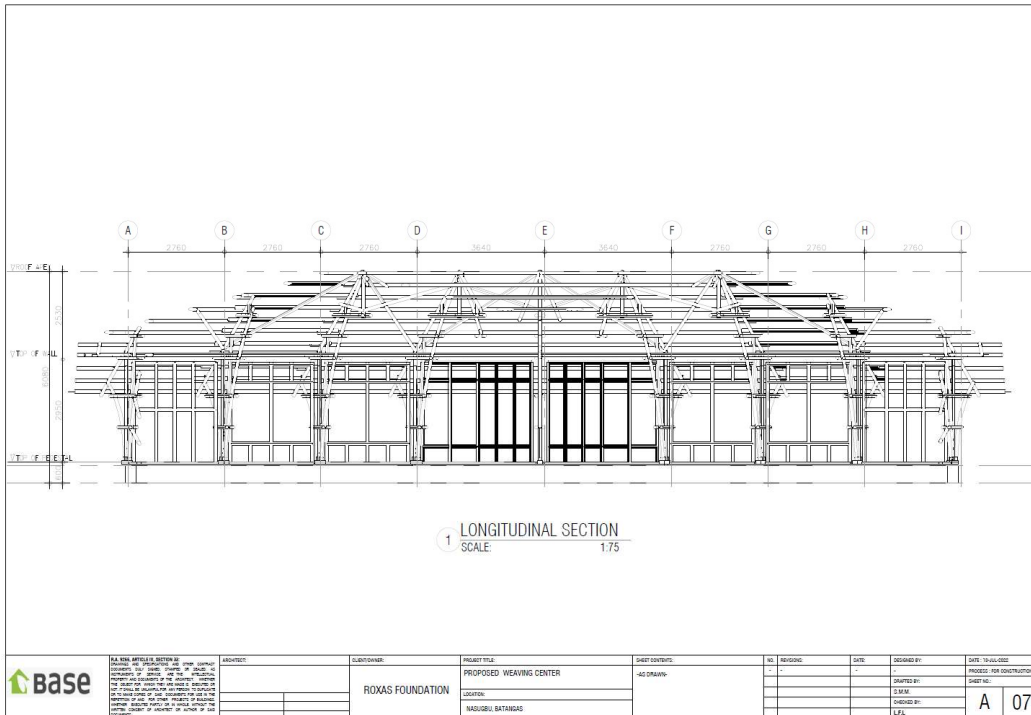
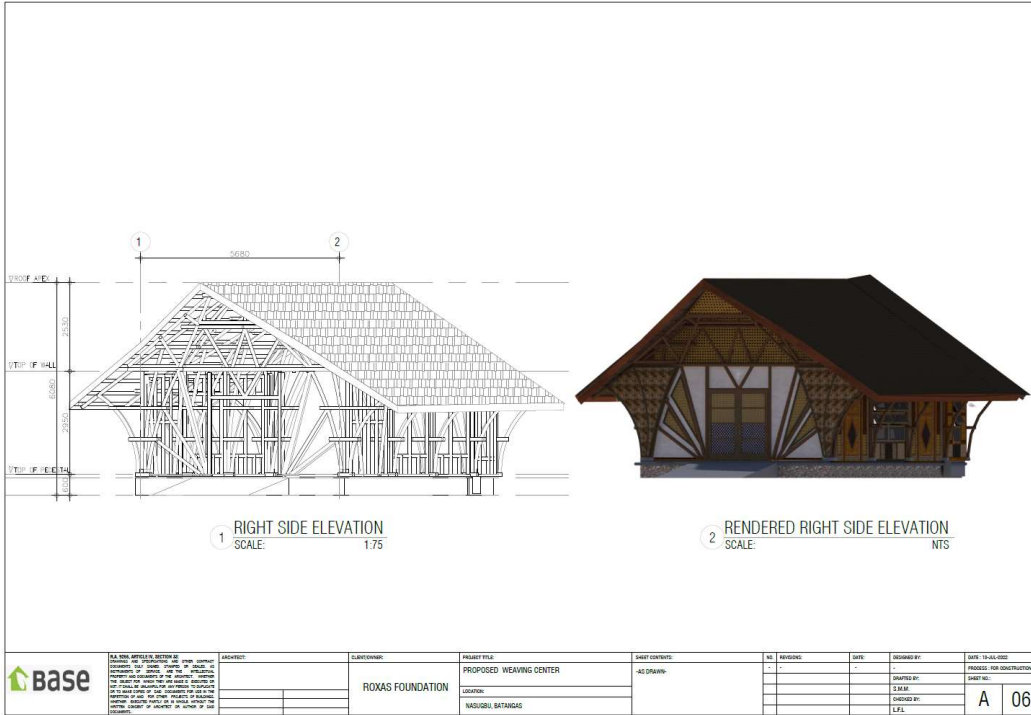
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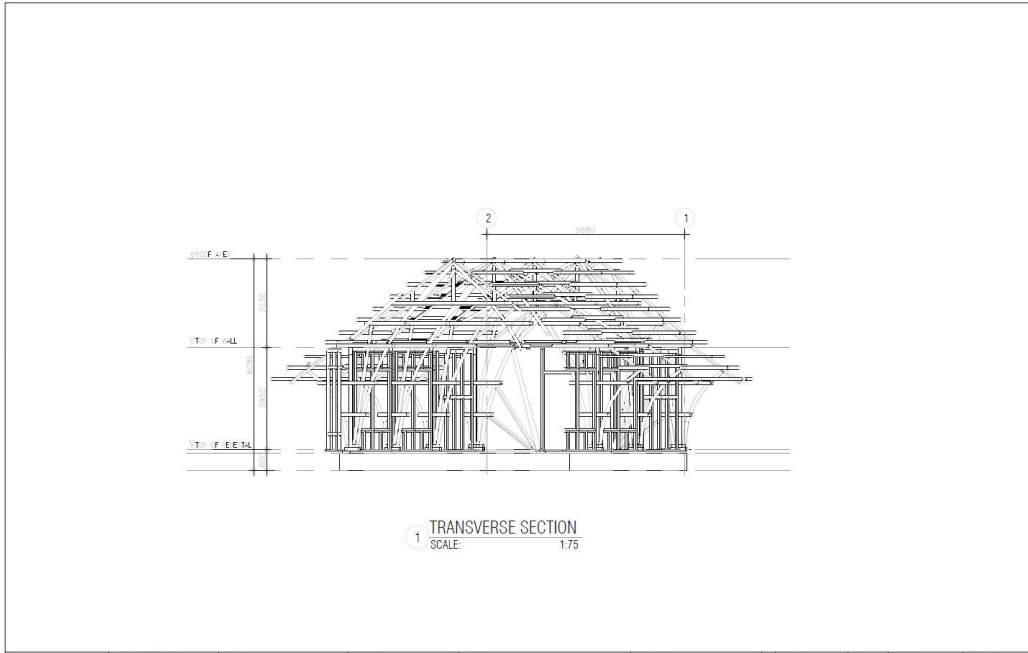
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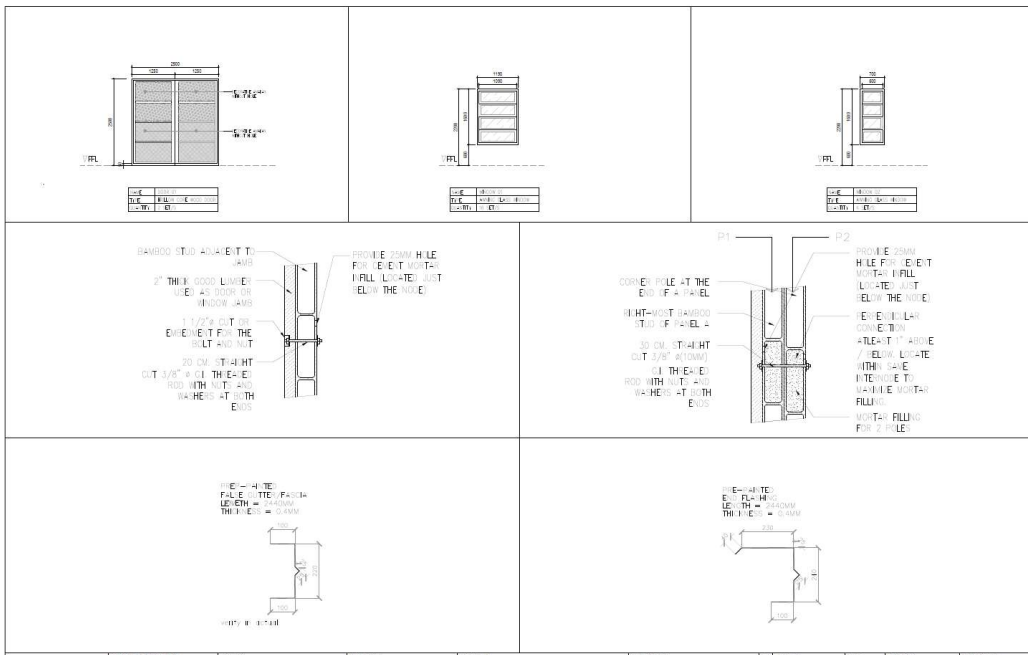




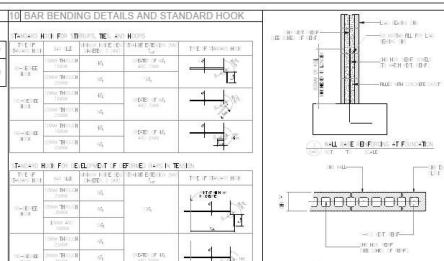
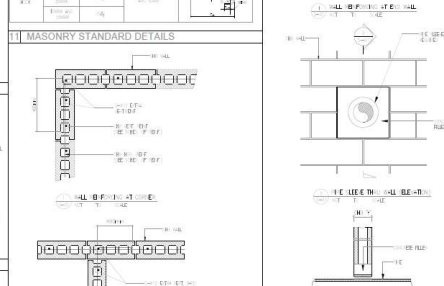
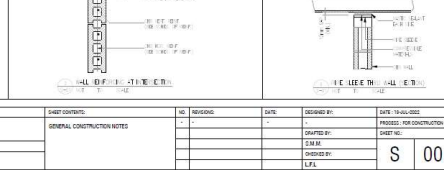


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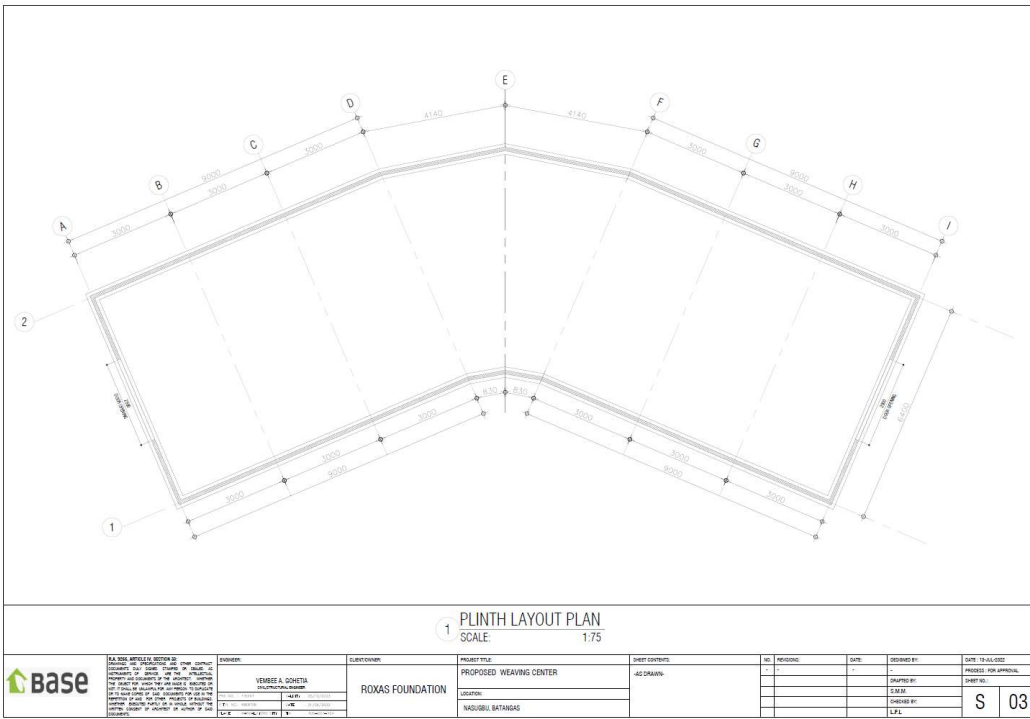
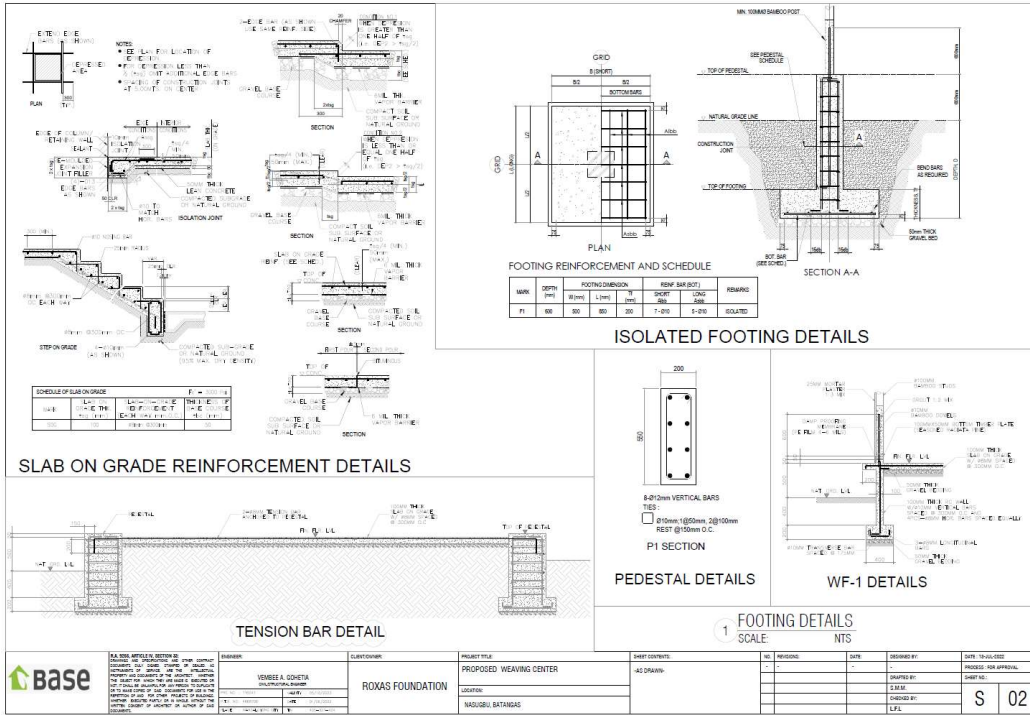
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			ROXAS FOUNDATION	PROPOSED WEAVING CENTER	40 DRAWING	-	-	-	-	DESIGNED FOR CONSTRUCTION	SHEET NO.	
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										CHECKED BY	L.F.L.	

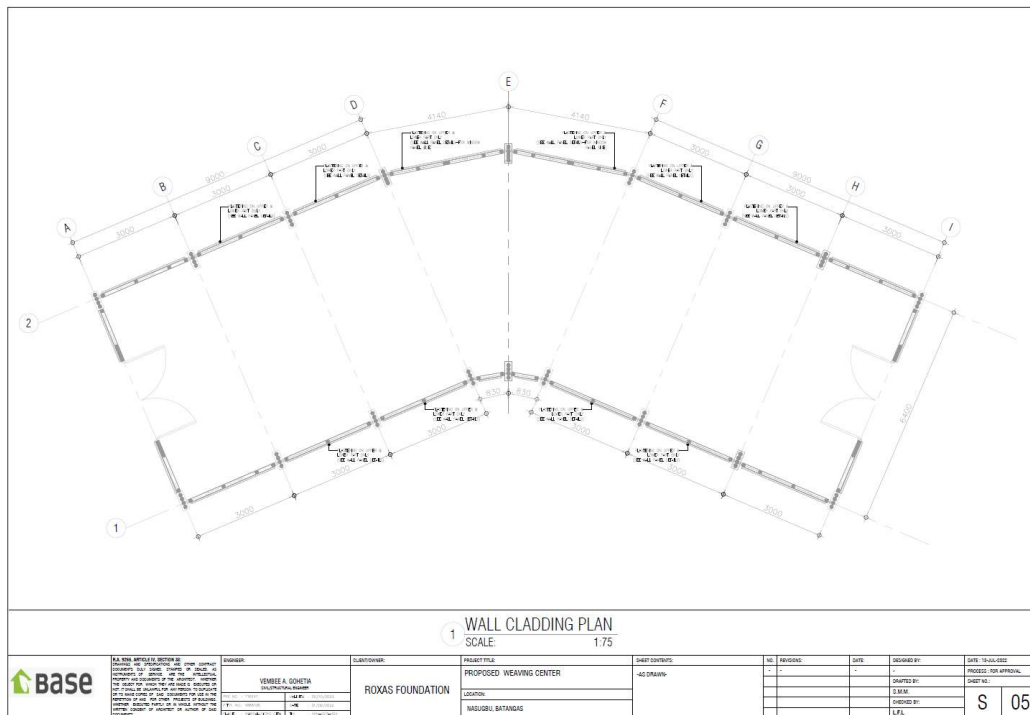
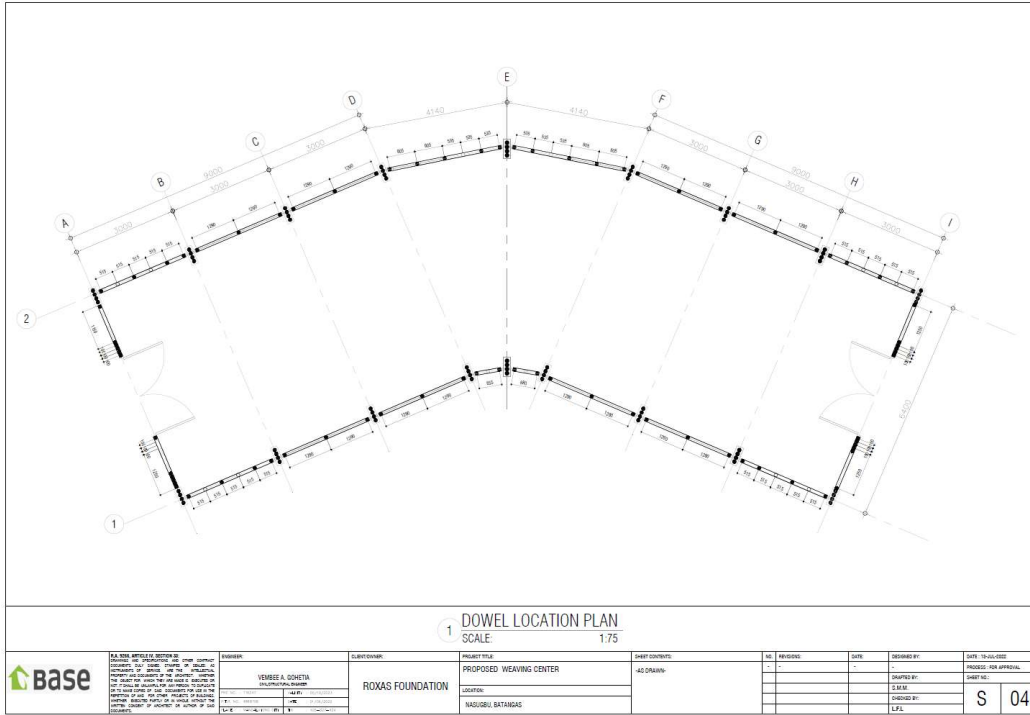


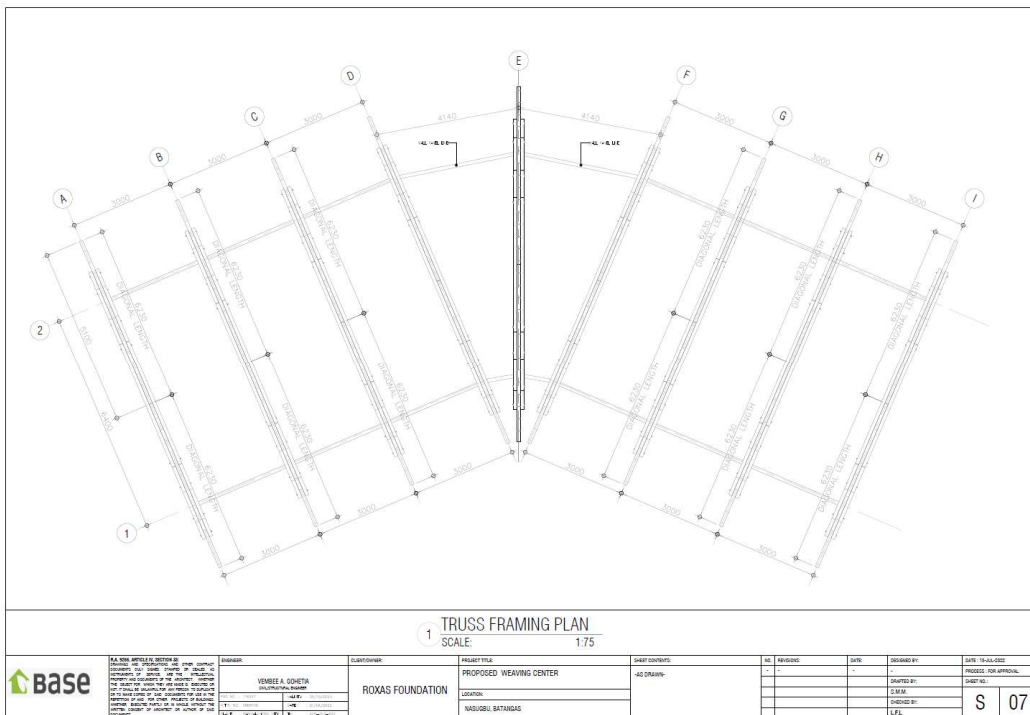
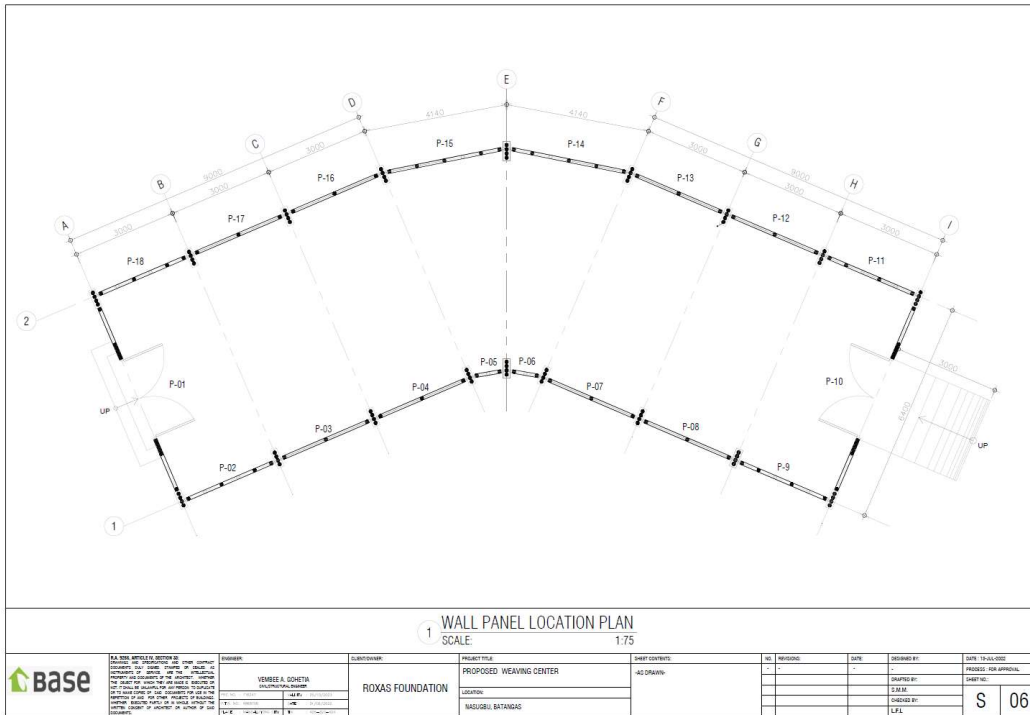
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										CHECKED BY	L.F.L.	

<p><b>1 GENERAL NOTES</b></p> <p>1. ALL DIMENSIONS ARE IN METERS UNLESS OTHERWISE SPECIFIED.</p> <p>2. ALL WORK SHALL BE ACCORDING TO THE LATEST EDITIONS OF THE PHILIPPINE NATIONAL STANDARDS (PNS) AND THE NATIONAL CONSTRUCTION CODE (NCC).</p> <p>3. THE CONTRACTOR SHALL BE RESPONSIBLE FOR OBTAINING ALL NECESSARY PERMITS AND APPROVALS FROM THE APPROPRIATE AGENCIES.</p> <p>4. THE CONTRACTOR SHALL MAINTAIN ACCESS TO ALL ADJACENT PROPERTIES AND UTILITIES AT ALL TIMES.</p> <p>5. ALL MATERIALS AND WORKMANSHIP SHALL BE SUBJECT TO INSPECTION AND APPROVAL BY THE ARCHITECT AND ENGINEER.</p> <p>6. THE CONTRACTOR SHALL BE RESPONSIBLE FOR PROTECTING ALL EXISTING UTILITIES AND STRUCTURES.</p> <p>7. ALL UTILITIES SHALL BE DEEPENED TO A MINIMUM OF 1.00 METER BELOW FINISHED GRADE.</p> <p>8. THE CONTRACTOR SHALL MAINTAIN A RECORD OF ALL MATERIALS AND WORKMANSHIP.</p> <p>9. ALL WORK SHALL BE COMPLETED WITHIN THE SPECIFIED TIME FRAME.</p> <p>10. THE CONTRACTOR SHALL BE RESPONSIBLE FOR OBTAINING ALL NECESSARY PERMITS AND APPROVALS FROM THE APPROPRIATE AGENCIES.</p>	<p><b>4 TIMBER</b></p> <p>1. ALL TIMBER SHALL BE DRY-KILN DRIED TO A MAXIMUM MOISTURE CONTENT OF 19%.</p> <p>2. ALL TIMBER SHALL BE TREATED WITH AN ANTI-TERMITICIDE.</p> <p>3. ALL TIMBER SHALL BE PROTECTED AGAINST WEATHERING.</p> <p>4. ALL TIMBER SHALL BE CUT TO SIZE AND SHAPED TO ORDER.</p> <p>5. ALL TIMBER SHALL BE STORED PROPERLY TO PREVENT WARPING AND SPLITTING.</p> <p>6. ALL TIMBER SHALL BE JOINED USING METAL BRACKETS AND BOLTS.</p> <p>7. ALL TIMBER SHALL BE PROTECTED AGAINST INSECT DAMAGE.</p> <p>8. ALL TIMBER SHALL BE MAINTAINED AND REPAIRED AS NEEDED.</p> <p>9. ALL TIMBER SHALL BE REPLACED IF DAMAGED OR DESTROYED.</p> <p>10. ALL TIMBER SHALL BE MAINTAINED AND REPAIRED AS NEEDED.</p>	<p><b>7 REINFORCED CONCRETE NOTES</b></p> <p>1. ALL REINFORCED CONCRETE SHALL BE CAST AND CURED PROPERLY.</p> <p>2. ALL REINFORCED CONCRETE SHALL BE PROTECTED AGAINST WEATHERING.</p> <p>3. ALL REINFORCED CONCRETE SHALL BE MAINTAINED AND REPAIRED AS NEEDED.</p> <p>4. ALL REINFORCED CONCRETE SHALL BE REPLACED IF DAMAGED OR DESTROYED.</p> <p>5. ALL REINFORCED CONCRETE SHALL BE MAINTAINED AND REPAIRED AS NEEDED.</p> <p>6. ALL REINFORCED CONCRETE SHALL BE REPLACED IF DAMAGED OR DESTROYED.</p> <p>7. ALL REINFORCED CONCRETE SHALL BE MAINTAINED AND REPAIRED AS NEEDED.</p> <p>8. ALL REINFORCED CONCRETE SHALL BE REPLACED IF DAMAGED OR DESTROYED.</p> <p>9. ALL REINFORCED CONCRETE SHALL BE MAINTAINED AND REPAIRED AS NEEDED.</p> <p>10. ALL REINFORCED CONCRETE SHALL BE REPLACED IF DAMAGED OR DESTROYED.</p>	<p><b>10 BAR BENDING DETAILS AND STANDARD HOOK</b></p> 
<p><b>2 DESIGN LOADS</b></p> <p>1. ALL DESIGN LOADS SHALL BE ACCORDING TO THE LATEST EDITIONS OF THE PHILIPPINE NATIONAL STANDARDS (PNS) AND THE NATIONAL CONSTRUCTION CODE (NCC).</p> <p>2. ALL DESIGN LOADS SHALL BE MAINTAINED AND REPAIRED AS NEEDED.</p> <p>3. ALL DESIGN LOADS SHALL BE REPLACED IF DAMAGED OR DESTROYED.</p> <p>4. ALL DESIGN LOADS SHALL BE MAINTAINED AND REPAIRED AS NEEDED.</p> <p>5. ALL DESIGN LOADS SHALL BE REPLACED IF DAMAGED OR DESTROYED.</p> <p>6. ALL DESIGN LOADS SHALL BE MAINTAINED AND REPAIRED AS NEEDED.</p> <p>7. ALL DESIGN LOADS SHALL BE REPLACED IF DAMAGED OR DESTROYED.</p> <p>8. ALL DESIGN LOADS SHALL BE MAINTAINED AND REPAIRED AS NEEDED.</p> <p>9. ALL DESIGN LOADS SHALL BE REPLACED IF DAMAGED OR DESTROYED.</p> <p>10. ALL DESIGN LOADS SHALL BE MAINTAINED AND REPAIRED AS NEEDED.</p>	<p><b>5 REINFORCING BAR</b></p> <p>1. ALL REINFORCING BARS SHALL BE ACCORDING TO THE LATEST EDITIONS OF THE PHILIPPINE NATIONAL STANDARDS (PNS) AND THE NATIONAL CONSTRUCTION CODE (NCC).</p> <p>2. ALL REINFORCING BARS SHALL BE MAINTAINED AND REPAIRED AS NEEDED.</p> <p>3. ALL REINFORCING BARS SHALL BE REPLACED IF DAMAGED OR DESTROYED.</p> <p>4. ALL REINFORCING BARS SHALL BE MAINTAINED AND REPAIRED AS NEEDED.</p> <p>5. ALL REINFORCING BARS SHALL BE REPLACED IF DAMAGED OR DESTROYED.</p> <p>6. ALL REINFORCING BARS SHALL BE MAINTAINED AND REPAIRED AS NEEDED.</p> <p>7. ALL REINFORCING BARS SHALL BE REPLACED IF DAMAGED OR DESTROYED.</p> <p>8. ALL REINFORCING BARS SHALL BE MAINTAINED AND REPAIRED AS NEEDED.</p> <p>9. ALL REINFORCING BARS SHALL BE REPLACED IF DAMAGED OR DESTROYED.</p> <p>10. ALL REINFORCING BARS SHALL BE MAINTAINED AND REPAIRED AS NEEDED.</p>	<p><b>8 BAMBOO</b></p> <p>1. ALL BAMBOO SHALL BE DRY-KILN DRIED TO A MAXIMUM MOISTURE CONTENT OF 19%.</p> <p>2. ALL BAMBOO SHALL BE TREATED WITH AN ANTI-TERMITICIDE.</p> <p>3. ALL BAMBOO SHALL BE PROTECTED AGAINST WEATHERING.</p> <p>4. ALL BAMBOO SHALL BE CUT TO SIZE AND SHAPED TO ORDER.</p> <p>5. ALL BAMBOO SHALL BE STORED PROPERLY TO PREVENT WARPING AND SPLITTING.</p> <p>6. ALL BAMBOO SHALL BE JOINED USING METAL BRACKETS AND BOLTS.</p> <p>7. ALL BAMBOO SHALL BE PROTECTED AGAINST INSECT DAMAGE.</p> <p>8. ALL BAMBOO SHALL BE MAINTAINED AND REPAIRED AS NEEDED.</p> <p>9. ALL BAMBOO SHALL BE REPLACED IF DAMAGED OR DESTROYED.</p> <p>10. ALL BAMBOO SHALL BE MAINTAINED AND REPAIRED AS NEEDED.</p>	<p><b>11 MASONRY STANDARD DETAILS</b></p> 
<p><b>3 FOUNDATION AND SOIL DATA</b></p> <p>1. ALL FOUNDATION AND SOIL DATA SHALL BE ACCORDING TO THE LATEST EDITIONS OF THE PHILIPPINE NATIONAL STANDARDS (PNS) AND THE NATIONAL CONSTRUCTION CODE (NCC).</p> <p>2. ALL FOUNDATION AND SOIL DATA SHALL BE MAINTAINED AND REPAIRED AS NEEDED.</p> <p>3. ALL FOUNDATION AND SOIL DATA SHALL BE REPLACED IF DAMAGED OR DESTROYED.</p> <p>4. ALL FOUNDATION AND SOIL DATA SHALL BE MAINTAINED AND REPAIRED AS NEEDED.</p> <p>5. ALL FOUNDATION AND SOIL DATA SHALL BE REPLACED IF DAMAGED OR DESTROYED.</p> <p>6. ALL FOUNDATION AND SOIL DATA SHALL BE MAINTAINED AND REPAIRED AS NEEDED.</p> <p>7. ALL FOUNDATION AND SOIL DATA SHALL BE REPLACED IF DAMAGED OR DESTROYED.</p> <p>8. ALL FOUNDATION AND SOIL DATA SHALL BE MAINTAINED AND REPAIRED AS NEEDED.</p> <p>9. ALL FOUNDATION AND SOIL DATA SHALL BE REPLACED IF DAMAGED OR DESTROYED.</p> <p>10. ALL FOUNDATION AND SOIL DATA SHALL BE MAINTAINED AND REPAIRED AS NEEDED.</p>	<p><b>6 STRUCTURAL STEEL</b></p> <p>1. ALL STRUCTURAL STEEL SHALL BE ACCORDING TO THE LATEST EDITIONS OF THE PHILIPPINE NATIONAL STANDARDS (PNS) AND THE NATIONAL CONSTRUCTION CODE (NCC).</p> <p>2. ALL STRUCTURAL STEEL SHALL BE MAINTAINED AND REPAIRED AS NEEDED.</p> <p>3. ALL STRUCTURAL STEEL SHALL BE REPLACED IF DAMAGED OR DESTROYED.</p> <p>4. ALL STRUCTURAL STEEL SHALL BE MAINTAINED AND REPAIRED AS NEEDED.</p> <p>5. ALL STRUCTURAL STEEL SHALL BE REPLACED IF DAMAGED OR DESTROYED.</p> <p>6. ALL STRUCTURAL STEEL SHALL BE MAINTAINED AND REPAIRED AS NEEDED.</p> <p>7. ALL STRUCTURAL STEEL SHALL BE REPLACED IF DAMAGED OR DESTROYED.</p> <p>8. ALL STRUCTURAL STEEL SHALL BE MAINTAINED AND REPAIRED AS NEEDED.</p> <p>9. ALL STRUCTURAL STEEL SHALL BE REPLACED IF DAMAGED OR DESTROYED.</p> <p>10. ALL STRUCTURAL STEEL SHALL BE MAINTAINED AND REPAIRED AS NEEDED.</p>	<p><b>9 MASONRY</b></p> <p>1. ALL MASONRY SHALL BE ACCORDING TO THE LATEST EDITIONS OF THE PHILIPPINE NATIONAL STANDARDS (PNS) AND THE NATIONAL CONSTRUCTION CODE (NCC).</p> <p>2. ALL MASONRY SHALL BE MAINTAINED AND REPAIRED AS NEEDED.</p> <p>3. ALL MASONRY SHALL BE REPLACED IF DAMAGED OR DESTROYED.</p> <p>4. ALL MASONRY SHALL BE MAINTAINED AND REPAIRED AS NEEDED.</p> <p>5. ALL MASONRY SHALL BE REPLACED IF DAMAGED OR DESTROYED.</p> <p>6. ALL MASONRY SHALL BE MAINTAINED AND REPAIRED AS NEEDED.</p> <p>7. ALL MASONRY SHALL BE REPLACED IF DAMAGED OR DESTROYED.</p> <p>8. ALL MASONRY SHALL BE MAINTAINED AND REPAIRED AS NEEDED.</p> <p>9. ALL MASONRY SHALL BE REPLACED IF DAMAGED OR DESTROYED.</p> <p>10. ALL MASONRY SHALL BE MAINTAINED AND REPAIRED AS NEEDED.</p>	<p><b>12 MASONRY STANDARD DETAILS</b></p> 

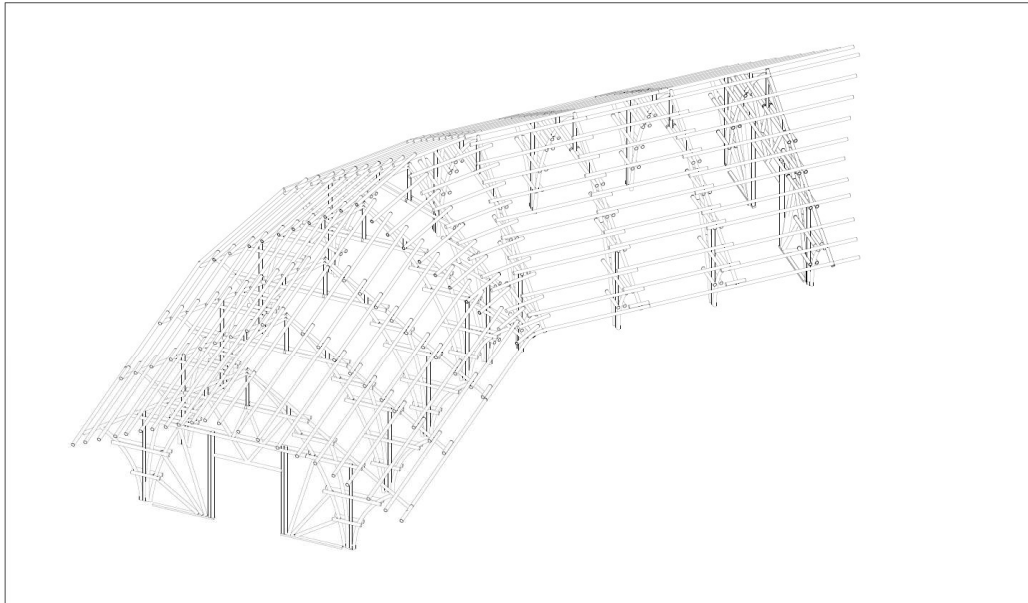
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<p><b>Base</b></p>	<p>DESIGNER: VERBEE A. DOMETA</p>	<p>SUBOWNER: ROXAS FOUNDATION</p>	<p>PROJECT TITLE: PROPOSED WEAVING CENTER</p>	<p>CLIENT: NABUQUI BATANGAS</p>	<p>DATE: 10/10/2023</p>
<p><b>Base</b></p>	<p>DESIGNER: VERBEE A. DOMETA</p>	<p>SUBOWNER: ROXAS FOUNDATION</p>	<p>PROJECT TITLE: PROPOSED WEAVING CENTER</p>	<p>CLIENT: NABUQUI BATANGAS</p>	<p>DATE: 10/10/2023</p>
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<p><b>Base</b></p>	<p>DESIGNER: VERBEE A. DOMETA</p>	<p>SUBOWNER: ROXAS FOUNDATION</p>	<p>PROJECT TITLE: PROPOSED WEAVING CENTER</p>	<p>CLIENT: NABUQUI BATANGAS</p>	<p>DATE: 10/10/2023</p>





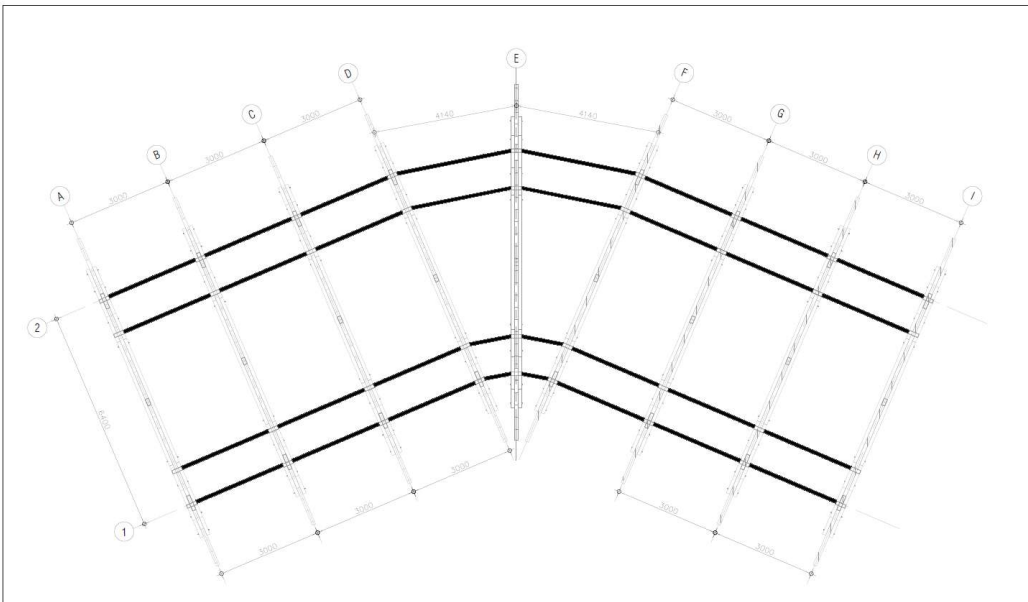






1 PURLINS FRAMING 3D LAYOUT  
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	<small>SAJAK APRIYATI SIDIQI Desain dan Konstruksi Struktur Baja dan Beton Dibangun dan Direnovasi. Untuk lebih jelasnya tentang jasa kami, silakan kunjungi website kami atau hubungi kami melalui nomor telepon yang tertera di bawah ini. Kami siap melayani dengan sepenuh hati dan profesionalisme.</small>	DESAINER	CLIENT/OWNER	PROJECT TITLE	SHEET CONTENTS	NO.	REVISIONS	DATE	DRAWN BY	DATE TO ALLIANCE	
		YEMEE A. SIDIQI <small>YEMEE A. SIDIQI Desain dan Konstruksi Struktur Baja dan Beton</small>	ROXAS FOUNDATION	PROPOSED WEAVING CENTER LOCATION: NAGUBU BATANGAS	40 DRAWING					DESIGNED FOR APPROVAL SHEET NO.	
										DRAWN BY: CHECKED BY: L.P.L.	S 10



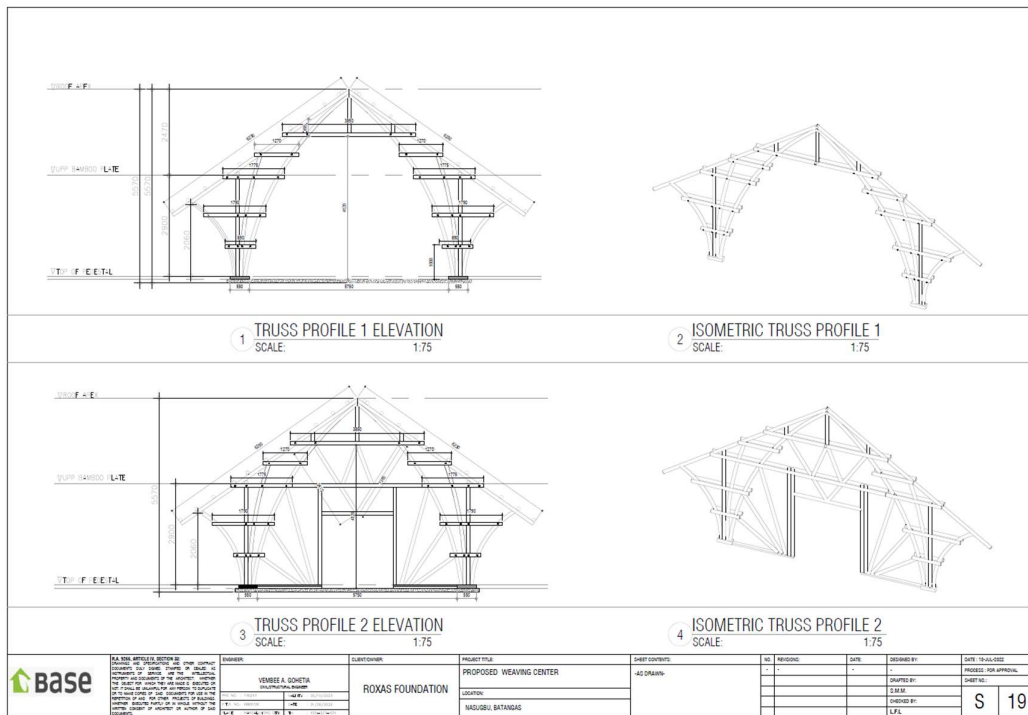
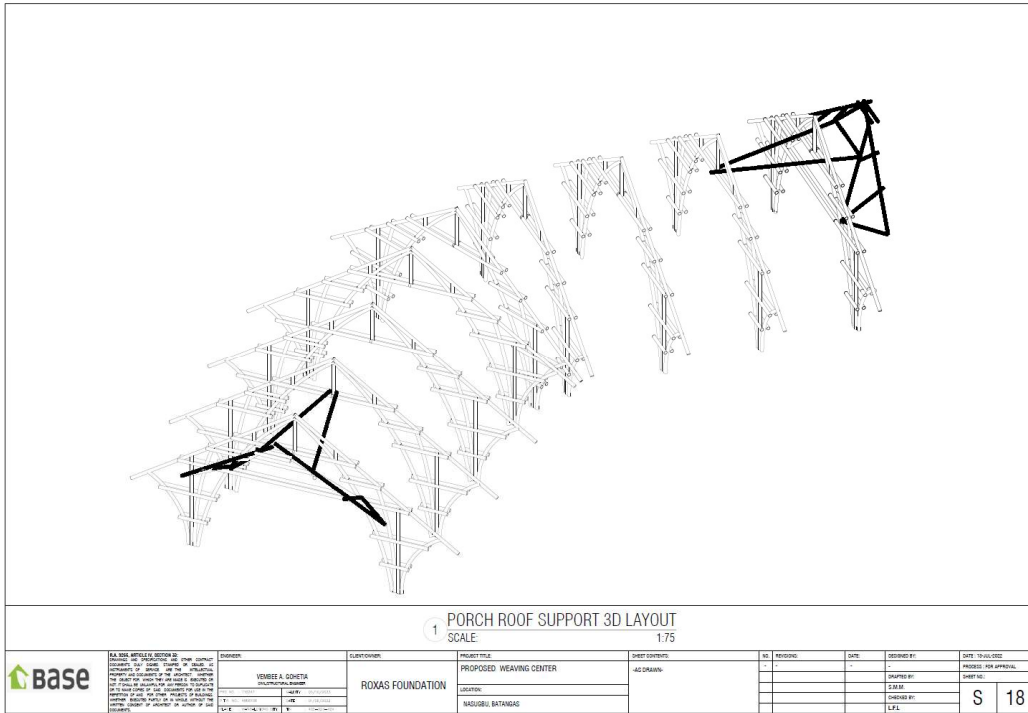
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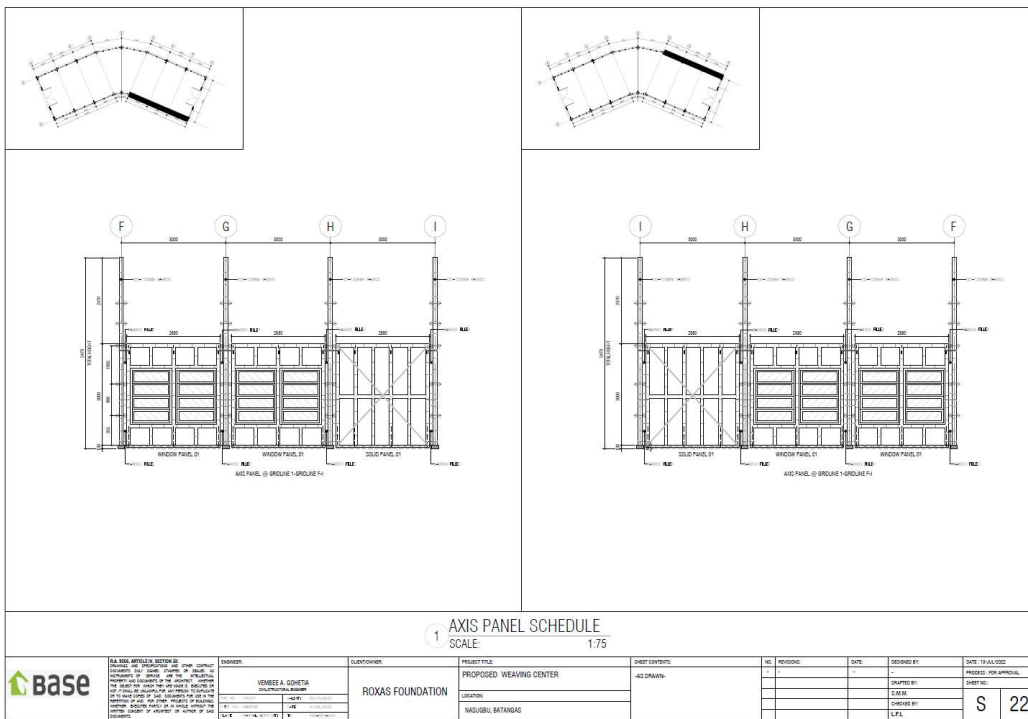
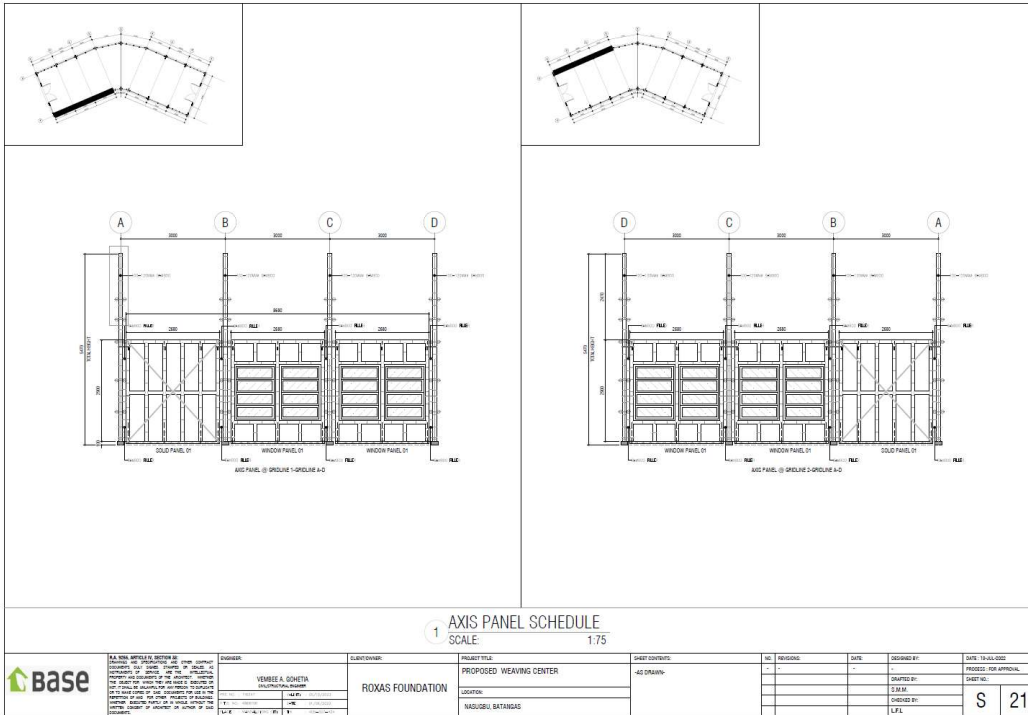
	<small>SAJAK APRIYATI SIDIQI Desain dan Konstruksi Struktur Baja dan Beton Dibangun dan Direnovasi. Untuk lebih jelasnya tentang jasa kami, silakan kunjungi website kami atau hubungi kami melalui nomor telepon yang tertera di bawah ini. Kami siap melayani dengan sepenuh hati dan profesionalisme.</small>	DESIGNER	CLIENT/OWNER	PROJECT TITLE	SHEET CONTENTS	NO.	REVISIONS	DATE	DRAWN BY	DATE TO ALLIANCE	
		YEMEE A. SIDIQI <small>YEMEE A. SIDIQI Desain dan Konstruksi Struktur Baja dan Beton</small>	ROXAS FOUNDATION	PROPOSED WEAVING CENTER LOCATION: NAGUBU BATANGAS	40 DRAWING					DESIGNED FOR APPROVAL SHEET NO.	
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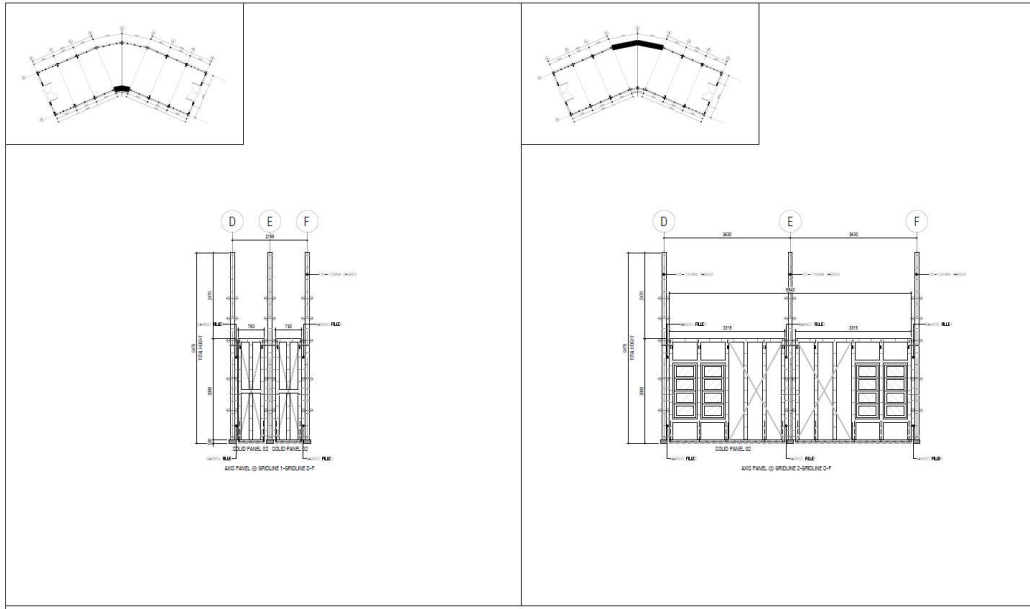






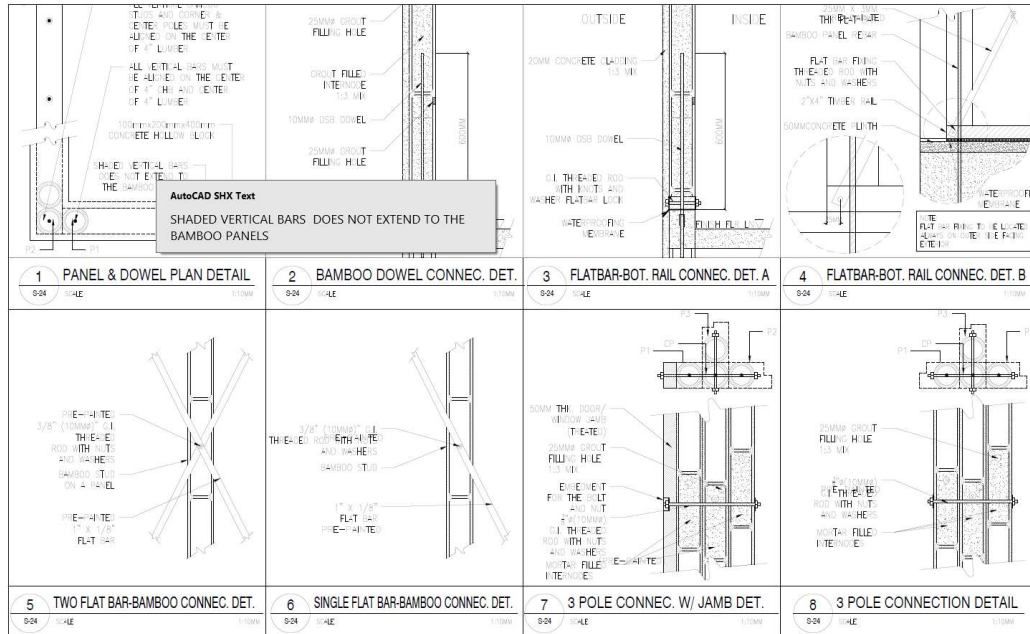




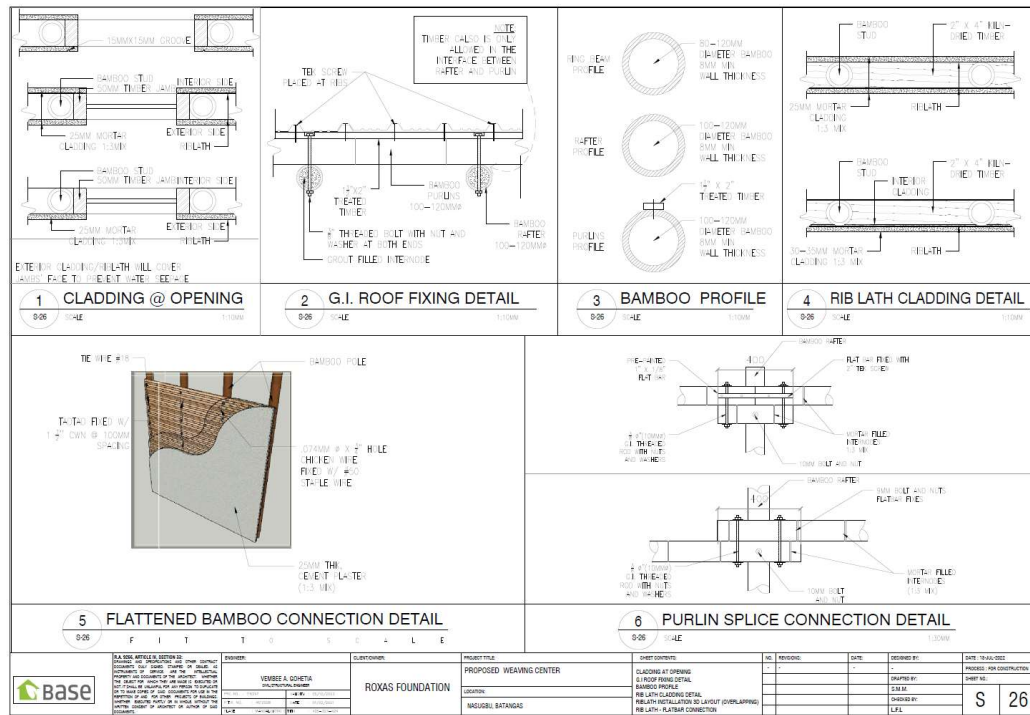
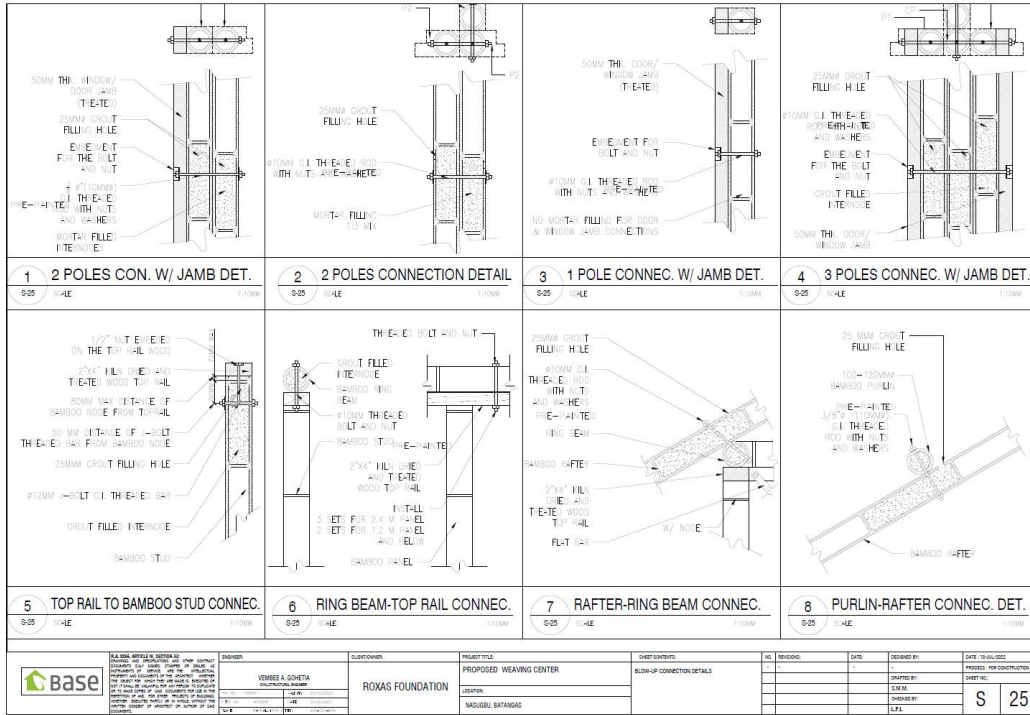


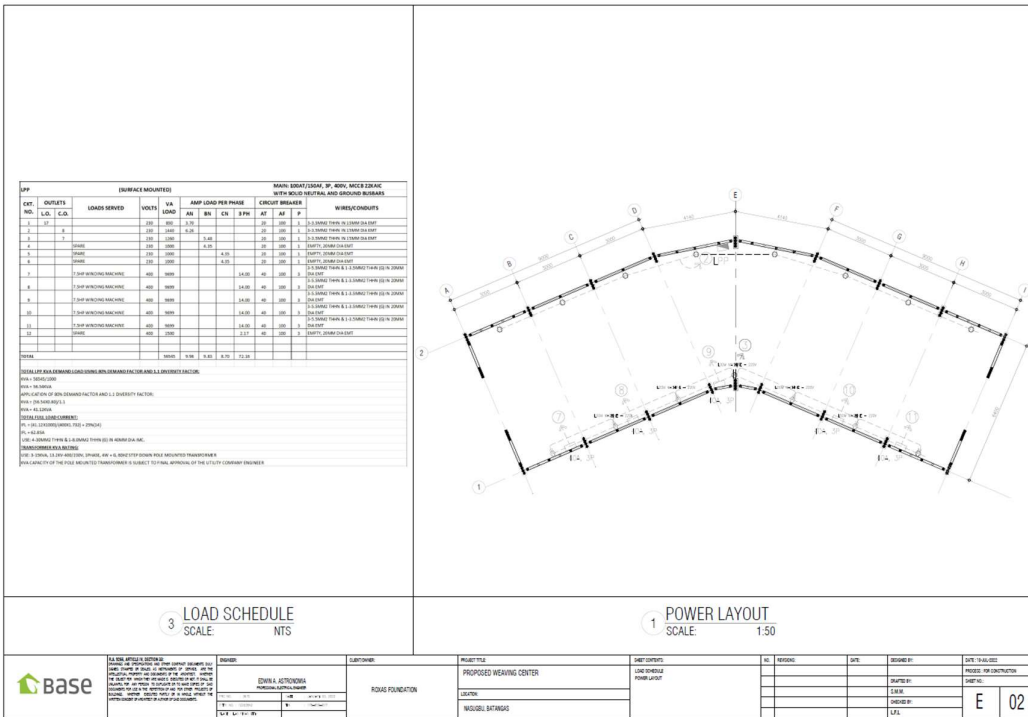
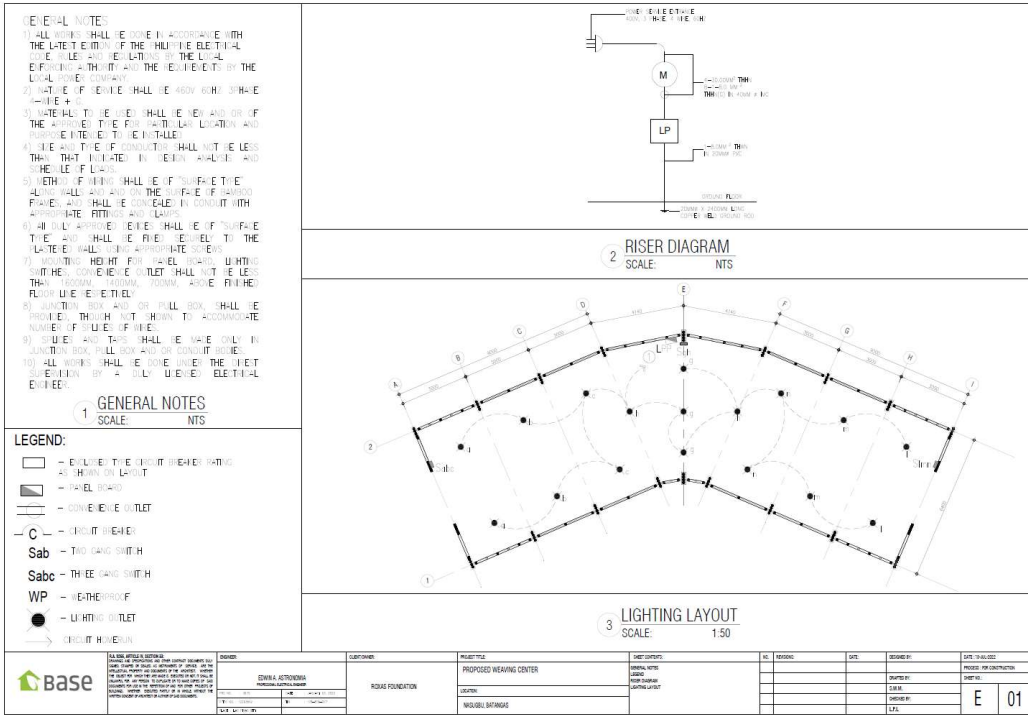
1 AXIS PANEL SCHEDULE  
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	<p>BASE ENGINEERING &amp; ARCHITECTURE 1000 N. W. 10th St., Suite 1000 Fort Lauderdale, FL 33304 Tel: (954) 561-1111 Fax: (954) 561-1112 www.base-engineering.com</p>	DESIGNER	CLIENT/OWNER	PROJECT TITLE	SHEET CONTENTS	NO.	REVISIONS	DATE	DESIGNED BY	DATE: 10-11-2022
		<p>YVESSE A. GONZALEZ ARCHITECT/ENGINEER</p>	<p>ROXAS FOUNDATION</p>	<p>PROPOSED WEAVING CENTER</p>	<p>40 DRAWINGS</p>	-	-	-	<p>PROCESSED FOR APPROVAL</p>	
		<p>DATE: 10-11-2022</p>	<p>LOCATION:</p>	<p>MAGSIBUL BATANGAS</p>	<p>DATE:</p>	<p>DESIGNED BY:</p>	<p>S.M.A.</p>	<p>CHECKED BY:</p>	<p>S</p>	<p>23</p>
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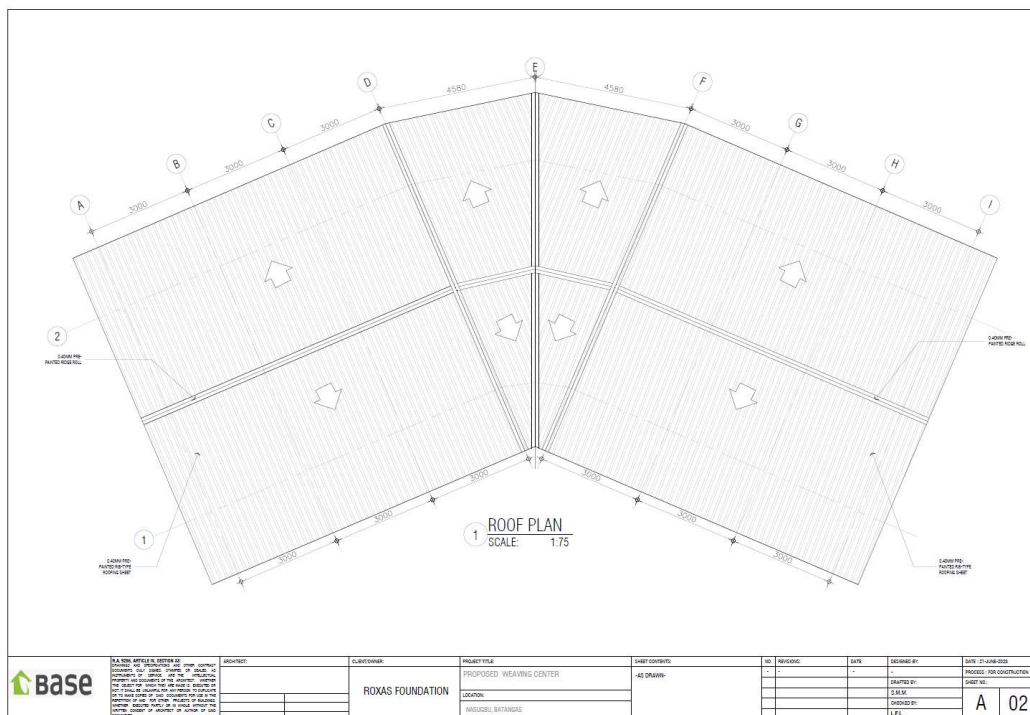
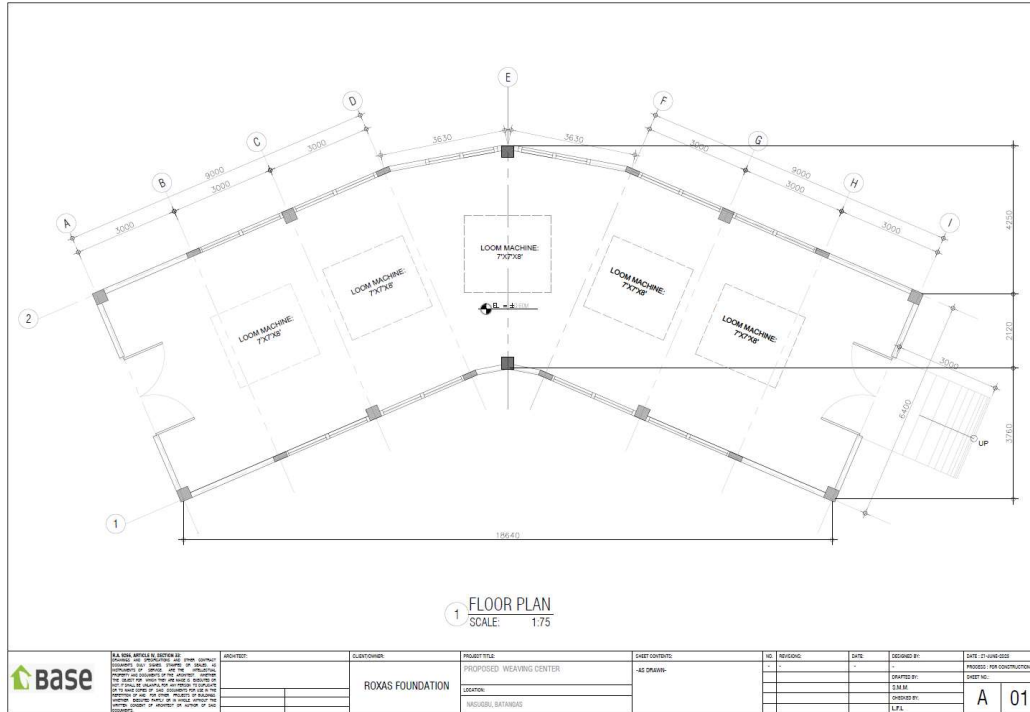
	<p>BASE ENGINEERING &amp; ARCHITECTURE 1000 N. W. 10th St., Suite 1000 Fort Lauderdale, FL 33304 Tel: (954) 561-1111 Fax: (954) 561-1112 www.base-engineering.com</p>	DESIGNER	CLIENT/OWNER	PROJECT TITLE	SHEET CONTENTS	NO.	REVISIONS	DATE	DESIGNED BY	DATE: 10-11-2022
		<p>YVESSE A. GONZALEZ ARCHITECT/ENGINEER</p>	<p>ROXAS FOUNDATION</p>	<p>PROPOSED WEAVING CENTER</p>	<p>BLOW UP CONNECTION DETAILS</p>	-	-	-	<p>PROCESSED FOR CONSTRUCTION</p>	
		<p>DATE: 10-11-2022</p>	<p>LOCATION:</p>	<p>MAGSIBUL BATANGAS</p>	<p>DATE:</p>	<p>DESIGNED BY:</p>	<p>S.M.A.</p>	<p>CHECKED BY:</p>	<p>S</p>	<p>24</p>
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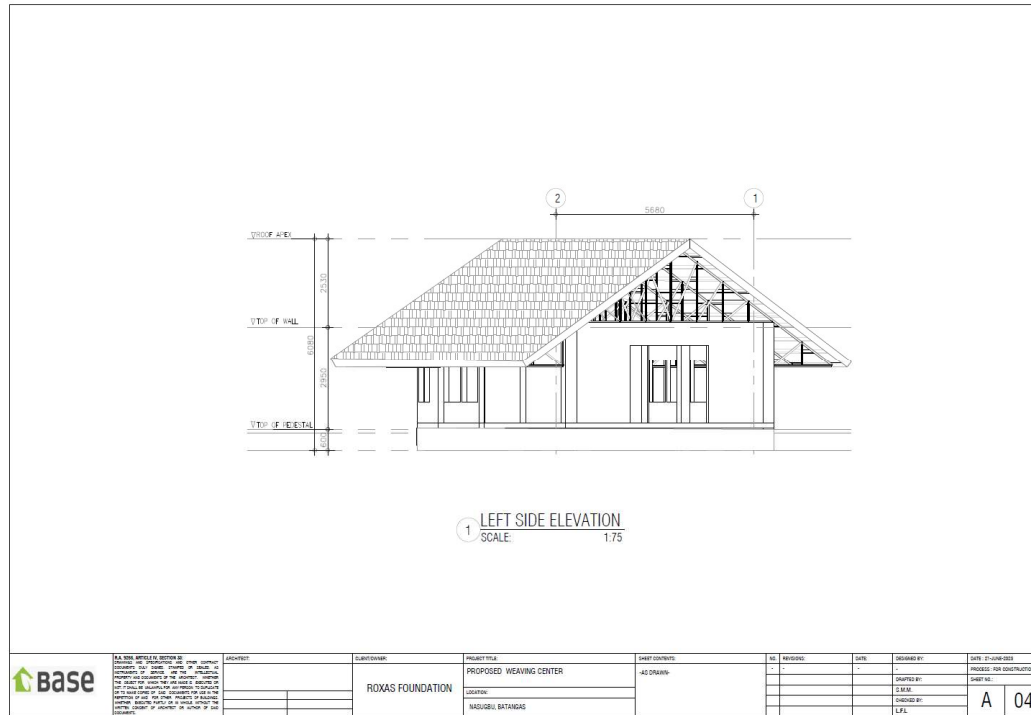


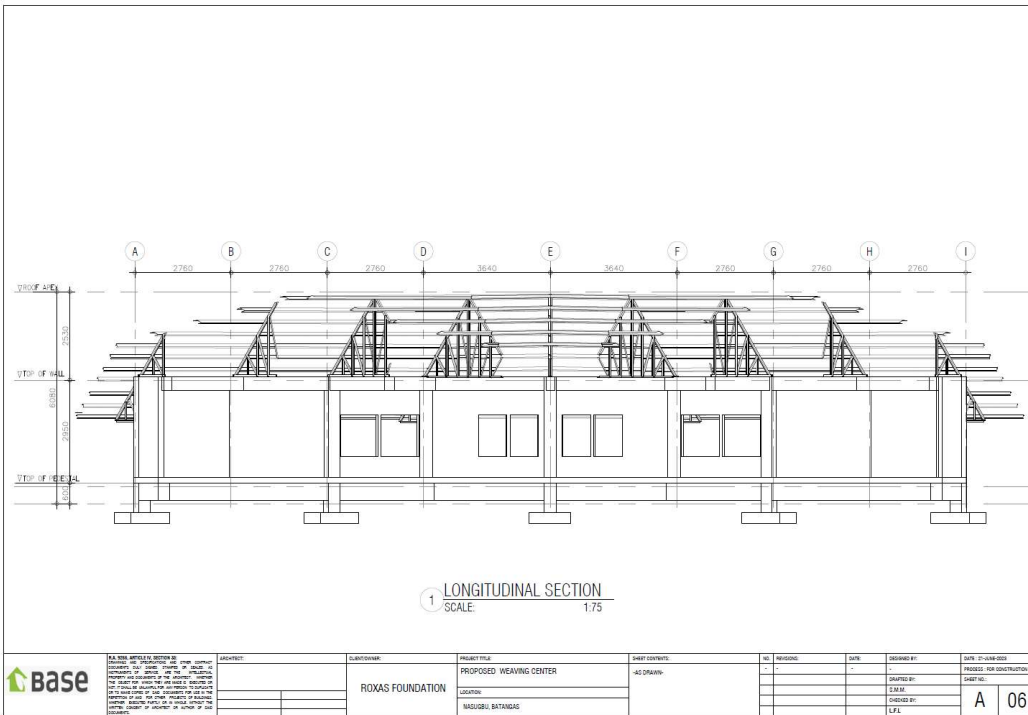
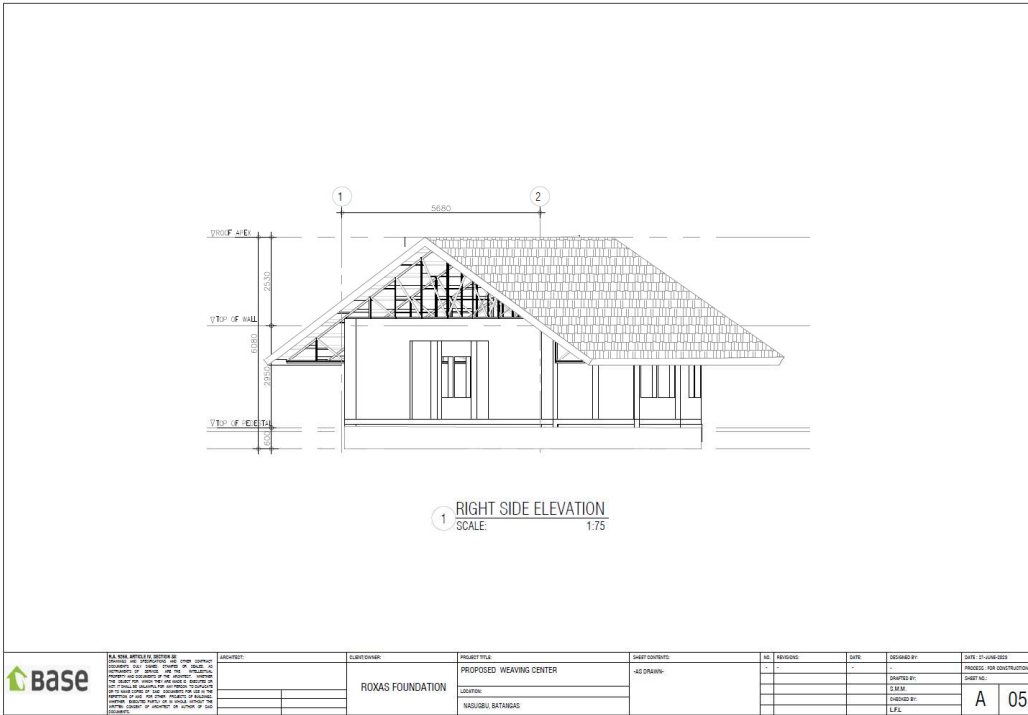


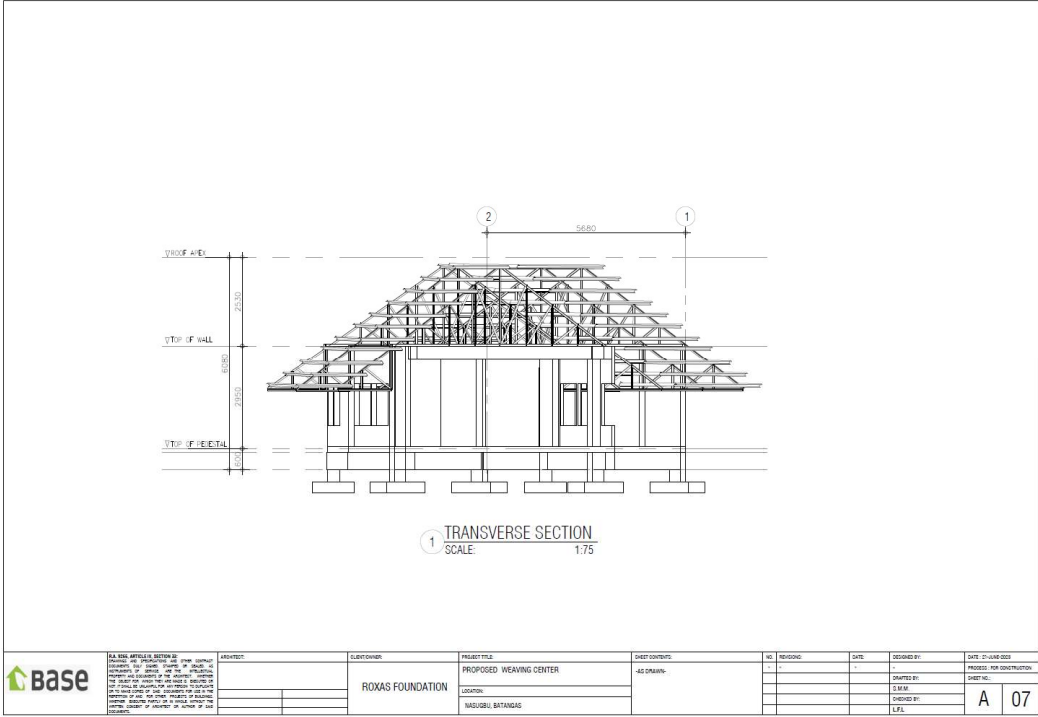
## A.2 Comparative concrete and steel building plans

Building plans in this section were provided by Base-Bahay foundation supporting the current research. Reinforced concrete and steel structures have been calculated to meet the Philippines current building code regarding earthquake and typhoon resistance.

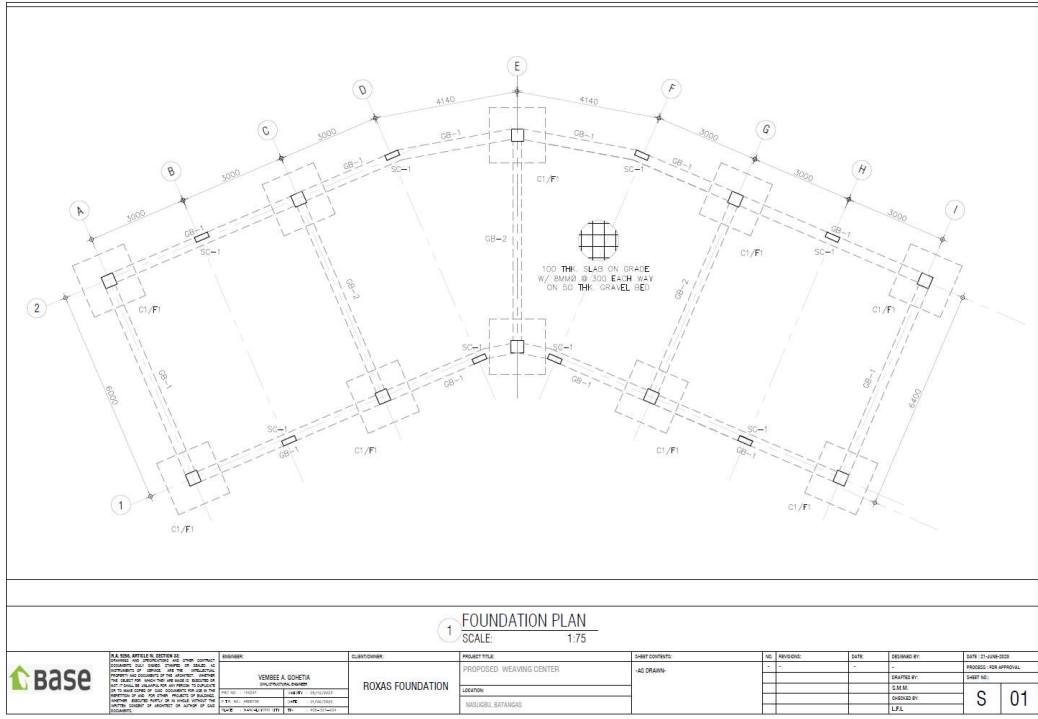




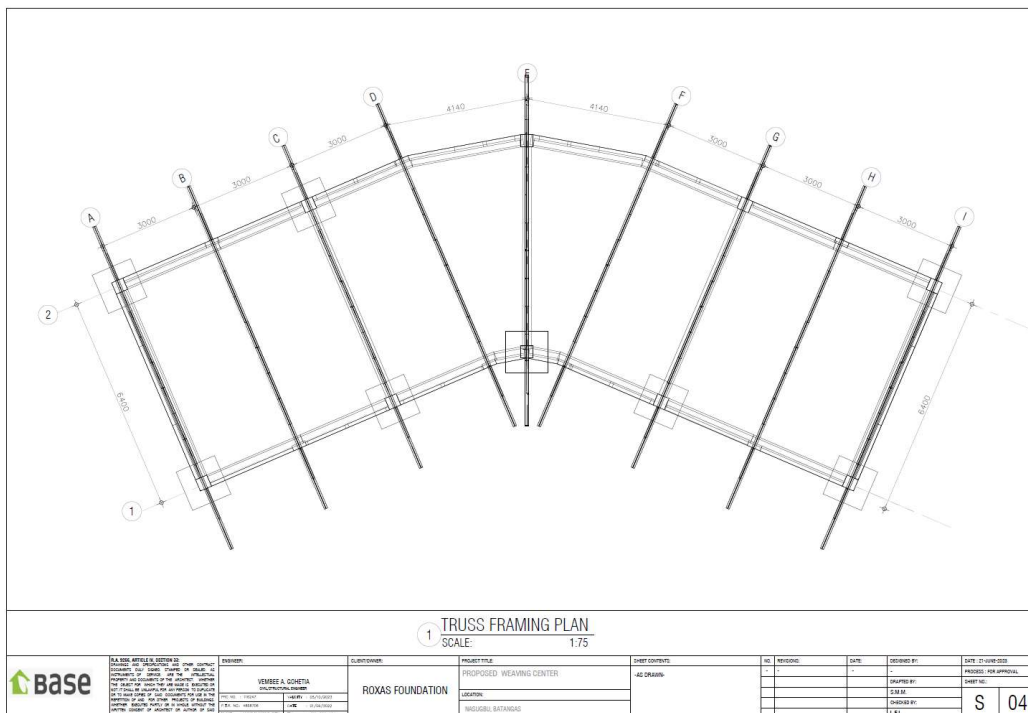
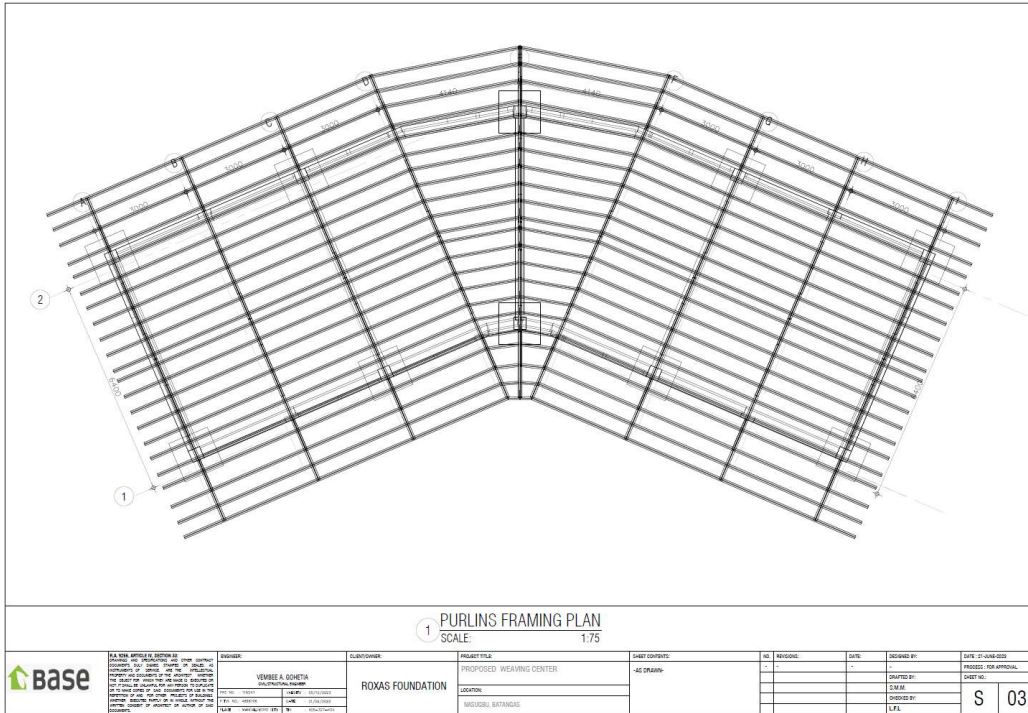




	<p><b>BASE ENGINEERING SYSTEMS</b>  <small>INCORPORATING ARCHITECTURE, ENGINEERING AND CONSTRUCTION SERVICES</small></p>	ADDRESS:	CLIENT/OWNER:	PROJECT TITLE:	DATE:	DESIGNED BY:	DATE: 27-JAN-2023
			ROXAS FOUNDATION	PROPOSED WEAVING CENTER	NO. REVISIONS:	SAFS:	DESIGNED BY:
				LOCATION:	NO. DRAWING:	DATE:	SHEET NO.
				MASUGUL BATANGAS			A 07



	<p><b>BASE ENGINEERING SYSTEMS</b>  <small>INCORPORATING ARCHITECTURE, ENGINEERING AND CONSTRUCTION SERVICES</small></p>	ADDRESS:	CLIENT/OWNER:	PROJECT TITLE:	DATE:	DESIGNED BY:	DATE: 27-JAN-2023
			VERISE A. OSMETA <small>MULTIDISCIPLINARY ENGINEER</small>	PROPOSED WEAVING CENTER	NO. REVISIONS:	SAFS:	DESIGNED BY:
			ROXAS FOUNDATION	LOCATION:	NO. DRAWING:	DATE:	SHEET NO.
				MASUGUL BATANGAS			S 01





# APPENDIX B: Measuring Equipment



## AIR TEMPERATURE

### Air temperature sensor (Pt100 output)



- Accurate Temperature measurements (0.1°C)
- 4-wires technology for long distance sensor cable
- Radiant screen units availability for outdoor measurement in direct sunlight and in meteorological applications
- Forced ventilation radiant screen availability
- Converters for 4-20 mA and RS485 Modbus-RTU outputs
- In house ISO17025 accredited calibration laboratory

Pt100 Air temperature sensor for indoor use and, coupled with a radiant screen, for meteorological applications. A 4-wire, Pt100 1/3 DIN B sensing element guarantees very good accuracy over an extended temperature range. This sensor is ideal for virtually any kind of environmental application.

#### Technical Specifications

Order numb.	DMA033A	DMA033.1	EST033
Connector	Free wires (4-wire)	Male connector for DWA5nn cables	Mini-Din connector
Cable	L=5 m	L=5 m	L=2 m
Data logger compatibility	M-Log (ELO008) Alpha-Log/E-Log	Using DWA5nn extension cable: M-Log (ELO008) Alpha-Log/E-Log	M-Log (ELO009) R-Log (ELRS10)

#### Common Technical Specifications

Temperature	Principle	Pt100 1/3 DIN Class AA (Class AA EN60751)
	Type	RTD 4 wires
	Measuring range	-50...70°C
	Accuracy	0.10°C (@0°C)
	Output	Pt100 DIN-IEC 751 table (EN 60751)
	Resolution	0.01°C (A/E/M/R-Log)
	Response time (T90 air)	30 s without protective filter, 6 min with protective filter

## RADIANT TEMPERATURE (TG)

### Black globe thermometer (Pt100 output)



- ◉ Accurate temperature measurement (0.1°C)
- ◉ Design made in compliance to ISO7726 standard
- ◉ High absorption paint on the copper globe (>0.98)
- ◉ IP66 protection rate
- ◉ Availability of external converters for 4...20 mA and Modbus-RTU outputs
- ◉ In-house ISO17025 calibration laboratory

The standard globe thermometer consists of a black-painted copper sphere with a diameter of 150 mm and a thickness of 0,4 mm. It contains a thermometer with its bulb at the center of the sphere. This sensor is described in the ISO7726 standard. Main scope of the radiant temperature measurement in meteorological applications is the possibility of estimate the Mean Radiant Temperature (T<sub>mr</sub>) which is one of the most important meteorological parameters governing human energy balance and the thermal comfort of man in micrometeorological measurements.

#### Technical Specifications

Order numb.	DMA121A	
Temperature	Sensitive element	Pt100 DIN-A (Class A EN60751)
	Type	RTD 4 wires
	Range	-50...70°C
	Accuracy	0.15°C (@0°C)
	Output	Pt100 DIN-IEC 751 table (EN 60751)
	Response time	20 min
	Operative temperature	-40...80°C
	Material	Copper
	Cable	L=5 m
	Power consumption	None
	Design	ISO7726
	Protection	IP66
	Data logger compatibility	M-Log (ELO008) R-Log (ELR515) E-Log A-Log

## AIR TEMPERATURE AND RELATIVE HUMIDITY

### Thermohygrometer



- Design and performances addressed to meteorological applications
- Fast return after saturation
- High protection from salty and polluted air
- High efficiency radiant screen
- Optional forced ventilation radiant screen
- ISO17025 traceability

Precise and reliable, this sensor is suitable for continuous meteorological measurements also in severe environments and in presence of steep thermal and hygrometric variations. DMA672.1, DMA672.5 temperature output is Pt100 element and 0...1 Vdc output for RH%. DMA672.3 output is 0...1 Vdc for both Temperature and RH%. DMA672.3 is very suitable for tropical weather in continuous high temperature and RH conditions. For outdoor application it should be coupled with a radiant screen.


#### Technical Specifications

Codice	DMA672.1	DMA672.5	DMA672.3
<b>Output</b>	RH%:0...1 Vdc. °C:Pt100 DIN-IEC 751 table (EN 60751) UART (A-Log)	RH%:0...1 Vdc. °C:Pt100 DIN-IEC 751 table (EN 60751)	2X0...1 V
<b>Power supply</b>	5...24 Vdc		5...24 Vdc or 5...16 Vac
<b>Power consumption</b>	2 mA		<5 mA
<b>Cable and connector</b>	L=3 m free wires (8 wires)	L=3 m + Male connector for DWA9xx extension cables	L=5 m free wires (8 wires), detachable
<b>Data logger compatibility</b>	M-Log (ELO008) A/E-Log (all models)	Using DWA9nn estension cable: M-Log (ELO008) E-Log A-Log (using ALIEM module)	M-Log (008) E-Log A-Log (using ALIEM module)

#### Common Technical Specifications

<b>Temperature</b>	Principle	RTD Pt100 1/3 DIN (Class AA EN60751)
	Measuring range	-50...100°C (DMA672.3: -40...60°C)
	Accuracy	0.1°C (@0°C)
	Resolution	0.01°C (A/M/R/ELog)
	Response time (T90)	Typical 4 sec (1 m/sec air flow)
	Long term stability	<0.1°C/year

Models E-Log

Code	ELO3305	ELO3515	ELO3305.1
			
<b>Description</b>	E-Log data logger. N.12 inputs by terminal block		
<b>Inputs type</b>	Terminal block		
<b>Analog inputs</b>	N.8 differential (N. 16 single-ended)		
<b>Digital inputs</b>	N.4 (on/off or frequency/counter)		
<b>Serial Ports</b>	N.2 RS232		N.1 RS232 N.1 RS485
<b>Radio</b>		<ul style="list-style-type: none"> <li>• Type: ZigBee</li> <li>• Frequency: ISM 2.4 GHz direct sequence channels</li> <li>• Power: 10 mW (+10 dBm)</li> </ul>	
<b>Sensor's auto-recognition</b>	NO		
<b>On/off outputs</b>	YES		
<b>Back-lit display</b>	NO		
<b>Threaded slot for tripod fixing</b>	NO		
<b>Internal battery</b>	NO		
<b>Plug for power battery charger</b>	YES		
<b>Included accessories</b>	RS232/USB adapter, RS232 cable, DIN-bar mounting		RS232/USB adapter, RS232 cable, DIN-bar mounting, adapter for RS485 cable wires

## SURFACE TEMPERATURE

### Surface temperature sensor (Pt100)



- Robust sensor for outdoor applications even in severe environmental conditions
- 4-wires Pt100 technology for long distance cable connections
- Ideal to be attached to the walls for wall surface temperature measurements in building assessments (U factor applications)
- Pt100 1/3 DIN B Class AA sensitive element for outstanding accuracy (0.15°C)
- Flat cable for cabling in narrow path (EST124)
- Accessories for 4...20 mA and RS485 signal output
- In-house ISO17025 accredited calibration laboratory

Plate sensor for surface temperature measurements. The compact dimensions allow installation even in small spaces. It can be easily fixed using silicon or adhesive band. Thermoconductive paste can be used to increase the heat exchange.

#### Technical Specifications

PN	DLE124A	DLE124A.1	EST124
Connector	Free wires (4-wires)	Cable+male connector suitable for DWASnn extension cables	Mini-DIN connector
Cable	L= 20 m - Ø 6 mm	L= 5 m - Ø 6 mm	L= 10 m flat
Cable type	Polyurethane external coating	Polyurethane external coating	Flat cable AWG28
Use	Indoor and outdoor	Indoor and outdoor	Indoor and outdoor
Data logger compatibility	M-Log (ELO008) E-Log A-Log	Using DWASnn extension cable: M-Log (ELO008) E-Log A-Log	M-Log (ELO009)

#### Common Technical Specifications

Temperature	Principle	Pt100 DIN A (Class A EN60751)
	Type	4 wire RTD
	Measurement range	-50...80°C
	Accuracy	0.15°C (@0°C)
	Output	Pt100 DIN-IEC 751 table (EN 60751)
	Resolution	0.01°C (A/M/E-Log)
	Response time (T90)	35 s

# APPENDIX C: Life Cycle Assessment Data

## C1. Bill of Materials (BOM) of case study CBSW building

Table C1 Bill of Materials for the case-study CBSW building. Items excluded from the assessment are highlighted in grey.

Item Code	Item	Quantity	Units	Modelling Approach
<b>1. PRELIMINARY WORKS</b>				
1.1	Coconut Lumber 2x2x10	23.8	pcs.	
1.2	Assorted CW Nails (3" and 1 1/2")	1.21	kg	
1.3	#60 Nylon String (37m/roll)	3.14	roll	
<b>2. FOUNDATION WORKS</b>				
<b>2A. EXCAVATION</b>				
<b>2B. GRAVEL BEDDING</b>				
2.1	2B.1. G1 Gravel 1"	18	m <sup>3</sup>	(i)
<b>2C. SOIL TREATMENT</b>				
2.2	2C.1. Termite-X Solution	12	ltr	
<b>2D. ISOLATED AND WALL FOOTING</b>				
2.3	Portland Cement Premium Type 1P	50	bg	(i)
2.4	Coarse Washed Sand	2.73	m <sup>3</sup>	(i)
2.5	Gravel 3/4 (crushed/selected)	5.46	m <sup>3</sup>	(i)
2.6	10mmØ x 6.00m RSB Grade 40	55	pc	(i)
2.7	8mmØ x 6.00m RSB Grade 33	32	pc	(i)
2.8	#16 Tie wire	58.2	kg	(ii)
<b>2.E.RC WALL AND PEDESTAL, BAMBOO DOWEL AND FORMWORKS</b>				
2.9.	Portland Cement Premium Type 1P	68	bg	(i)
2.10.	Coarse Washed Sand	3.75	m <sup>3</sup>	(i)
2.11.	Gravel 3/4 (crushed/selected)	7.51	m <sup>3</sup>	(i)
2.12.	12mmØ x 6.00m RSB Grade 40	39	pc	(i)
2.13.	10mmØ x 6.00m RSB Grade 40	112	pc	(i)
2.14.	8mmØ x 6.00m RSB Grade 33	42	pc	(i)
2.15.	#16 Tie wire	9.77	kg	(ii)
2.16.	Phenolic plywood 1.22m x 2.44m x 12mm thick	12.36	pc	
2.17.	1x2x10 good lumber	29.35	pc	
2.18.	1 1/2" CWN	0.7	kg	(ii)
2.19.	2 1/2" CWN	0.7	kg	(ii)
2.20.	damp proofing: 4-6mils polyethylene sheets	8.73	m <sup>2</sup>	

Table C1 (Continued)

<i>Item Code</i>	<i>Item</i>	<i>Quantity</i>	<i>Units</i>	<i>Modelling Approach</i>
<b>2.F. BACK FILL &amp; COMPACTION</b>				
2.21.	Fill Materials (Item 200)	43.24	m <sup>3</sup>	
<b>2.G. SLAB-ON-GRADE</b>				
2.22.	Portland Cement Premium Type 1P	144	bg	(i)
2.23.	Coarse Washed Sand	7.99	m <sup>3</sup>	(i)
2.24.	Gravel 3/4 (crushed/selected)	15.98	m <sup>3</sup>	(i)
2.25.	8mmØ x 6.00m RSB Grade 33	227	pc	(i)
2.26.	#16 Tie wire	6.01	kg	(ii)
<b>3. FABRICATION OF PANELS</b>				
<b>3.A. STRUCTURAL WALL PANELS</b>				
3.1.	2x4x8' S4SKD Lumber (lower plate)	102.47	bd.ft	(i)
3.2.	Treated Bamboo Pole 2.44m	50	pc	(iii)
3.3.	Treated Bamboo Pole 3.0m	100	pc	(iii)
3.4.	Treated Bamboo Pole 4.0m	4	pc	(iii)
3.5.	1/8 x 1 x 6m Flat Bar (3mm thick)	16	pc	(i)
3.6.	1/2"Ø x 3.00m Threaded Rod	9.33	pc	(ii)
3.7.	1/2"Ø Nut	210	pc	(ii)
3.8.	1/2"Ø Washer	210	pc	(ii)
3.9.	CWN 2 1/2"	6.42	kg	(ii)
3.10.	3/8"Ø x 3.00m Threaded Rod (on flat bar)	3.7	pc	(ii)
3.11.	3/8"Ø Nut	148	pc	(ii)
3.12.	3/8"Ø Washer	148	pc	(ii)
3.13.	Red Primer Paint	2.23	ltr	(iv)
3.14.	Paint Thinner	2.23	bottle	(i)
3.15.	Solignum (brown)	2.58	ltr	
3.16.	wood glue/ stikwel (connecting wood frames)	0.63	ltr	(i)
3.17.	1 1/2" CWN (connecting wood frames)	0.23	kg	(ii)
<b>4 DOOR &amp; WINDOW JAMBS</b>				
4.1.	2 x 4 x 8' S4S KD Lumber	285.22	bd.ft	
4.2.	Solignum (brown)	7.18	lit	
4.3.	wood glue/ stikwel (connecting wood frames)	1.74	lit	

Table C1 (Continued)

<i>Item Code</i>	<i>Item</i>	<i>Quantity</i>	<i>Units</i>	<i>Modelling Approach</i>
4.4.	1 1/2" nails (connecting wood frames)	0.51	kg	
4.5.	3" nails (connecting wood frames)	0.57	kg	
<b>5. WALL PANELS</b>				
5.1.	Treated Bamboo Pole 2.44m	46	pc	(iii)
5.2.	3/8"Ø x 3.00m Threaded Rod	8.73	pc	(ii)
5.3.	3/8"Ø Nut	120	pc	(ii)
5.4.	3/8"Ø Washer	120	pc	(ii)
5.5.	Red Primer Paint	0.28	ltr	(iv)
5.6.	Paint Thinner	0.28	bottle	(i)
5.7.	CWN 2 1/2"	1	kg	(ii)
5.8.	4" concrete nail	0.73	kg	(ii)
5.9.	Portland Cement Premium Type 1P	17.10	bag	(i)
5.10.	washed fine sand	1.50	cu.m.	(i)
<b>6. ROOF &amp; TRUSSES</b>				
<b>6.A. FABRICATION AND INSTALLATION OF TRUSSES, COLUMN-TRUSS STRUTS AND HIP RAFTER WITH MORTAR FILL</b>				
6.1.	Treated Bamboo Pole 2.44m	167	pc	(iii)
6.2.	Treated Bamboo Pole 3.00m	68	pc	(iii)
6.3.	Treated Bamboo Pole 4.00m	208	pc	(iii)
6.4.	Treated Bamboo Pole 5.00m	80	pc	(iii)
6.5.	Treated Bamboo Pole 6.5m	36	pc	(iii)
6.6.	1/2" Ø x 3m full threaded rod	36	pc	(ii)
6.7.	1/2" nuts	630	pc	(ii)
6.8.	1/2" washers	630	pc	(ii)
6.9.	metal primer	1.46	lit	(iii)
6.10.	paint thinner	1.46	bot	(i)
6.11.	portland cement type 1p	34.35	bags	(i)
6.12.	washed sand	3.01	m3	(i)
<b>6.B. INSTALLATION OF PURLINS with mortar</b>				
6.13.	Treated Bamboo Pole 2.44m	12	pc	(iii)
6.14.	Treated Bamboo Pole 3.00m	8	pc	(iii)
6.15.	Treated Bamboo Pole 4.00m	98	pc	(iii)
6.16.	Treated Bamboo Pole 5.00m	38	pc	(iii)

Table C1 (Continued)

<i>Item Code</i>	<i>Item</i>	<i>Quantity</i>	<i>Units</i>	<i>Modelling Approach</i>
6.17.	Treated Bamboo Pole 6.5m	16	pc	(iii)
6.18.	3/8" Ø x 3m full threaded rod	36	pc	(ii)
6.19.	3/8" nuts	352	pc	(ii)
6.20.	3/8" washers	352	pc	(ii)
6.21.	metal primer	0.82	lit	(iv)
6.22.	paint thinner	0.82	bottle	(i)
6.23.	1"x2"x8ft long KD wood	223.61	bdft	(i)
6.24.	solignum brown	15	lit	
6.25.	2" wood tekscrew	910	pc	
6.26.	portland cement type1p	10.08	bag	(i)
6.27.	washed sand	0.88	cu.m.	(i)
<b>6.C. INSTALLATION OF ROOF SHEETS</b>				
6.28.	Pre-painted Rib-type 0.4mm thick Roof Sheet x 3.60m long	338	sqm	
6.29.	Fascia cover 0.4mm thick x 2.44m, prepainted	20.94	pc	
6.30.	End flashing 0.4mm thick x 2.44m, prepainted	5.81	pc	
6.31.	Ridge Roll 0.4mm thick x 2.44m, prepainted	12.14	pc	
6.32.	2 1/2" wood tek screw	3696.4	pc	
6.33.	Blind Rivets 5/32x1/2"	6.00	box	
6.34.	Blind Rivets 5/32x3/4"	1.00	box	
6.35.	Vulcaseal	4.00	lit	
<b>7. WALL CLADDING</b>				
7.1.	Masonry Cement	91.23	bag	(i)
7.2.	washed fine sand	7.98	cu.m.	(i)
7.3.	0.25m x 3m long treated tad-tad	192.29	pcs	(iii)
7.4.	CWN 1 1/2"	11.05	Kg	(ii)
7.5.	#18 Tie Wire	2.60	Kg	(ii)
7.6.	3/4" hole chicken wire #20 (4ft width)	6.56	roll	(ii)
7.7.	staple wire #50 (1pack=1000staples)	6	packs	
7.8.	1 1/2" concrete nail	0.8	Kg	(ii)
<b>8. DOORS AND WINDOWS</b>				
8.1.	2.5mx2.5m Double Swing Door	2	set	
8.2.	3 1/2"x 3 1/2" Loose Pin Hinges	16	pc	
8.3.	Door Knob	2	pc	
8.4.	16 - 1.19x1.6m Awning Glass Window (W1)	30.464	sq.m.	

Table C1.1 (Continued)

<i>Item Code</i>	<i>Item</i>	<i>Quantity</i>	<i>Units</i>	<i>Modelling Approach</i>
8.5.	4 - 0.70x1.6m Awning Glass Window (W2)	4.48	sq.m.	
<b>9. ELECTRICAL WORKS</b>				
<b>10. PAINTING WORKS</b>				
<b>11. MISCELLANEOUS AND CONSUMABLES</b>				
11.1.	chalk stone (for rebars)	2	pc	
11.2.	4" Cutting Disc (for cutting of rod and rebars)	2	pc	
11.3.	4" grinding Disc (for cutting of rod)	1	pc	
11.4.	1/2 x 8 Drill Bit (for drilling bamboo)	2	pc	
11.5.	3/8" x 8" Drill Bit (for drilling bamboo)	2	pc	
11.6.	3/8" x 4" Metal Bit (for drilling flat bar)	2	pc	
11.7.	25mm x 6" Flat Bit (for mortar hole)	2	pc	
11.8.	5/32" x 3" Metal Drill Bit (for tin sheet)	2	pc	
11.9.	5/32" Drill Bit (Masonry)	2	pc	
11.10.	Dewalt Cutt Off Disc (Metal Cutting) 355x3x25.4mm	1	pc	
11.11.	3/4" Paint Brush (for flat bar, nuts and washers)	2	pc	
11.12.	1/2" Flat Bit (for tek screw head)	2	pc	
11.13.	1/2" x 16" Drill Bit long (for drilling bamboo)	2	pc	
11.14.	3/8" x 16" Drill Bit long (for drilling bamboo)	2	pc	
11.15.	Hacksaw Blade	2	pc	
11.16.	Paint Brush 4" (for solignum)	2	pc	
11.17.	Flat Bit, 32mm (1-1/4") (for wood frame)	2	pc	
11.18.	tek screw adaptor	2	pcs	
11.19.	1/8" hole screen seiver (for washed fine sand)	1	l.m.	
<b>12. DECORATIVE ELEMENTS</b>				
12.1.	Amakan	6	pc	
12.2.	Tadtad	5	pc	

## C2. Bill of Materials (BOM) of comparative case study building

Table C2 Bill of Materials for the comparative concrete and steel case-study building. Items excluded from the assessment are highlighted in grey

Item Code	Item	Quantity	Units	Modelling Approach
<b>1. PRELIMINARY WORKS</b>				
1.1'	1.1. Coconut Lumber 2x2x10			
1.2'	1.2. Assorted CW Nails (3" and 1 1/2")			
1.3'	1.3. #60 Nylon String (37m/roll)			
<b>2. FOUNDATION WORKS</b>				
<b>2A. Excavation</b>				
<b>2B. GRAVEL BEDDING</b>				
2.1'	2B.1. G1 Gravel 1"	18	m3	(i)
<b>2C. SOIL TREATMENT</b>				
2.2'	2C.1. Termite-X Solution			
<b>2D. ISOLATED AND WALL FOOTING (with concrete spacer)</b>				
2.3'	Portland Cement Premium Type 1P	78.44	bg	(i)
2.4'	Coarse Washed Sand	4.28	m3	(i)
2.5'	Gravel 3/4 (crushed/selected)	8.57	m3	(i)
2.6'	RSB	1751.12	kg	(i)
2.7'	#16 Tie wire	91.30	kg	(ii)
<b>2.E.RC WALL</b>				
2.8'	Portland Cement Premium Type 1P	101.81	bg	(i)
2.9'	Coarse Washed Sand	5.61	m3	(i)
2.10'	Gravel 3/4 (crushed/selected)	11.24	m3	(i)
2.11'	RSB	39.00	pc	(i)
2.12'	#16 Tie wire	14.63	kg	(ii)
2.13'	Phenolic plywood 1.22m x 2.44m x 12mm thick			
2.14'	1x2x10 good lumber			
2.15'	1 1/2" CWN	1.05	kg	(ii)
2.16'	2 1/2" CWN	1.05	kg	(ii)
2.17'	damp proofing: 4-6mils polyethylene sheets	8.73	m2	
<b>2.F. BACK FILL &amp; COMPACTION</b>				
2.18'	Fill Materials (Item 200)	43.24	m3	

Table C2 (Continued)

Item Code	Item	Quantity	Units	Modelling Approach
<b>2.G. SLAB-ON-GRADE</b>				
2.19'	Portland Cement Premium Type 1P	144	bg	(i)
2.20'	Coarse Washed Sand	7.99	m3	(i)
2.21'	Gravel 3/4 (crushed/selected)	15.98	m3	(i)
2.22'	8mmØ x 6.00m RSB Grade 33	227	pc	(i)
2.23'	#16 Tie wire	6.01	kg	(ii)
<b>3. WALLS, COLUMNS AND BEAMS</b>				
<b>3A COLUMNS AND BEAMS</b>				
3.1'	Portland Cement Premium Type 1P	156.40	bg	(i)
3.2'	Coarse Washed Sand	8.68	m3	(i)
3.3'	Gravel 3/4 (crushed/selected)	17.36	m3	(i)
3.4'	RSB	5423.08	kg	(i)
3.5'	#16 Tie wire	6.01	kg	(ii)
<b>3B CHB WALLS</b>				
3.6'	CHB Blocks	109	m2	(ii)
3.7'	Cement for mortar	2275.92	kg	(i)
3.8'	Sand for Mortar	4.74	m3	(i)
3.9'	Cement for plaster	349.89	kg	(i)
3.10'	Sand for plaster	1.45	m3	(i)
<b>4 DOOR &amp; WINDOW JAMBS</b>				
4.1'	2 x 4 x 8' S4S KD Lumber	285.22	bd.ft	
4.2'	Solignum (brown)	7.18	lit	
4.3'	wood glue/ stikwel (connecting wood frames)	1.74	lit	
4.4'	1 1/2" nails (connecting wood frames)	0.51	kg	
4.5'	3" nails (connecting wood frames)	0.57	kg	
<b>6. ROOF &amp; TRUSSES</b>				
<b>6.A. TRUSSES AND PURLINS</b>				
6.1'	Steel Trusses	8439	kg	(i)
6.2'	Steel Purlins	2736	kg	(i)

Table C2 (Continued)

<i>Item Code</i>	<i>Item</i>	<i>Quantity</i>	<i>Units</i>	<i>Modelling Approach</i>
<b>8. DOORS AND WINDOWS</b>				
8.1'.	2.5mx2.5m Double Swing Door	2	set	
8.2'.	3 1/2" x 3 1/2" Loose Pin Hinges	16	pc	
8.3'.	Door Knob	2	pc	
8.4'.	16 - 1.19x1.6m Awning Glass Window (W1)	30.464	sq.m.	
8.5'.	4 - 0.70x1.6m Awning Glass Window (W2)	4.48	sq.m.	
<b>9. ELECTRICAL WORKS</b>				
<b>10. PAINTING WORKS</b>				
<b>11. MISCELLANEOUS AND CONSUMABLES</b>				
<b>12. DECORATIVE ELEMENTS</b>				
12.1'.	Amakan	6	pc	
12.2'.	Tadtad	5	pc	

### C3. Calculations for modelling approach (i)

Table C3 Calculations and minor assumptions for building products modelled with approach (i). Subtitles in green correspond to the Ecoinvent processes listed in tables 5 and 6.

gravel and sand quarry operation   gravel, round   Cutoff, U
<ul style="list-style-type: none"> <li>• Bulk Density of aggregates: 1200kg/m<sup>3</sup> to 1750 kg/m<sup>3</sup> (Shahriar, n.d.)</li> </ul>
market for polyurethane adhesive   polyurethane adhesive   Cutoff, U
<ul style="list-style-type: none"> <li>• Density: 1.2g/cm<sup>3</sup>=1.2kg/l (MatWeb Material Property, n.d.)</li> </ul>
reinforcing steel production   reinforcing steel   Cutoff, U
<ul style="list-style-type: none"> <li>• Density: Grade 40 steel density: 7.8g/cm<sup>3</sup> (ASTM International, 2023) i.e. 7,800 kg/m<sup>3</sup></li> <li>• 8mmØ x 6.00m RSB Grade 40 bars' mass calculation: Volume: <math>(\pi \cdot (4 \cdot 10^{-3})^2) \cdot 6 \text{ m}^3 = 3.01\text{E-}04\text{m}^3</math> Mass: <math>(4.712\text{E-}4\text{m}^3) \cdot (7,800 \text{ kg/m}^3) = 2.352\text{kg}</math></li> <li>• 10mmØ x 6.00m RSB Grade 40 bars' mass calculation: Volume: <math>(\pi \cdot (5 \cdot 10^{-3})^2) \cdot 6 \text{ m}^3 = 4.712\text{E-}4\text{m}^3</math> Mass: <math>(4.712\text{E-}4\text{m}^3) \cdot (7,800 \text{ kg/m}^3) = 3.676\text{kg}</math></li> <li>• 12mmØ x 6.00m RSB Grade 40 bars' mass calculation: Volume: <math>(\pi \cdot (6.5 \cdot 10^{-3})^2) \cdot 6 \text{ m}^3 = 6.786\text{E-}4\text{m}^3</math> Mass: <math>(4.712\text{E-}4\text{m}^3) \cdot (7,800 \text{ kg/m}^3) = 5.293\text{kg}</math></li> </ul>
sawnwood, beam, softwood, dried (u=20%), planed  Cutoff, U
<ul style="list-style-type: none"> <li>• bdf is a volume measure equivalent to 12x12x1 inches: i.e., <math>12 \cdot 0.0254 \cdot 12 \cdot 0.0254 \cdot 0.0254 = 0.00236 \text{ m}^3</math> per bdf</li> </ul>
steel production, low-alloyed, hot rolled   steel, low-alloyed, hot rolled   Cutoff, U
<ul style="list-style-type: none"> <li>• Typical density of low alloyed steel: 7.5 to 8.05g/cc (ASTM International, 2023) i.e., 7500 to 8050 kg per m<sup>3</sup></li> <li>• Flat bar size: 1/8 x 1cm x 6m Flat Bar (3mm thick) i.e., <math>0.003175 \cdot 0.01 \cdot 6 = 1.91 \cdot 10^{-4} \text{ m}^3</math></li> <li>• Minimum mass: <math>(1.91 \cdot 10^{-5}) \cdot 7500 = 1.42875\text{kg}</math> Maximum mass: <math>(1.91 \cdot 10^{-5}) \cdot 8050 = 1.533525\text{kg}</math></li> </ul>

## C4. Calculations for modelling approach (ii)

Table C4 Calculations and minor assumptions for building products modelled with approach (ii). Subtitles in purple correspond to the processes listed in Table 7 and Table 8, and whose inputs are described in

Table 10.

(n) chicken wire
<ul style="list-style-type: none"> <li>• From Base-Bahay's inventory: each mesh has <math>20\text{m}^2</math>. Because the width is 4ft (1.2192m), then the estimated length is 16m.</li> <li>• A chicken wire of the same aperture having <math>45 \times 1.22 = 54.9\text{m}^2</math>, weights 8.8kg (Shandong Xingying Environmental Energy Technology Co. LTD, n.d.). Thus, a mesh of <math>20\text{m}^2</math> weights approximately 3.2kg</li> </ul>
(n) nuts
<ul style="list-style-type: none"> <li>• Mass of each 1/2" nut: 0.07lb (Portland Bolt &amp; Manufacturing Company, n.d.) i.e. 0.03175kg per pc (or 31.49pc/ kg)</li> <li>• Diameter of a 1/2" (nominal) nut: 1" (Atlanta Rod and Manufacturing, n.d.) i.e. radius: <math>0.5" = 1.27\text{cm}</math> (i.e. the nominal diameter equals the radius of the nut) Height of a 1/2" (nominal) nut: <math>31/64" = 1.23\text{cm}</math></li> <li>• Approximation of surface area: Hexagon of 1.27cm radius, has area: <math>2.19\text{cm}^2 = 2.19 \times 10^{-4}\text{m}^2</math> Outer area: <math>0.0123 \times 0.0127 \times 6 + 2.19 \times 10^{-4} = 1.16 \times 10^{-3}\text{m}^2</math> i.e. <math>1.16 \times 10^{-3}\text{m}^2</math> of coating per nut Thus: <math>31.49 \times 1.16 \times 10^{-3} = 3.64 \times 10^{-2}\text{m}^2</math> per kg of nuts</li> </ul>
(n) threaded rods
<ul style="list-style-type: none"> <li>• Dimensions: 0.0127m diameter, 3m length. Thus volume is: <math>\pi \times (0.0127/2)^2 \times 3 = 3.80\text{E-}04\text{m}^3</math></li> <li>• Surface area: <math>\pi \times (0.0127) \times 3 = 0.011969\text{m}^2</math> per rod</li> <li>• Typical density of low alloyed steel: 7.5 to 8.05g/cc (ASTM International, 2023)</li> <li>• Minimum mass: <math>(3.80\text{E-}04) \times 7500 = 2.85\text{kg}</math> Maximum mass: <math>(3.80\text{E-}04) \times 8050 = 3.06\text{kg}</math></li> <li>• Minimum pc per kg: 0.327 pc per kg Maximum pc per kg: 0.351 pc per kg</li> <li>• Minimum Surface area per kg: <math>0.039\text{m}^2</math> per kg Maximum Surface area per kg: <math>0.042\text{m}^2</math> per kg</li> </ul>

Table C4 (Continued)

(n) washers
<ul style="list-style-type: none"><li>• Dimensions: 0.0127m inner diameter, 0.03m outer diameter, 0.003 thickness Thus volume is: <math>0.003 * (\pi * (0.03/2)^2 - \pi * (0.0127/2)^2) = 1.74E-6m^3</math></li><li>• Surface area: <math>\pi * 0.03 + \pi * 0.0127 + (\pi * (0.03/2)^2 - \pi * (0.0127/2)^2) = 9.83E-4m^2</math></li><li>• Typical density of low alloyed steel: <math>8g/cc = 8000kg/m^3</math></li><li>• Mass of 1 washer: <math>(1.74E-6m^3) * (8000kg/m^3) = 1.74 * 10^{-6} * 8000 = 0.014kg</math> per piece Thus, there's 71.8pc/kg</li><li>• Coating per kg: <math>71.8 * 9.83E-4m^2 = 0.071m^2</math></li></ul>

## C5. Calculations for modelling approach (iv)

Table C5 Calculations and minor assumptions for building products modelled with approach (iv)

metal primer
<ul style="list-style-type: none"><li>• Reference EPD: Gloria, T. P. (2018)</li><li>• Reference flow to functional unit: 1.48kg (Market-based life scenario) (Gloria, 2018, p. 6)</li><li>• Traci GWP for the 1.48kg (Market-based life scenario): 2.83 kgCO<sub>2</sub>eq (incl Bio Carb) (Gloria, 2018, p. 6) i.e. 1.91kgCO<sub>2</sub>eq per kg</li><li>• But A1-A3 impacts (stage 1) are 92% of the impacts (Gloria, 2018, p. 14) Thus the A1-A3 TRACI GWP impacts are: 1.76kgCO<sub>2</sub>eq per kg</li><li>• ReCiPe GWP (which is IPCC 2013 method) can be approximated from the Traci GWP with a conversion factor of 1.03. ) (Dong et al., 2021, p. 7) Thus, the IPCC 2013 impact is: 1.76*1.03=1.812kgCO<sub>2</sub>eq per kg</li></ul> <p>Conversion factors:</p> <ul style="list-style-type: none"><li>• Typical density of a metal primer: 1.43kg/l</li></ul>

## C6. Calculations of transportation distances

Table C6 Calculations of transportation distances of building materials. Materials that are not included in the table are transported from a manufacturing site in Manila and therefore have the same A4 distance as cement in the first entry of the table.

(n) cement A4
<ul style="list-style-type: none"> <li>• Transportation from Manila, where cement manufacturing site is located (Base Bahay, personal communication, June 15, 2023)</li> <li>• Distance from Manila to Reparo, Nasugbu (Google, n.d.-b): 113km</li> </ul>
(n) gravel A4
<ul style="list-style-type: none"> <li>• Assumption: gravel is purchased from a near-by quarry in the Nasugbu region.</li> <li>• Transportation from nearest gravel quarry (Google, n.d.-d): 19km</li> </ul>
(n) nails A4
<ul style="list-style-type: none"> <li>• Transportation from Manila, where plausibly nails manufacturing site is located (Base Bahay, personal communication, June 15, 2023)</li> <li>• Transportation from Manila. Same distance as cement transportation from Manila to Nasugbu: 113km</li> </ul>
(n) reinforcing steel A4
<ul style="list-style-type: none"> <li>• Transportation from China, where plausibly RSB manufacturing site is located (Base Bahay, personal communication, June 15, 2023)</li> <li>• Plausible manufacturing site: Shandong Ruixin Metal Products Co., Ltd.; major RSB manufacturer in China (Made in China, n.d.)</li> <li>• Location factory &amp; distance to Shanghai port: 309km (Google, n.d.-a)</li> <li>• Plausible transport from Shanghai to manila port: <math>1,225\text{nm}=1225*1.852=2269\text{km}</math> (Shiptraffic.net, n.d.)</li> <li>• Transportation from Manila. Same distance as cement transportation from Manila to Nasugbu: 113km</li> </ul>
(n) sand A4
<ul style="list-style-type: none"> <li>• Assumption: gravel is purchased from a near-by quarry in the Nasugbu region.</li> <li>• Transportation from nearest sand quarry (Google, n.d.-e) 27 km</li> </ul>

Table C6 (Continued)

(n) sawnwood A4
<ul style="list-style-type: none"><li>• Transportation from Canada, where sawnwood manufacturing site is located (Base Bahay, personal communication, June 15, 2023)</li> <li>• Plausible manufacturing site: Plateau sawmill- biggest sawmill in Canada (Sawmill Database, n.d.) Location of Plateau sawmill &amp; distance to Vancouver port: 898km (Google, n.d.-c)</li> <li>• Plausible transport from Vancouver to manila port: (Shiptraffic.net, n.d.): <math>19,477\text{nm} = 19477 * 1.852 = 36,071\text{km}</math></li> <li>• Same distance as cement transportation from Manila to Nasugbu: 113km</li> <li>• Feasible density: <math>435\text{kg/m}^3</math> (Ruttenborg, 2020)</li></ul>

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