Hygrothermal analysis of wooden frame and cross-laminated timber walls for energy efficiency and durability in Bhutanese climate

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Abstract

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Much research on building envelopes and energy efficiency in Bhutan has been done, however the importance of hygrothermal analysis on timber envelopes has received limited attention. Is constructing all residential buildings with timber in the Bhutanese climate feasible? A simulation-based methodology of white box modeling software Design-Builder and WUFI Pro is used to analyze the feasibility of timber construction. Typical Bhutanese buildings are more energy in-efficient due to poor thermal and leaky buildings envelope. The baseline building has an energy demand of 269.5 kWh/m^{2}a in cold climates and 193.0 kWh/m^{2}a in warm and humid climates. The proposed building, with timber frame and cross-laminated timber (CLT), has energy demand of 93.7 kWh/m^{2}a by following prescriptive ASHRAE standards and 85.8 kWh/m^{2}a by using Passivhaus building envelope in cold climates, with energy savings of 51% and 62%, respectively. For warm and humid climates, the proposed building has energy demand of 168.7 kWh/m^{2}a by following prescriptive ASHRAE standard and 151.2 kWh/m^{2}a for Passivhaus standard, saving 11% and 18% energy, respectively. For hygrothermal performance 24 configurations have been studied for WFW and 72 configurations for CLT wall. 88% of the WFW fail in the cold climate except for those configurations which have both vented and vapor barrier. However, warm and humid weather does not give any moisture problem to WFW. The CLT assemblies pass the durability test in all the simulated configurations including XPS,EPS, MW insulation. The conclusion of the research is simulation based, and further experimental validation is required.

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Dedication

To my loving daughter Yeezhin Chozom Wangchuk, the only one in the family who did not know how far Canada was and yet spent two years with distant love from her parents. Learning how to talk and seeing you step into your first school from 11,000 miles away is our greatest sacrifice.

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Abbreviation

CLT	Cross Laminated Timber
WFW	Wood Frame Wall
WUFI	Warme Und Feuchete Instationar
PH	Passivhaus
ASHRAE	American Society of Heating, Refrigerating and Air-Conditioning Engineers
TOE	Tone of Oil Equivalent
EE	Energy Efficient
MoWHS	Ministry of Work and Human Settlement
DES	Department of Engineering Service
RSI	R-value System International
HVAC	Heating Ventilation and Air Conditioning
RH	Relative Humidity
ACH	Air Change Per Hour
AB	Air Barrier
WRB	Water Resistive Barrier
VP	Vapor Barrier
MI	Mold Index

Chapter 1: Introduction

1.1 Background

Wood is one of the earliest construction materials and, if appropriately durable species are specified and maintained correctly, can perform adequately for extremely long periods. An ancient structure Horyuji Temple in Nara, Japan, is a five-story tall timber pagoda that is 1400 years old. In terms of modern and future use, there is a current renaissance in tall-wood construction being driven on two fronts: the advent of a range of new engineered wood products and an increasing interest by architects and designers in tackling global CO2 emissions through carbon-positive environmentally sustainable building design (Woodard & Milner, 2016). One of the main ways of utilizing wood in buildings is cross-laminated timber. It was first conceived in the 1980s by a German engineer and professor, Julius Natterer, and now it is one of the widely used construction materials around Europe and North America (Agha Mohammadi & Shah Mohammadi, 2023). Cross laminated timber (CLT) elements consist of layers of wood lamellae that are laminated perpendicular to each other. In Europe and North America, a typical CLT element consists of 3, 5, 7 or 9 layers, glued together (Teibinger & Dolezal, 2021). Element thicknesses range from 60 to 320 mm. CLT elements typically exhibit widths and lengths of up to 3.5 and 16 meters, respectively (Skagseth et al., 2022). A basic exterior CLT construction wall assembly normally consists of a CLT panel (interior surface), thermal insulation, a wind barrier, a drainage gap, and exterior cladding(Skullestad et al., 2016). Wood frame wall (WFW) is another dominant category for timber construction in North America. It consists of wood frames as structural members, which can be filled with insulation(Canadian Wood Council, 2002). This spacing may be changed to 12 or 24 inches (300 or 610 mm) at the center, depending on the load and the limitations imposed by the type and thickness of the wall covering used. Wider studs may be used to provide space for more insulation. Insulation beyond that which can be accommodated within a stud space can also be provided by other means, such as rigid or semi-rigid insulation or batts between insulation sheathing to the outside of the studs (Kumaran et al., 2003). Hygrothermal analysis is a relatively new field. The fundamentals date back to the 1950s (Lstiburek et al., 2016a) . Analysis was observation and experience based. The primary focus was rain and groundwater control. As insulation was introduced into assemblies, energy flows were altered, resulting in materials remaining wetter for extended periods (Künzel, 2022). Simultaneously, new building materials were introduced that were inherently more water sensitive(Zerbe et al., 2015). The focus shifted from rain and groundwater to vapor movement through air transport and molecular diffusion(Kumaran, 2009a). Analysis remained rooted in observation and experience, i.e., a "build it, wet it, watch what happens" methodology. In the 1980s, with the advent of numerical analysis and computer availability, it was believed that a shift from observation and experience to numerical methods based on physics was possible. Numerous models were developed but none with good predictive capability. In the 1990s, this changed based on work done in Canada (Kumaran et al. 1994) and Sweden (Viitanen and Ritschkoff 1991). These models were principally research tools rather than design tools. Work done in Germany in 2000 changed the modeling status quo (Künzel 2002) . Hygrothermal analysis is more critical with the high performance and energy efficient building envelope due to having greater thickness of insulation (Boardman & Glass, 2020; Glass et al., 2013).

1.2 Energy Efficiency Scenario in Bhutan

Bhutan is at the stage of planning for energy-efficient (EE) building codes and certification of EE buildings (Department of Renewable energy, 2018). As shown in Figure 1, it has a well-developed roadmap for achieving energy efficiency in building, appliance, and industry sectors. It is estimated that total energy savings of 22,026 tonnes of oil equivalent (TOE) will be achieved by the end of 2030 in the building sector by following energy efficiency measures. Department of Engineering Service MoWHS has produced a report (DES, 2020), Bhutan energy baseline for the building sector, in which a detailed study has been made to analyze the feasibility of improving the thermal performance of building envelopes in terms of energy saving. It concluded that Bhutan has a great opportunity to introduce insulation which will be economically viable for the refurbishment of old buildings as well as new buildings to be built. Different working agencies are assigned to complete the task as shown in Figure 1 to achieve the energy efficient goals. Bhutan needs to introduce a new method of construction material that can fit the energy-efficient buildings roadmap, and which can give better energy efficiency with durability.

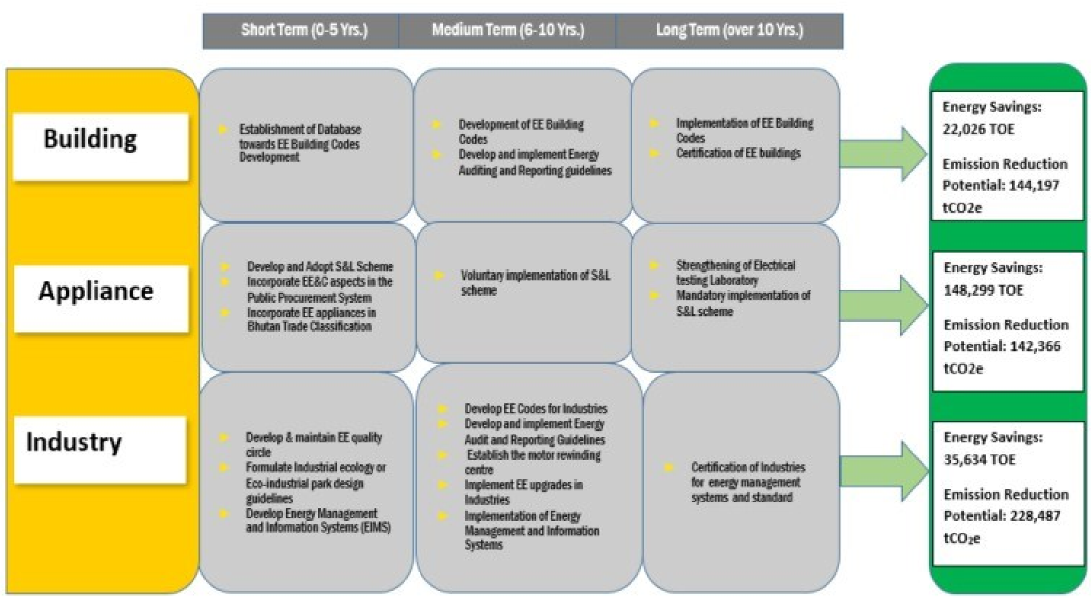


Figure 1. energy efficiency road map framework, DRE MOEA 2018

A comprehensive primary survey of 1875 households across 20 Dzongkhags were carried out to estimate the energy consumption in the residential sector (DRE, 2015). The building sector contributes to 42% of the total energy consumption in 2014. Building Sector consumes energy primarily in the form of electricity, biomass, and solid/liquid fuel (LPG, kerosene etc.). The building energy audit observations reveal that buildings in Bhutan have a high level of dependence on firewood for space heating and cooking.(DRE, 2015b)

Energy consumption in the building sector amounted to 270,356 TOE in 2014 with the Residential segment consuming 213,422 TOE of energy and Commercial & Institutional segment consuming 56,934 TOE of energy. Figure 2 shows the thermal energy consumption in buildings standing at 242,916 TOE, the electrical energy consumption is 27,440 TOE for the year 2014(DRE, 2015a)

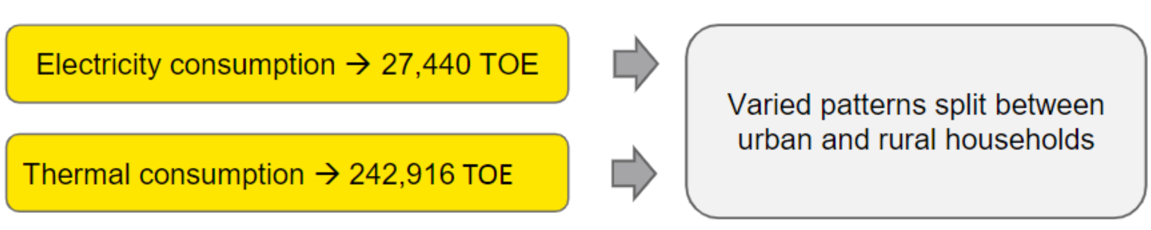


Figure 2. major areas of energy consumption in buildings (DRE, 2015a)

Bhutan has made significant progress in increasing access to electricity in recent years and achieved almost 100 per cent access rate in 2018. Energy efficiency improvement needs to be boosted across all sectors to achieve a 3 per cent annual improvement, reducing energy intensity from 3.75 megajoules per US dollar (MJ/US$) to 2.54 MJ/US$ by 2030(DRE, 2022).

Bhutan's energy intensity in 2017 was estimated to be 3.75 MJ/US$. Energy intensity in Bhutan has declined at an average annual rate of 4.8 per cent between 1990 and 2010. A doubling of the 1990-2010 improvement rate is required to achieve the sustainable development goal (SDG) 7.3 target, which requires an average annual rate increase of 9.6 per cent between 2010 and 2030. This would be an extremely challenging target, in which energy intensity will need to reduce to

1.25 MJ/US$. In consultation with stakeholders, a conservative energy efficiency improvement target of 3.0 per cent per annum has been agreed which will align with the suggested global energy efficiency improvement rate (DRE, 2022). The average energy consumption for a residential apartment building in Bhutan is 97 kWh/m² (DES, 2020). It is an incredible figure if it is the result of being heated or cooled to a thermal comfort level. But this is only the result of heating a living room and keeping the rest of the rooms unheated.

1.3 Need for Hygrothermal Analysis

Analysis of hygrothermal conditions in low-energy houses is important because of their likely sensitivity for excessive moisture(Bomberg & Shirtliffe, 2009; Glass et al., 2013; Kumaran, 2009b; Künzel, 2022; Sandberg, 2009). In case of Bhutan, it has not done any research when it comes to hygrothermal analysis of a building envelope. Currently Bhutan does not have a low energy building, nor a building constructed entirely out of timber, therefore it does not have dominant moisture problems(DES, 2020). The need for hygrothermal analysis is critical for the future energy efficient buildings in Bhutan if its construction materials were made up entirely of timber. The significant factors affecting the durability of building enclosure assemblies include HAM (heat, air, moisture transport) and how building materials are designed together. The building physics of HAM transport is explained in appendix 1. A potential impact and the unintended consequences of energy-efficient measures on moisture management need to be researched for Bhutanese climate. Building energy codes, when developed in Bhutan, will require increasing levels of thermal control for the building enclosure(DES, 2020). The roadmap measures include increased insulation R-value. Energy code criteria for reduced heat flow across the building enclosure contribute to increased building envelope efficiency(Department of Renewable energy, 2018; DRE, 2022; Lstiburek et al., 2016b). However, reduced heat flow also slows down the wall’s ability to dry, increasing the risk of moisture-related issues. Building assemblies may start or periodically become wet but can have acceptable performance and provide a long, useful service life when allowed to dry. Problems occur when buildings stay wet long enough under adverse conditions for materials to deteriorate (FPInnovations, 2013; Künzel, 2022; Spinu, 2012). Across the world, the energy requirement becomes more stringent with every new code being revised. The new code comes with more R-Value, which can be achieved by increasing insulation thickness or using insulation with lower thermal conductivity. This process reduces heat transfer but also the drying potential of the building envelope, which results in the risk of durability (Lstiburek, 2002). For Bhutan, the energy efficiency requirement is in development, and as it progresses towards low-energy buildings, the need for durability risk assessment for future buildings is critical. That is why hygrothermal simulation for the proposed research in timber envelope with energy efficiency is not only critical but necessary.

1.4 Research Problem

The analysis on moisture safe timber residential buildings which are more energy efficient than existing buildings in Bhutan has been given less focus fundamentally at the research level. There is a dire need to find out if the high-performance timber materials are good fit for construction practices in Bhutanese climate.

1.5 Research Objectives

This research aims to study feasibility of substituting modern construction material like concrete and masonry by Timber frame and cross-laminated timber (CLT) in terms of energy efficiency and hygrothermal performance for residential buildings in Bhutan. This study aims to achieve the following objectives.

1. To examine space heating and cooling demand of timber envelope by adopting energy

code of corresponding ASHRAE climate zone and passivhaus standard,

2. To analyze the role of thermal insulation types in controlling heat and moisture transfer through the CLT building envelope,
3. To determine the need for vapor barriers in CLT and WFW building envelope, and
4. To check durability of different WFW and CLT assemblies in Bhutanese climate.

1.6 Research Question

Is it feasible to construct all residential buildings with timber in Bhutanese climate?

1.7 Limitation of Research

1. The research is entirely simulation-based and only be used as a reference for further experimental validation before applying the recommendation to practical use.

2. In the research, the Passivhaus standard is referred only to the building envelope characteristics, and the maximum energy demand of 60 kWh/m2a and heating or cooling demand of 15 kWh/m2a is not considered due to other factors like ventilation which is beyond the scope of this research. Only building envelope u value, window u factor, and airtightness values are adopted and analyzed to simplify the energy simulation, as reflected in Table 4.

3. Insulation materials in Bhutan must be imported from other countries, which is crucial for carbon emissions. However, the Impact of insulation materials on carbon footprint has not been analyzed.

1.8 Research Outline

This thesis is divided into five chapters. The introduction and goals of the study are described in the first chapter. The second chapter covers literature review and need for hygrothermal analysis in Bhutan. Chapter three discusses the methodology adopted for research based on intensive simulation. The results are discussed in chapter four. The fifth chapter summarizes the study's findings and introduces the recommendations for future research.

Chapter 2 literature review

2.1 Overview

Urban areas in Paro have 70 % of its walls made up of bricks, 10% of its walls made of hollow blocks, 13% made of stone/rammed earth and only 7% made of wood frame walls without insulation. Rural areas in Paro have 6% of its walls made up of bricks, 0% of its walls made of hollow blocks, 90% made of stone/rammed earth and only 4% made of wood frame walls without insulation. Whereas 95 % of the walls in Samdrup Jongkhar are made of bricks (DRE, 2015). In a national effort to promote traditional construction practice using rammed earth and timber framed, government introduced a scheme in 2018 in which rural areas are allowed to build only 2 story using modern construction material and not permitted to construct 3 story building if RCC frame structure are used (MoWHS, 2018). The rural areas could only construct 3 stories with traditional practices of using rammed earth and timber frame. However, people's perspective has always been towards modern construction methods, and the rule was subsequently removed in 2021.

Nuns training centre @ Choni Lhamo

Traditional Bhutanese house with rammed earth wall@ Jordi

Traditional duplex with rammed earth and wood frame @ world habitat | Traditional window @Namzang | Timber frame duplex @shutterstock

Figure 3. traditional construction of Bhutan

Figure 3 shows the traditional way of construction Bhutanese homes, the material used made it energy inefficient and had very less thermal comfort(Jentsch et al., 2017).

Concrete and brick construction @ramblin bill | Paro City @ Kuensel | Construction detail

Brick construction without insulation | Samdrup Jongkhar @kinley BBS | Construction detail

Figure 4. common modern construction in Bhutan

Figure 4 represents the modern construction practice that goes on in the country currently, this too does not have energy efficient building design components and equally uncomfortable for the occupants(Jentsch et al., 2017).

Bhutan has 71% of the land area covered under forest. 60% of the land to be protected for all times to come by constitution of Bhutan. (T.nidup, 2019) estimated that even by using 11% access of timber forest would be enough to build 360000 homes which will be needed for 50 years to come. This will also have an equivalent effect of removing 1.4 million cars from the road every year in terms of co2 emission. The findings are in alignment for Bhutan to remain as a carbon negative country. Government of Bhutan is trying to introduce new building material of timber and has made a pilot project constructed out of engineered wood glulam to replace structural members of concrete in 2020. Also, research into feasibility in terms of cost on CLT is currently being carried out by MoWHS.

Building and energy codes and standards across the world have undergone or are currently undergoing revisions, and the minimum thermal requirements for wood-frame building enclosure and CLT assemblies are now more stringent (Chang, Yoo, et al., 2020). From a thermal perspective, timber building enclosures are inherently more energy efficient than steel frame, concrete, or masonry construction—primarily because of reduced thermal bridging through the wood structural elements, including the wood studs, columns, beams, and floors . Wood also has environmental benefits because it is a renewable resource, sequesters carbon, and has less embodied energy than most alternative materials(FPInnovations, 2013). Minimum thermal insulation requirements vary by climate zone and space-conditioning needs. Buildings in colder climate zones generally require more insulation than those in temperate or warm climate zones. As the cost of energy increases, higher R-value targets in all climate zones become economically justifiable(FPInnovations, 2019).

Cross-laminated timber (CLT) is a relatively new building system of interest many countries but nonexistent in Bhutan. It is helping to define a new class of timber products known as massive or “mass” timber. It is potentially cost-competitive and is a suitable candidate for some applications that currently use concrete, masonry, and steel. CLT is an innovative wood product introduced in the early 1990s in Austria and Germany and has been gaining popularity in European residential and non-residential applications(FPInnovations, 2019). In the mid-1990s, Austria undertook an industry-academia joint research effort that resulted in the development of modern CLT. After several slow years, construction in CLT increased significantly in the early 2000s, partially driven by the green building movement. (FPInnovation, 2013). Mass timber buildings with CLT can provide potential for energy savings. Guo et al. studied the energy-saving and carbon-reducing performance of CLT buildings in the severe cold region of China through a computational simulation approach. The results showed that residential buildings constructed with CLT panels outperformed RC buildings, mostly in terms of energy savings (29.4%) and reduced carbon emissions (24.6%) (Guo et al., 2017). Simulations conducted by Setter et al. on CLT buildings in Minneapolis (USA) showed savings of 38% in annual heating energy, while the CLT house in Phoenix (USA) showed savings of 17% in annual cooling energy(Setter et al., 2019). Tettey et al. also indicates that CLT may require between 20% and 37% less energy than concrete for heating and cooling, respectively (Tettey et al., 2019).

(Kraniotis et al., 2023) has investigated the hygrothermal performance of nature-based insulation materials in two timber-based wall systems: i) stud wall and ii) externally insulated cross-laminated timber (CLT). Six nature-based insulation materials were selected for the analysis. The analyses have focused on optimizing exterior wall configurations to avoid moisture-related problems, i.e., interstitial condensation and mold growth, in the wall constructions under various climates in Europe. For this purpose, three European locations representing respective geographical parts of Europe and corresponding climate zones, were selected as input for the simulations: Oslo (Northern Europe), Paris (Central Europe), and Barcelona (South Europe), while different exterior and interior claddings were considered. A commercial 1D hygrothermal software, i.e., WUFI Pro 1D, was used for the computation of the hygrothermal performance of the wall systems, while the add-on software WUFI Bio has been further employed for the detailed evaluation of the risk for biodegradation. The results show both the wall systems, i.e., stud wall and CLT, function similarly in Oslo, while in Barcelona, the CLT systems show better performance. Furthermore, the ventilated air cavity back from the exterior cladding positively affects all assembly configurations (Kraniotis et al., 2023).

Wood buildings have been widely constructed worldwide and account for 90% of single-family homes in North America, 45–70% in parts of Europe (Asdrubali et al., 2017; Kosny et al., 2014; Nunes et al., 2020). Moreover, it is well-known that wood buildings are lightweight and easy to build. In comparison to other construction methods, such as steel framing, concrete, and masonry. Wood buildings systems have also better thermal performance because wood is a natural insulation material, not to mention the fact that wooden structures can be easily built and insulated, which consequently leads to energy savings (FPInnovation, 2013). A wood-frame envelope (building) with appropriate insulation can provide an environment that is 5◦C warmer in winter and 10◦C cooler in summer (Aslani et al., 2019).

2.2 Energy Efficiency and Hygrothermal Performance of Residential Buildings in Bhutan.

Bhutan seems lacking to embrace modern development for building in terms of thermal performance. Most buildings in Bhutan were made of timber, rammed earth, and stone without insulation (Pieter & Van Jaarsveld, 2019; Wangchuk, 2022, Sandberg, 2009). Modern constructions are made up of mineral based materials like bricks and concrete. In both cases, the thermal performance is inferior by international standards like American Society of Heating, Refrigerating and Air-Conditioning Engineers (ASHRAE) and passivhaus (Jentsch et al., 2017; Wangchuk, 2022). Studies in building thermal performance in Bhutan have been done and R-value System International (RSI) of the residential buildings is 0.67- 1. Furthermore, air tightness tests show that due to poorly sealed joints between construction elements, windows, and doors, many buildings have high infiltration rates, reaching up to 7 air changes per hour(DES, 2020; Jentsch et al., 2017). Bhutan has roughly 164,000 residential buildings (National Statistics Bureau, 2007), Of these buildings, 35.9 % have walls made of earth or stone, 24.9 % of cement-bounded bricks or stone walls, 13.9 % have concrete walls, and 12.9 % have timber walls. While the world has witnessed the extensive use of insulation in building envelopes, Bhutan is just starting to introduce in its residential building . Insulation materials are not common in Bhutan due to the lack of knowledge on the advantage of thermal insulating materials, and the unavailability of local insulating materials (Wangchuk, 2022), (DES, 2020). In research done by (DES, 2020; Lhundup & Powdel, 2020), up to 64% -90% of energy saving can be achieved by using insulation. Bhutan still does not have energy efficiency standards (Pieter & Van Jaarsveld, 2019), which inevitably makes its building without a good thermal performance.

Durability regarding timber construction has never been studied for Bhutanese context. However, heat, air, and moisture transfer are coupled and interact closely, they should not be treated separately. Improving a building envelope's energy performance will cause moisture-related problems (*ASHRAE Handbook Fundamentals*, 2017),(Glass et al., 2013),(Kumaran, 2009c),(Bomberg & Shirtliffe, 2009). Conversely, water evaporation and moisture removal by other means require energy. A sophisticated moisture control strategy can ensure adequate durability for modern, energy-efficient building assemblies (Bomberg & Shirtliffe, 200;FPInnovations, 2013; Künzel et al., 2005). Effective moisture control design must deal with all hygrothermal (heat and humidity) loads acting on the building envelope. A key design consideration with low-energy houses is their likely sensitivity to excessive moisture because a building with high thermal resistance requires thick layers of thermal insulation (Fedorik et al., 2021). The type and amount of thermal insulation material significantly impacts energy loss. Conductive heat losses in houses represent a significant part of the total energy loss. The lower the energy consumption target is set, the more critical the thermal insulation. The hygrothermal performance of highly energy-efficient buildings should be analyzed to determine whether the design creates a damp risk and conditions suitable for biological growth. There is not much research on energy efficiency due to insulation in Bhutan. However, evaluating the impact of unique design such as timber and construction practices on the hygrothermal performance of buildings is very critical. Therefore, this research is the first one with an attempt to further analyze on moisture problems in the timber building envelope with insulation in Bhutan.

2.3 Identified Research Gap.

From the literature review, it can be concluded that Bhutan is in the developing phase of its construction sector, where the benefit of insulation and durable building structures popularized by timber assemblies is at the beginning stage. Due to limited research into the applications of timber envelope (CLT and wood frame building) in Bhutan, the energy saving potential, and durability of the timber is not well investigated. Therefore, this research bridges the knowledge gap lacking in Bhutan, which has been tested in North American construction technology using both wood frame and cross-laminated building assembly.

Chapter 3 Methodology

To find out feasibility of replacing existing construction material with timber, this research follows a quantitative approach with white box modelling using Design Builder for energy efficiency analysis and WUFI Pro for hygrothermal analysis. The white-box model is fundamentally based on conserving mass, energy, and momentum. The standard approach to making a white-box model is bottom-up: building envelope, occupants, schedules, heating, ventilation, air conditioning (HVAC) systems and parameters(Tohidi et al., 2022).

3.1 Stage One: Data Collection

3.1.1 Regions and Cities Considered for The Study

The regional areas in Bhutan experiences variation in their climatic condition across short distances due to taking in the regions' altitude. (DES, 2020) However, the architectural features and construction practices are much similar. The building design does not offer climatic resilience; they are cold in winter and hot in summer.

Figure 5. new climatic classification for Bhutan based on heating cooling and dehumidification degree days @ DES 2019

The new climate has been assigned to Bhutan by (DES, 2020) the need to classify has been found necessary as due to altitude variations in every district. The climate classification according to heating cooling and dehumidification degree days for various cities in Bhutan is shown in Figure 5. Further contribution can be made by classifying the climate according to ASHRAE Standards.

		HDD @ 18 degree Celsius	CDD @ 10 degree Celsius
1	Paro	2030	1113
2	Thimphu	1752	1416
3	Gasa	3036	0
5	Bumthang	2156	537
6	Chukha	30	4450
7	Dagana	760	1458
8	Haa	2926	0
9	Lhuntse	350	3343
10	Mongar	685	2043
11	Tashi Yangtse	775	1719
12	Pema Gatshel	763	1720
13	Punakha	876	1692
14	Samdrup Jongkhar	171	3314
15	Samtse	12	4361

Table 1. heating degree day and Colling degree day of Bhutan

Table 6 is a simplified calculation of HDD and CDD of the available weather stations in Bhutan. According to HDD, the climate classification of Paro falls in zone 4B of the ASHRAE climate, requiring an Rvalue of 19.6(3.5rsi), and climate for Samdrup Jongkhar falls in zone 2A requiring 15.6 (2.7 rsi).

Climate Zone	Wood-frame, above-grade wall		Wood-frame roof—insulation entirely above deck		Wood-frame roof—attic and other	
	Minimum effective assembly [R-value (RSI)]	Nominal [R-value (RSI)]	Minimum effective assembly [R-value (RSI)]	Nominal [R-value (RSI)]	Minimum effective assembly [R-value (RSI)]	Nominal [R-value (RSI)]
Zone 1 (A & B)	15.6 (2.7)	13.0 + 3.8 ci (2.3 + 0.7 ci)	25.6 (4.5)	25.0 ci (4.4 ci)	47.6 (8.4)	49.0 (8.6)
Zone 2 (A & B)	15.6 (2.7)	13.0 + 3.8 ci (2.3 + 0.7 ci)	25.6 (4.5)	25.0 ci (4.4 ci)	47.6 (8.4)	49.0 (8.6)
Zone 3 (A, B, & C)	15.6 (2.7)	13.0 + 3.8 ci (2.3 + 0.7 ci)	25.6 (4.5)	25.0 ci (4.4 ci)	47.6 (8.4)	49.0 (8.6)
Zone 4 (A, B, & C)	19.6 (3.5)	13.0 + 7.5 ci (2.3 + 1.3 ci)	25.6 (4.5)	25.0 ci (4.4 ci)	47.6 (8.4)	49.0 (8.6)
Zone 5 (A, B, & C)	22.2 (3.9)	13.0 + 10.0 ci (2.3 + 1.8 ci)	25.6 (4.5)	25.0 ci (4.4 ci)	47.6 (8.4)	49.0 (8.6)
Zone 6 (A & B)	22.2 (3.9)	13.0 + 10.0 ci (2.3 + 1.8 ci)	31.3 (5.5)	30.0 ci (5.3)	47.6 (8.4)	49.0 (8.6)
Zone 7	22.2 (3.9)	13.0 + 10.0 ci (2.3 + 1.8 ci)	35.7 (6.3)	35.0 ci (6.2 ci)	58.8 (10.4)	49.0 (8.6)
Zone 8	31.3 (5.5)	13.0 + 18.8 ci (2.3 + 3.3 ci)	35.7 (6.3)	35.0 ci (6.2 ci)	58.8 (10.4)	49.0 (8.6)
ci = continuous insulation, where denoted						

Table 2. the minimum effective and nominal R-value requirements for the assemblies of residential building enclosures, as per ASHRAE 189.1-2011 (adapted from Tables A-1 to A-8 for IP R-values), by climate zone.

Bhutan has limited weather file and could be only found for cold climate in Paro. For warm and humid the nearest weather station is 24 km away and it is in Tangla India. Tanglas climate file is not sufficient to give an accurate representation of the climate in SamdrupJongkhar, but for practical reasons the climate file for the closest location to the project in question tends to be used when evaluating specific building assemblies. The closest location may not be the climate file that most accurately describes the area in question, but it is often picked in practice where microclimate data cannot be found (Skagseth et al., 2022). Hence the weather data from Tangla is used to represent the weather for the warm and humid climate located in Samdrup Jongkhar. The reason for selection of Tangla's weather data has been shown in Figure 6.

Climate Zone	Weather Sites
0	Ho Chi Minh City Dubai
1	Miami, FL
2	Houston, TX
	Phoenix, AZ
3	Atlanta, GA
	El Paso, TX
	Los Angeles, CA
4	Philadelphia, PA
	Albuquerque, NM
	Seattle, WA
5	Chicago, IL
6	Minneapolis, MN
7	Duluth, MN
8	Fairbanks, AK

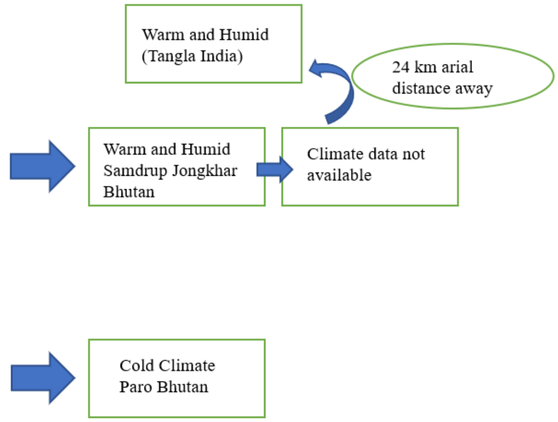


Figure 6. ASHRAE climate zone and comparison with 2 locations in Bhutan

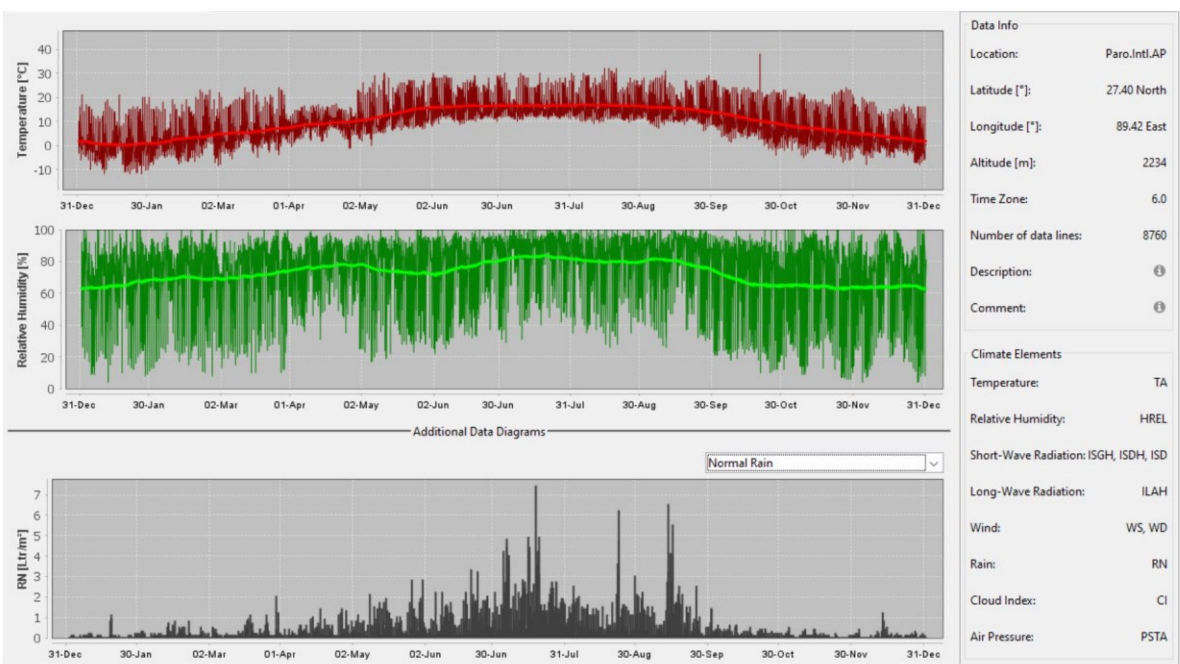


Figure 7. hourly weather data for Paro (cold climate), showing temperature, relative humidity,

and rain fall.

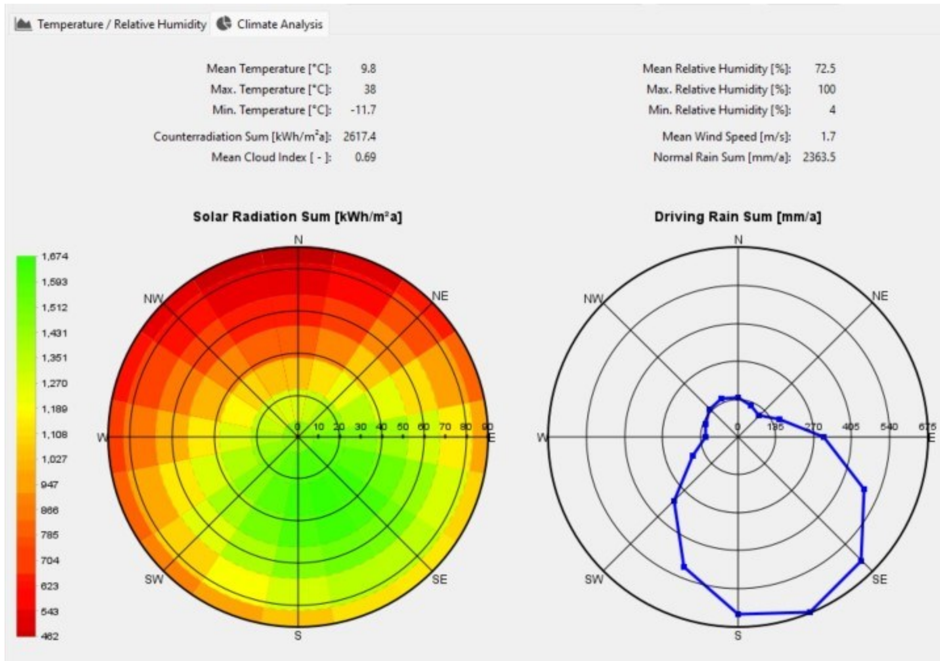


Figure 8. climate analysis for Paro (cold climate) showing solar radiation and wind driven rain.

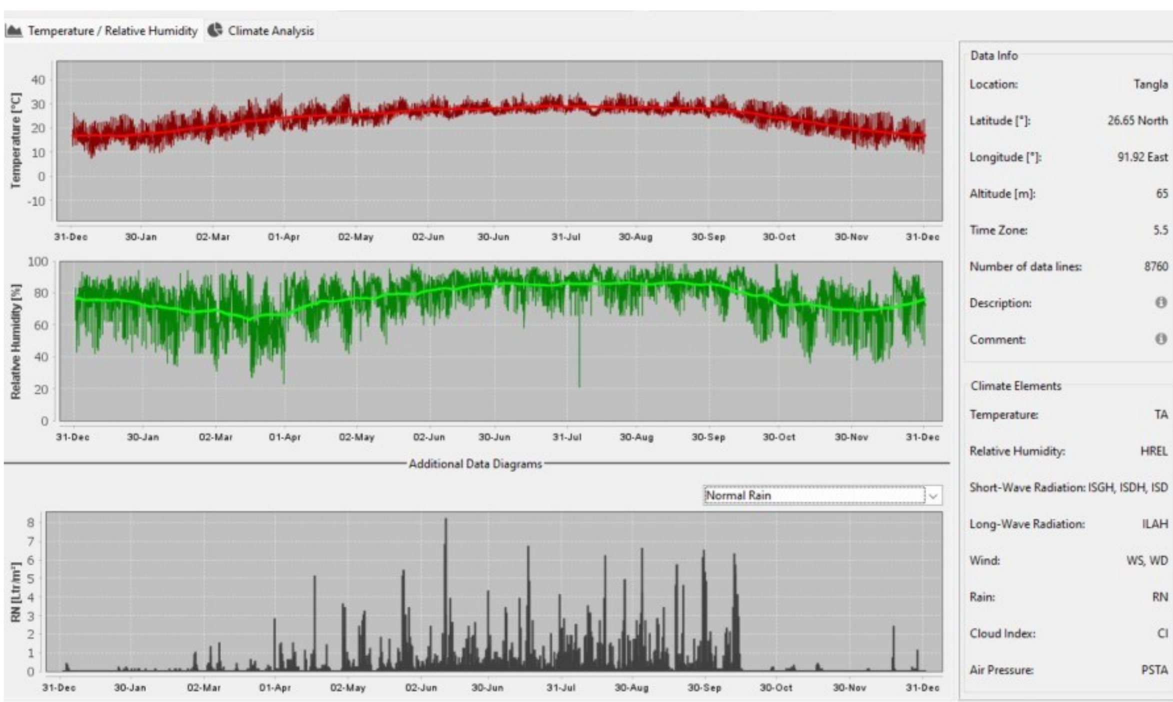


Figure 9. hourly weather data for Samdrup Jongkhar (warm and humid climate), showing

temperature, relative humidity, and rain fall.

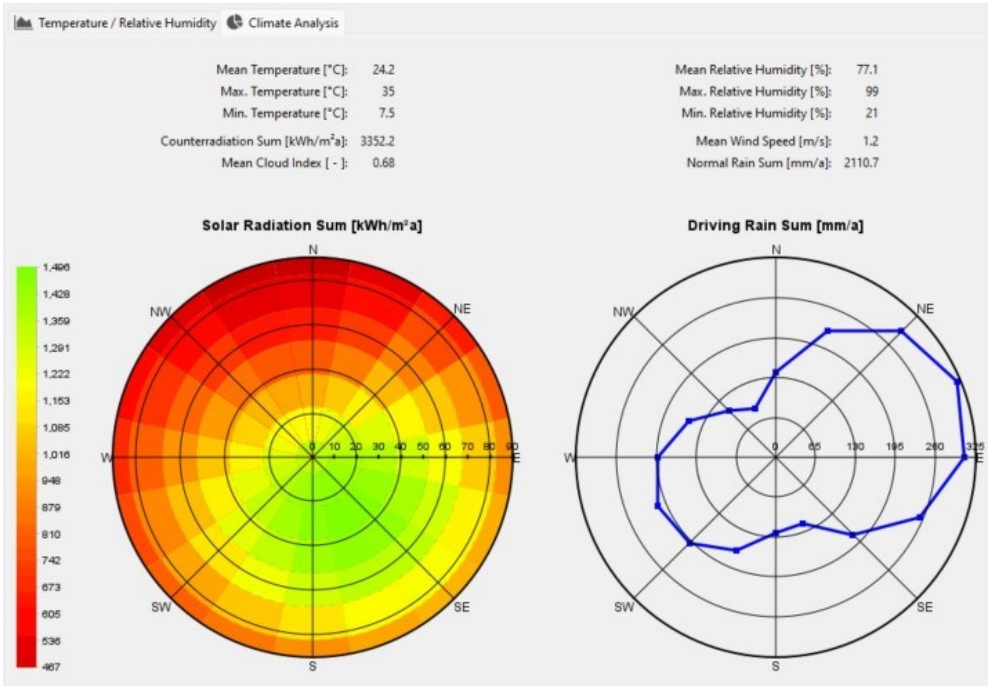


Figure 10. climate analysis for Samdrup Jongkhar (warm and humid climate) shows solar radiation and wind driven rain.

3.1.2 Building and Wall Configuration

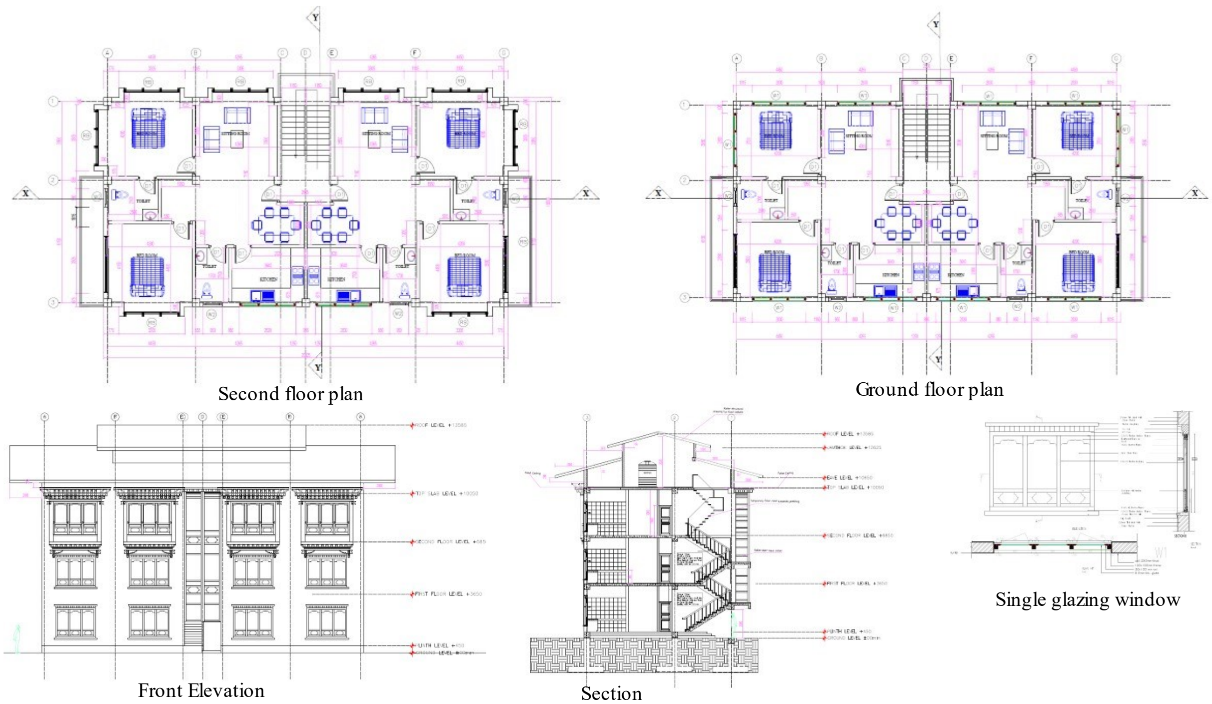


Figure 11. case study building found in both cold climate (Paro) and warm and humid climate (SamdrupJongkhar)

External wall	250 mm brick	U value : 2.164 w/m^2k
Window area	27%	
Window glass	Single glazing	U factor: 4.52 w/m^2k
floor	100 mm Plain cement concrete	U value : 3.68 w/m^2k
Ceiling	100 mm reinforced cement concrete	U value : 4.996 w/m^2k
Pitch roof	5 mm CGI sheet	U value : 7.12 w/m^2k
Attic	Ventilated	
Air tightness	Leaky	5-10 ACH_{50}

Table 3. properties of case study building

The case study building is a common building stock of modern houses. The building considered for this study is a 3-story (~11 m) building with an overhanging roof of (1.5 m) and is assumed to be in the city center. The building includes two-bedroom apartments with six units. The details of the building can be found in Figure 11. The building has a simple electric heater for the heating season in a cold climate and a window-split air conditioner for a cooling season in a warm and humid climate. However, there is no thermostat to control the room's temperature; heating and cooling must be put on and off manually. The external envelope is constructed of 250mm red, burnt brick with a single glazing window made of a wooden frame. The thermal characteristics of the building and air tightness are given in Table 3.

For the proposed wall configuration considering from exterior to interior, a prevalent massive timber wall assembly and WFW encompasses a(n): 1.cladding, 2.drainage cavity, 3.air barrier/water-resistive barrier, 4. OSB, 5. CLT/wood stud, 6.vapour barrier, 7. gypsum board and 8. as an interior paint. The material and thickness of insulation depend on the climate zone in which the building is located (Defo et al., 2023). The insulation thickness varied with the climate zone and according to ASHRAE standard or passivhaus standard. For climate zones 4B (Paro), the minimum thermal resistance value, RSI, as recommended by the (*ASHRAE Handbook Fundamentals*, 2017) for above-grade opaque walls is 3.5 m2 K/W, and for passivhaus standard is 6.7 m2 K/W.

3.2 Stage Two: Design Builder Analysis

The nodal approach is based on the principle that each building zone is a single volume defined as a set of physical variables in uniform states. A node typically represents a room, a floor, or a hall, as a result, one zone is equivalent to a node with its own physical parameters, such as temperature, humidity, pressure, etc. The heat and moisture balance equations can be solved using matrix computing methodology for each node of the whole building volume .The nodal approach is a one-dimensional approach that is currently employed in this research using Design builder 15 shows a full description of the nodal approach methodology computing for energy simulation (Hamdaoui et al., 2021).

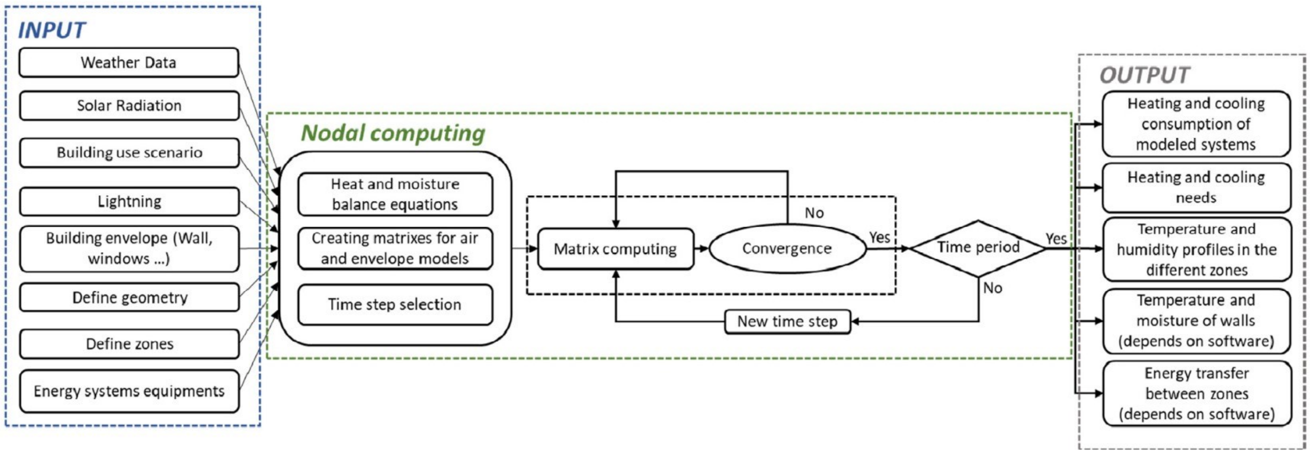


Figure 12: detailed schematic description of the nodal approach for energy simulation. (Hamdaoui et al., 2021)

Design Builder is used to estimate the energy demand of a baseline case study building as well as proposed buildings with timber envelope made up of CLT corresponding to the ASHRAE standard and passivhaus standard. The CLT wall assembly has been used for energy efficiency simulation to find out the energy demand of the building studied. Therefore, the following variables are identified for the simulation.

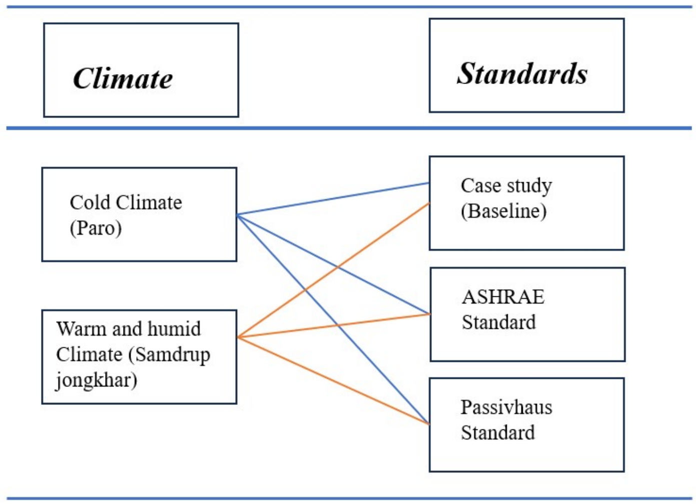


Figure 13. variables identified for energy efficiency analysis.

	Cold climate (Paro)	Warm and humid (Samdrup Jongkhar)
Case study (baseline)	Wall U value – 2.164 w/m^2k	Wall U value – 2.164 w/m^2k
	Roof U value – 4.996 w/m^2k	Roof U value – 4.996 w/m^2k
	Infill – 7 ACH_{50}	Infill – 7 ACH_{50}
ASHRAE Standard	Wall U value – 0.365 w/m^2k	Wall U value – 0.504 w/m^2k
	Roof U value – 0.273 w/m^2k	Roof U value – 0.273 w/m^2k
	Infill – 2 ACH_{50}	Infill – 2 ACH_{50}
Passivhaus Standard	Wall U value – 0.15 w/m^2k	Wall U value – 0.15 w/m^2k
	Roof U value – 0.15 w/m^2k	Roof U value – 0.15 w/m^2k
	Infill – 0.6 ACH_{50}	Infill – 0.6 ACH_{50}

Table 4. building envelope data

Figure 13 represents the variables for energy efficiency simulation. There are 2 variables for the analysis which are climate and standards. The first variable (Climate) has 2 elements which are cold climate (paro) and warm and humid climate (Samdrup Jongkhar). The second variable (standards) has 3 elements namely case study (baseline), ASHRAE standard and passivhaus standard. This leads to 6 simulation sets making it 3 each for both the climates. Variable (standards) comes with its own thermophysical properties such as u value for wall, u value of roof, u factor for window, and air filtration rate which are given in Table 4.

Typology	Windows	Properties	values	sources
Case study (Baseline)	Single glazing 6 mm with wood frame	SHGC at normal incidence	0.72	ASHRAE fundamentals 2017, chapter 15, table 10
		U factor	4.52 w/m^2k	ASHRAE fundamentals 2017, chapter 15, table 4
ASHRAE cold climate	Double glazing with wood frame	SHGC at normal incidence	0.4	ASHRAE standard 90.1, table 5.5.4
		U factor	2.27 w/m^2k	
ASHRAE warm and humid	Double glazing with wood frame	SHGC at normal incidence	0.25	ASHRAE standard 90.1, table 5.5.2
		U factor	4.26 w/m^2k	

Passivhaus Standard	Tripple glazing with wood frame	SHGC at normal incidence	0.20	Passivhaus standard/ (PHI 2023; Straube, 2009)
		U factor	1.45 w/m^2k	

Table 5. SHGC and U factor for various windows used for design builder simulation

Note : U factor for passivhaus is 0.8, but U factor of 1.45 refereed from ASHRAE fundamentals for triple glazing window is used for the simulation.

	Unit	**Source**
Occupancy	24 people in 499 m^2 conditioned area = (0.048)	Design assumption
Domestic hot water (DHW)	25 liters, 60 ℃ per person = (1.22 $l/m^2\ day$)	Passive house institute
Illuminance	125 lux	NECB 2020, Table A-8.4.3.2.(2)-B
computer equipment	6.5 w/m^2	NECB, 2020, Table 4.2.1.6
Miscellaneous	2.5 w/m^2	
Holiday	16 days	Bhutanese Calendar
Heating set point	22 ℃	ASHRAE standard 55
Heating set back	18 ℃	
Cooling set point	24 ℃	
Cooling set back	28 ℃	

Table 6. design builder constant inputs

Note: The standards from NECB and passive house institute and ASHRAE have been chosen to have diverse standards. Since Bhutan does not have any of the standards for thermal comfort and energy efficient building.

3.2.1 Modeling and Simulation

This section explains the simulation parameters for the energy demand as well as heating and cooling demand of the baseline and proposed building.

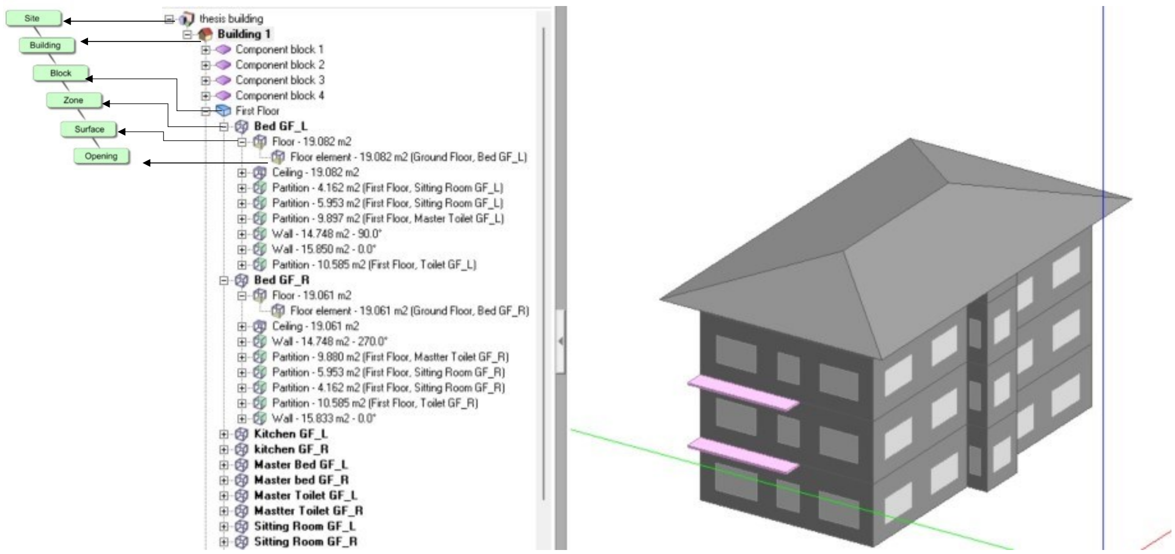


Figure 14. data hierarchy of design builder

3.2.1.1 Data Inheritance

Default data is inherited from the level above in the hierarchy, so block data is inherited from building level, zone data is inherited from block data and surface data from zone data. This arrangement allows to make settings at building level which can become active throughout the whole building; or make settings at block level to change data for all zones/surfaces in the block.

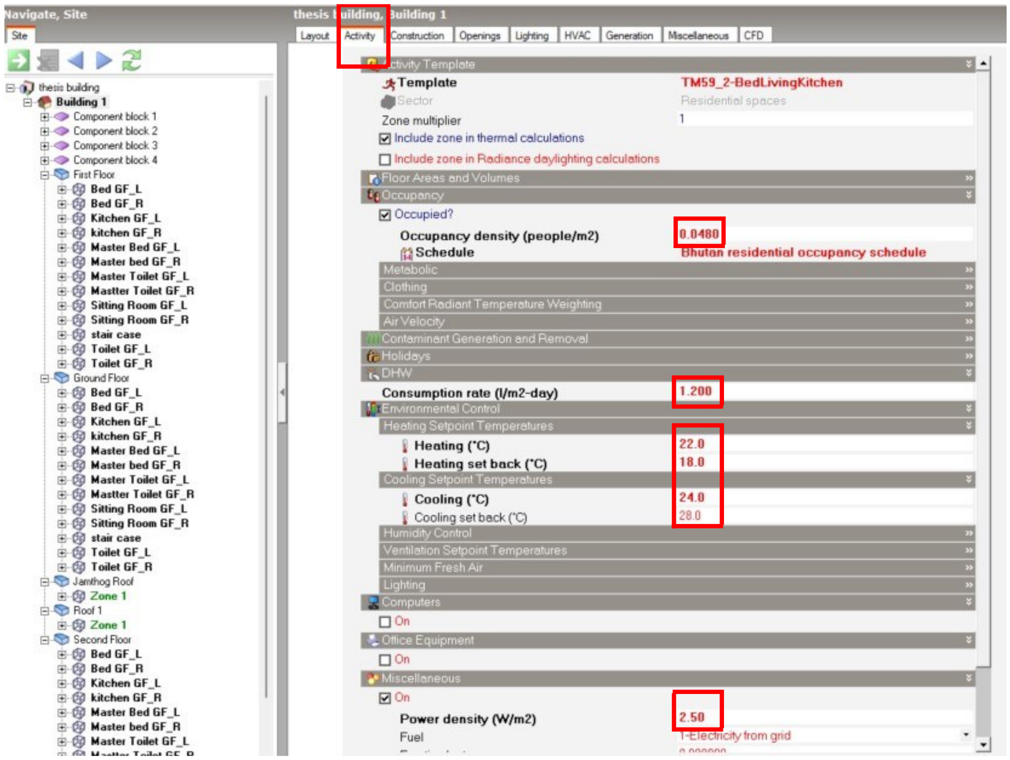


Figure 15. activity tab of design builder

3.2.1.2 Activity Tab

When the Occupancy method is set to 1-Occupancy density I can set the number of people per unit floor area. It is usually most convenient to load this data from the Activity template. The building is assumed to accommodate 24 people in 499 m2 conditioned area (0.048 occupancy density). For domestic hot water (DHW) the Passivhaus standard of 25 liters, 60 °C per person (1.22 l/m2day) is selected for all building simulations.

Heating setpoint temperature

Defines the ideal temperature (i.e., the setting of the heating thermostat) in the space when heating is required. Its meaning depends on the Temperature control calculation option. Operative temperature (MAT=MRT)/2 is used for the simulation. The heating set point is fixed at 22℃

Heating setback setpoint temperature

Some buildings require a low level of heating during unoccupied periods to avoid condensation/frost damage, prevent the building from becoming too cold, and reduce peak heating requirements at startup. A heating setback of 18 ℃ is used.

Cooling setpoint temperature

Defines the ideal temperature (i.e., the setting of the cooling thermostat) in the space when cooling is required. Its meaning depends on the Temperature control calculation option. Operative temperature (MAT=MRT)/2 is used for the simulation. The cooling set point is fixed at 24 ℃

Cooling setback setpoint temperature

Some buildings require a low level of cooling during unoccupied periods to prevent the building from becoming too hot and to reduce the startup cooling load the next morning. A cooling setback of 28 ℃ is used.For computer equipment the miscellaneous option is used which has a power density of 2.5 w/m2 referred to by NECB.

3.2.1.3 Construction Tab

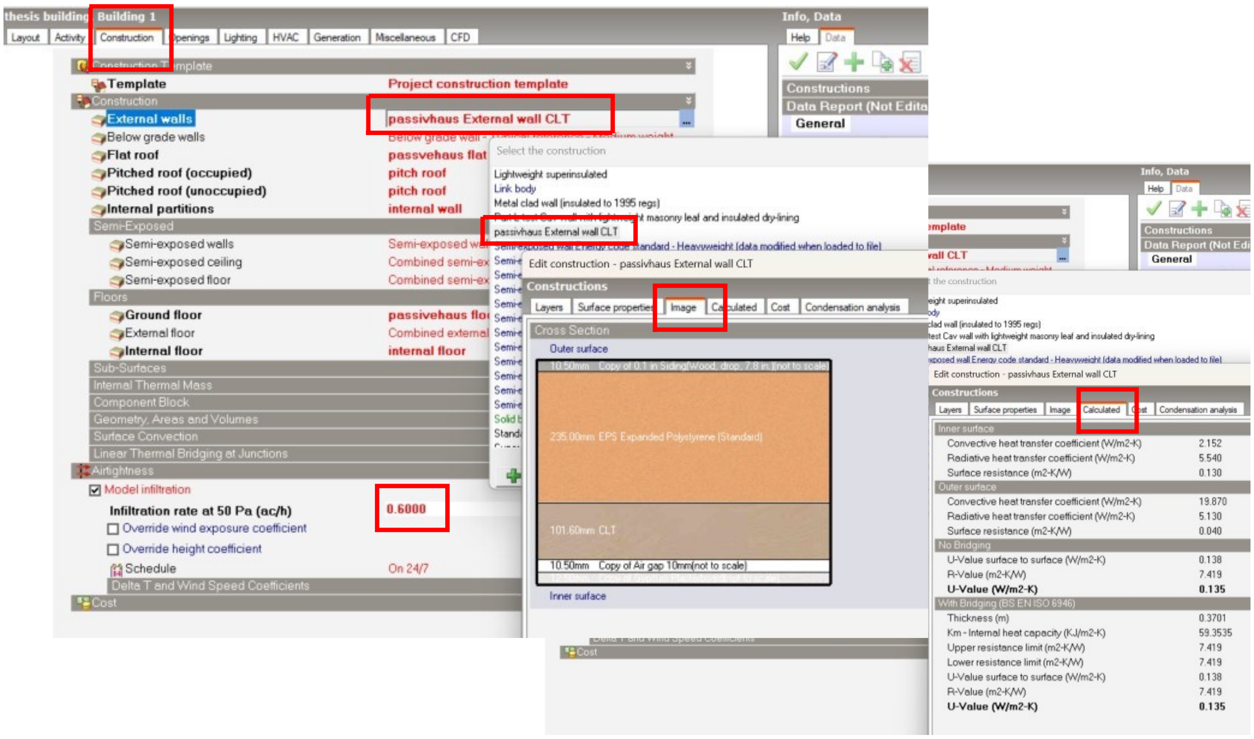


Figure 16. construction tab of design builder

From the Construction tab, one can open the group header boxes to edit the detailed makeup of the construction of walls, roofs, floors, ceilings, partitions etc., used in the building. The default/inheritance system used in DesignBuilder allows to define building constructions quickly and easily by loading data from templates and by making global settings at building, block and zone levels. DesignBuilder provides great flexibility in how block and zone geometry is defined and passed through to the various calculations. Various options include building blocks drawn using external measurements while providing correct internal zone geometry for floor area and zone volume calculations derived from actual surface thickness.

It is in this tab that thermophysical properties of the building envelope are defined. All the variations in the baseline building, ASHRAE standard building and passivhaus standard building are defined in this as shown in the figure. Also, the airtightness of the building is defined here.

3.2.1.4 Opening Tab

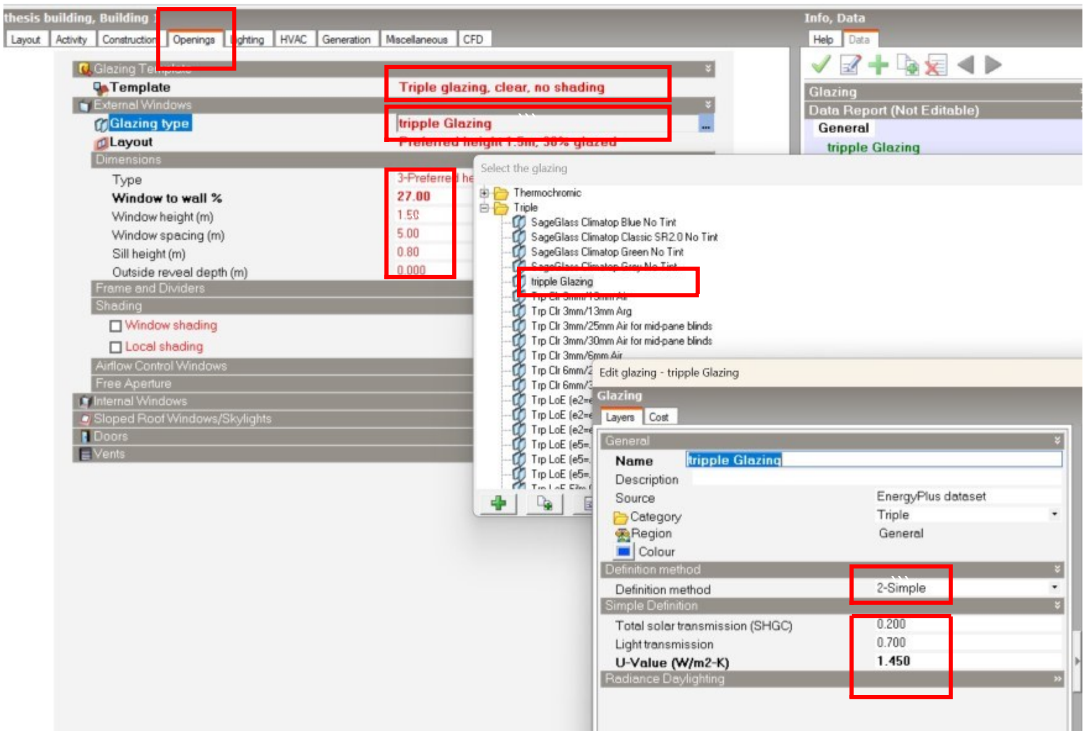


Figure 17. opening tab of design builder

This is a powerful tool to assign the properties of a window that is being used to model. The case study apartment has a wall to window ratio of 27%. And the details of the window can also be assigned here. There are two methods of assigning the window properties, simple method, and detailed method. For the simulation, a simple method is used in which SHGC, light transmittance and u value of the window for corresponding standard is refereed from ASHRAE and Passivhaus standard. This method makes more sense than the detailed method because the research is trying to achieve a general recommendation for the building performance.

3.2.1.5 HVAC Tab

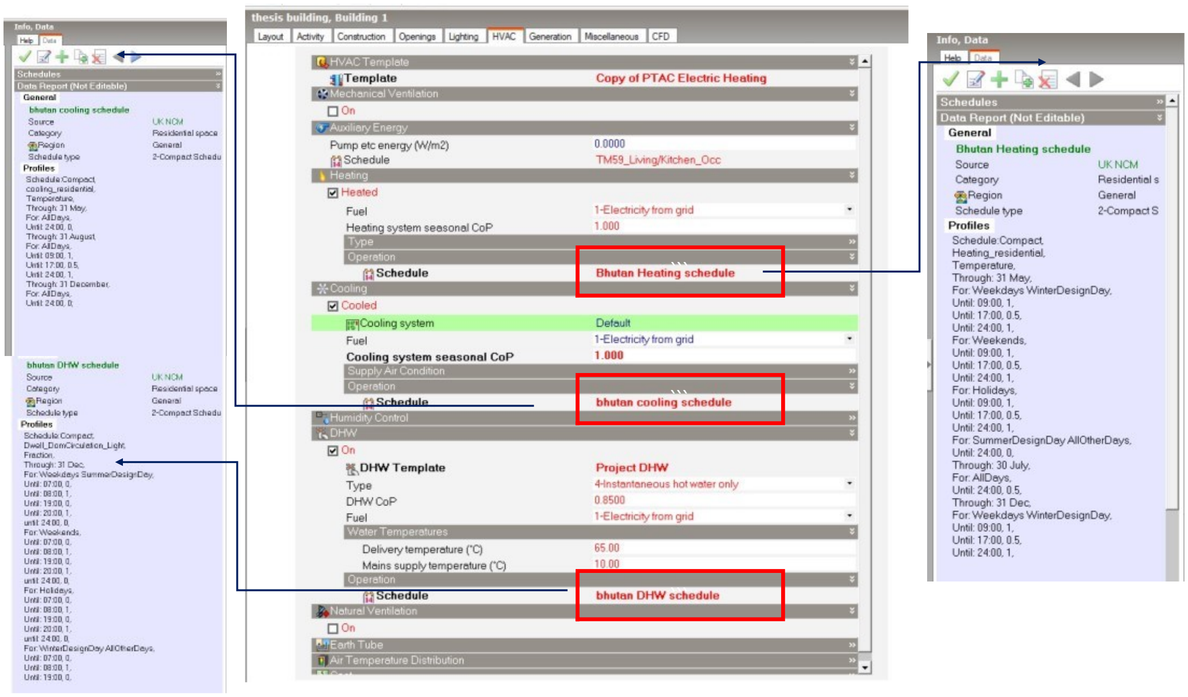


Figure 18. HVAC tab indicating Cooling and Heating Schedule in cold climate.

The building is scheduled to be heated from January to May with setpoint temperature from 12 am to 9 am, then with setback temperature from 9 am to 5 pm, and again heated to set point temperature from 5pm to 12 am. From May 31 to July 30 the building is heated with setback temperature the whole day. From August 1st to December 31st the schedule is repeated like from January to May month. For the Cooling schedule Only 3 months from May to August is cooled at with the schedule as shown above.

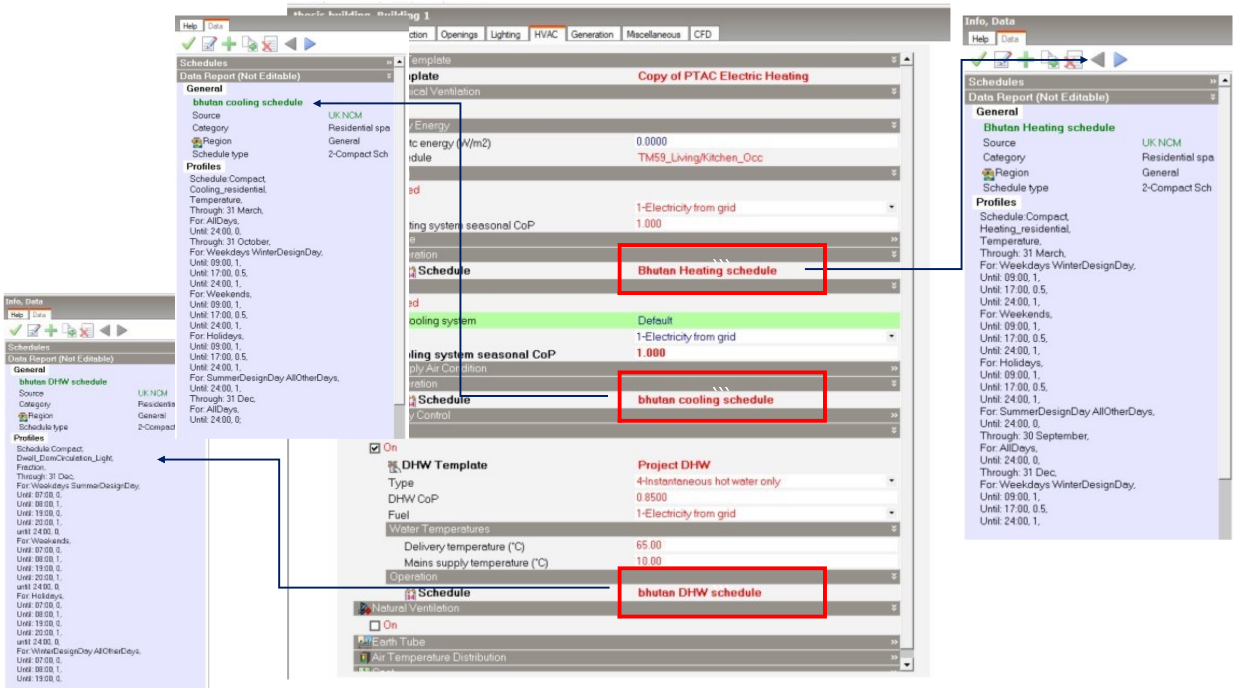


Figure 19. HVAC tab indicating cooling and heating schedule in warm and humid climate.

The building is scheduled to be heated from October 1st to March 31st with setpoint temperature from 12 am to 9 am, then with setback temperature from 9 am to 5 pm, and again heated to set point temperature from 5pm to 12 am. From April 1st to September 31st the building is cooled with setpoint temperature from 12 am to 9 am, then with setback temperature from 9 am to 5 pm, and again cooled again to set point temperature from 5pm to 12 am.

3.3 Stage Three: WUFI Analysis

This study used WUFI Pro 6.7 to analyze the hygrothermal performance of the exterior wall. The details of the wall being studied for hygrothermal simulation have been given in appendix 3. Considering the typical climate effects such as wind-driven rain, solar radiation, capillary transmission, and so on, the WUFI Pro fully realizes the theoretical calculation of the non-stationary hygrothermal performance of building components under real climate conditions

(Park et al., 2019). Other programs and traditional methods, such as the Glaser Method, do not consider these effects and are thus limited to only evaluating winter condensation effect (Künzel et al., 2005).

3.3.1 WUFI Hygrothermal Theory and Model Overview

The calculation process of simulation is demonstrated in Figure 20. The necessary input data include detailed information about the proposed building components, such as the assembly of the wall layer and orientation. It is also important to provide accurate initial conditions, material parameters, and climatic conditions to ensure the simulation accurately reflects real conditions.

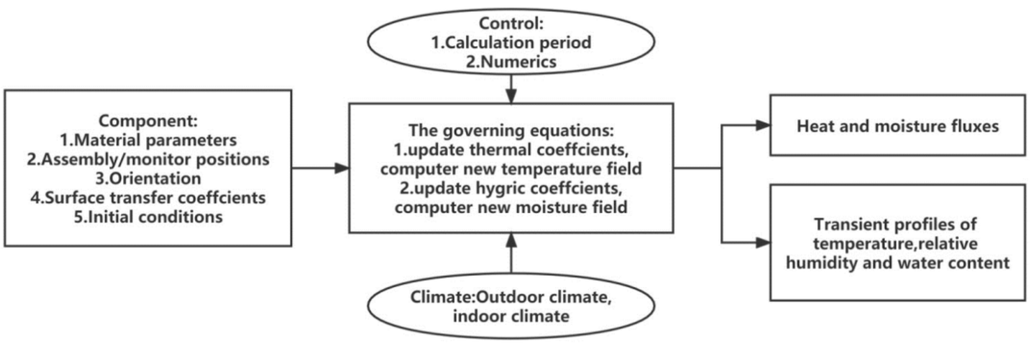


Figure 20. flow chart of the calculation technique on which the WUFI Pro computer program is based (Künzel, 1995a)

The governing equations for heat and moisture transport are given in Equation (1) and (2), respectively(Künzel, 2022):

$$\frac{\partial H}{\partial \vartheta}\frac{\partial \vartheta}{\partial t} = \frac{\partial}{\partial x}\left(\gamma \frac{\partial \vartheta}{\partial x}\right) + h_v \frac{\partial}{\partial x}\left(\frac{\delta_a}{\mu}\frac{\partial p}{\partial x}\right) \quad (1)$$

$$\rho_w \frac{\partial u}{\partial \emptyset}\frac{\partial \emptyset}{\partial t} = \frac{\partial}{\partial x}\left(\rho_w D_w \frac{\partial u}{\partial \emptyset}\frac{\partial \emptyset}{\partial x}\right) + \frac{\partial}{\partial x}\left(\frac{\delta_a}{\mu}\frac{\partial p}{\partial x}\right) \quad (2)$$

Where H is the enthalpy of moist building material (J/m^3); ϑ and $\emptyset$ are the temperature (°C) and RH (-); γ refers to the thermal conductivity of materials (W/mk); h_v is the evaporation enthalpy of water (J/Kg); μ is the water vapor resistance factor (-); p is the water vapor partial pressure

(Pa); ρ_w is the density of water (kg/m^3); u is the water content (m^3/m^3); and D_w is the liquid transport coefficient (m^2/s).

The program uses Fick's law to model the movement of water vapor, Darcy's law to model liquid transport, and Fourier's law to model the transfer of heat. The moisture balance includes the gradients in relative humidity and vapor pressure; the heat energy balance includes heat conduction between the building materials and the specific heat of evaporation of the inflowing wet air (Künzel et al., 2005).WUFI Pro utilizes the finite volume technique for spatial discretization of transport equations; this allows for the accurate calculation of heat and moisture fluxes at each point in the domain, which are then used to iteratively solve the governing equations for the next time step (Ibrahim et al., 2019). This fully implicit scheme is used for time discretization, which ensures that the transient behavior of the system is accurately captured. The solver computes temperature and relative humidity profiles by iteratively solving the heat and mass balance equations until convergence is achieved.

3.3.2 Hygrothermal Simulation Conditions

WUFI Pro 6.7 to analyze hygrothermal performance, which requires settings for wall construction, initial conditions, indoor and outdoor climate, etc. Some of the settings are shown in Table 7.

Parameters	Simulation Conditions
Analysis period	3 years (1st January 2023, to 1st January 2025)
Initial relative humidity	80 %
Initial temperature of the component	23℃
Heat transfer coefficient	Exterior heat transfer coefficient : 17 $\frac{w}{m2k}$

	Interior heat transfer coefficient : 8 $\frac{w}{m2k}$ Ground short-wave reflectivity : 0.2 (standard value) Adhering fraction of rain : 0.7
Indoor climate	According to EN 15026/WTA6-2
Analysis orientation	North for cold climate, South for warm and humid climate
Air infiltration (vented cavity)	50 ACH (Straube & Finch, 2009a)
Air exfiltration (leakage)	16 ACH (Künzel et al., 2011)
Rain load	1% of rain load behind cladding, 0.01 % on the wood sheathing behind water control layer. (Lstiburek et al., 2016)

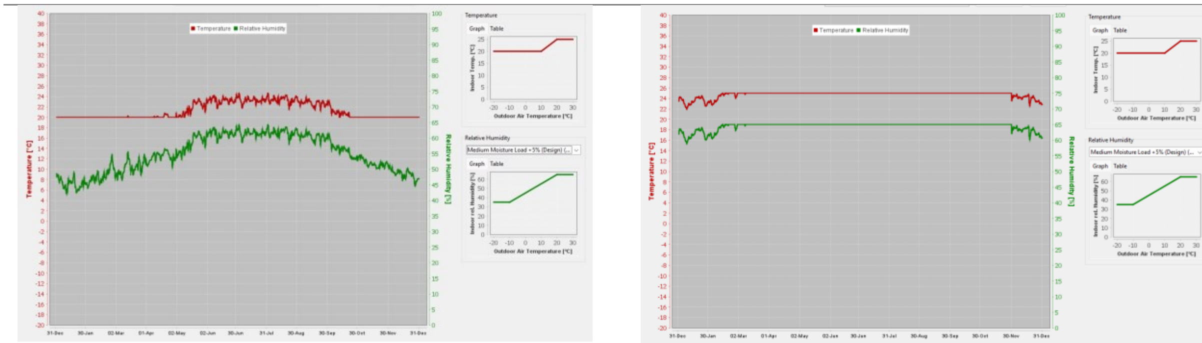
Table 7. hygrothermal simulation conditions

The initial temperature and humidity state of the exterior building components should be determined by considering the storage conditions of the components and the climatic conditions during construction, as well as the human comfort temperature range specified by (ASHRAE standard 55-2010, 2010). The heat transfer coefficients and resistances describe the exchange of heat between a surface and the surroundings. This heat transport is affected by several different transport mechanisms (Künzel et al., 2005):

- heat conduction through the air adjacent to the surface.
- convective transport by air flows.
- emission of long-wave radiation.

In building physics, the heat transfer coefficient is influenced by various factors such as temperature and the surface characteristics of the wall, as well as depending on the local conditions. However, for simplicity, it is often assumed to be a constant value. WUFI simplifies this coefficient and provides selectable typical values. For this study, the exterior heat transfer coefficient was set at 17 W/m2K and the interior heat transfer coefficient was set at 8 W/m2K. It is important to note that the simplification of the heat transfer coefficient may not accurately capture the true complexities of the system. However, by using typical values provided by WUFI, this simplification can still provide valuable insights and predictions for the building's thermal performance (Li et al., 2023). The probable range of ventilation rates depend on the cladding type, cavity dimensions, and venting arrangement, and are driven by thermal and moisture buoyancy and wind pressures. (Straube & Finch, 2009) investigated the use of the WUFI "source and sink" approach in a one-dimensional model to simulate ventilation. It was concluded that 50 ACH for stucco and wood siding cladding can be used for 19 mm drainage space. For the air leakage modeling there are many researchers who predict the air leakage for different air tightness of envelope. For air leakage the ventilation rate is assumed constant and amounts to 16 ACH (Künzel et al., 2011). This air change rate has been determined by assuming that the indoor air circulation through the cavity results in the same moisture excess of 250 g/m² during the heating season which must dry out during the summer together with the amount of condensate caused by vapor diffusion.

In the simulation process of WUFI Pro, the indoor temperature and humidity conditions were determined by the outdoor air temperature, as shown in Figure 21. indoor temperature and relative humidity for cold climate and warm and humid climate Figure 21 , according to EN 15026/WTA6-2 (Li et al., 2023).



Cold climate (Paro)	Warm and humid (Samdrup Jongkhar)

Figure 21. indoor temperature and relative humidity for cold climate and warm and humid climate

The hygrothermal parameters for each construction of the wall are shown in Table 8 and Table 9.

The data for the material is taken from the WUFI database.

Hygrothermal properties of WFW

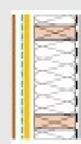
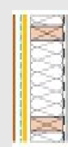
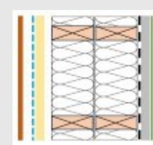
Wall	Material	Bulk density kg/m3	Porosity(m3/ m3)	Heat Capacity (J/kgk)	Thermal conductivity (W/mK)	Diffusion Resistance Factor	Layer Thickness (m)	ASHRAE cold climate (Zone 4B) U value (w/m2k)	ASHRAE warm and humid climate (Zone 2B) U value (w/m2k)	Passivhaus Standard building envelope. U value (w/m2k
Wall 1-24	Wood siding/stucco	740/ 1955.5	0.666/ 0.225	1879.87/ 839.37	0.094/ 0.396	53.04/ 355.73	0.0105/ 0.02	0.365	0.504	0.15
	Unvented/Air layer	1.3	0.99	999.82	0.13	0.56	0.02			
	3M 3015 VP	130.06	0.001	2291.89	2.25	296.5	0.001			
	OSB	650	0.95	1879.87	0.094	812.56	0.0125			
	Glass fiber board	122	0.99	839.06	0.035	1.91	0.15/ 0.10/ 0.30			
	Vapor Barrier	120	0.6	1500	0.42	3002.5	0.001			
	Gypsum board	625	0.706	870	0.16	7.03	0.0125			
	Latex paint	1199.9	0.001	988.1	0.2077	12.88	0.001			

Table 8. hygrothermal properties of wood frame wall (WFW)

Hygrothermal properties of CLT

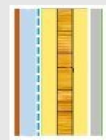
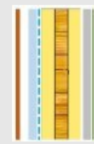
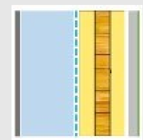
Wall	Material		Bulk density kg/m3	Porosity (m3/m3)	Heat Capacity (J/kgk)	Thermal conductivity (W/mK)	Diffusion Resistance Factor	Layer Thickness (m)	ASHRAE cold climate (Zone 4B) U value (w/m2k)	ASHRAE warm and humid climate (Zone 2B) U value (w/m2k)	Passivhaus Standard building envelope. U value (w/m2k
Wall 25-96	Wood siding/stucco		740/ 1955.5	0.666/ 0.225	1879.87/ 839.37	0.094/ 0.396	53.04/355.73	0.0105/ 0.02	0.365	0.504	0.15
	Unvented/Air layer		1.3	0.99	999.82	0.13	0.56	0.02			
	Insulation	XPS/	40	0.95	1500	0.04	450	0.05/0.021/0.235			
		EPS/	15	0.95	1500	0.04	30	0.05/0.021/0.235			
		mineral wool	60	0.95	850	0.04	1.3	0.05/0.021/0.235			
	3M 3015 VP		130.06	0.001	2291.89	2.25	296.5	0.001			
	CLT		410.01	0.74	1300	0.098	499.04	0.1016			
	Gypsum board		625	0.706	870	0.16	7.03	0.0125			
	Latex paint		1199.9	0.001	988.1	0.2077	12.88	0.001			

Table 9. hygrothermal properties of CLT wall

3.3.3 Mold Growth Index and Moisture Content

Mold growth index, which is a function of temperature, RH and duration, and the material sensitivity class, is calculated to assess susceptibility of the sheathing to mold growth, following ASHRAE standard 160–2016 (ASHRAE standard 160, 2016). Mold growth index is a numerical value varying from 0 (no mold growth) to 6 (100% visual coverage). A mold growth index is shown in Table 10 and mold index (MI) under 1 is considered as an acceptable threshold by ASHRAE 160. The mold MI is calculated for the interior surface of sheathing for all three wetting scenarios, using "sensitive" class for the OSB sheathing and CLT.

Mold index
0 : No growth
1 : Some growth visible under microscope
2 : Moderate growth visible under microscope, coverage more than 10 %

3 : Some growth detected visually; thin hyphae found under microscope
4 : Visual coverage more than 10 %
5 : Coverage more than 50 %
6 : Tight coverage, 100 %

Table 10. description of mold index (MI) according to Viitanen model (Isaksson et al., 2010; Viitanen, 2001)

For the classification, the 'signal light' is employed by the software Table 11; the green light shows low or no risk for biodegradation, the yellow light reflects moderate risk and additional control may be needed and the red light reveals high risk for biodegradation and therefore the construction is considered as not acceptable.

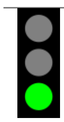
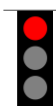
	ASHRAE 160 : Mould index up to 1 Usually, acceptable
	ASHRAE 160 : Mould index 1-3 Not classified accordingly in ASHRAE 160 Additional criteria or investigations are needed for assessing acceptability
	ASHRAE 160 : Mould index above 3 Usually not acceptable

Table 11. Signal light classification with WUFI pro plugin VTT (Isaksson et al., 2010; Kraniotis et al., 2023)

Moisture content is another performance indicator used in this research to check the durability of the sensitive layers of the building envelope. Any wall assembly which has moisture content 20% or more are classified unsafe for construction (Defo et al., 2023; Li et al., 2023; Straube & Finch, 2009b; Teibinger & Dolezal, 2021; Zegen Reich et al., 2021).

Chapter 4. Results and Discussion

4.1 Energy Efficiency Analysis

To demonstrate the value of a highly thermally efficient and airtight building enclosure, the energy demand of a 3-storey 6-unit in Paro, Bhutan (Climate Zone 4B, heating-dominated) and Samdrup Jongkhar, Bhutan (climate zone 2A, Cooling dominated) was simulated using a design-builder energy model. The variable selected for the energy modeling is given in Figure 22.

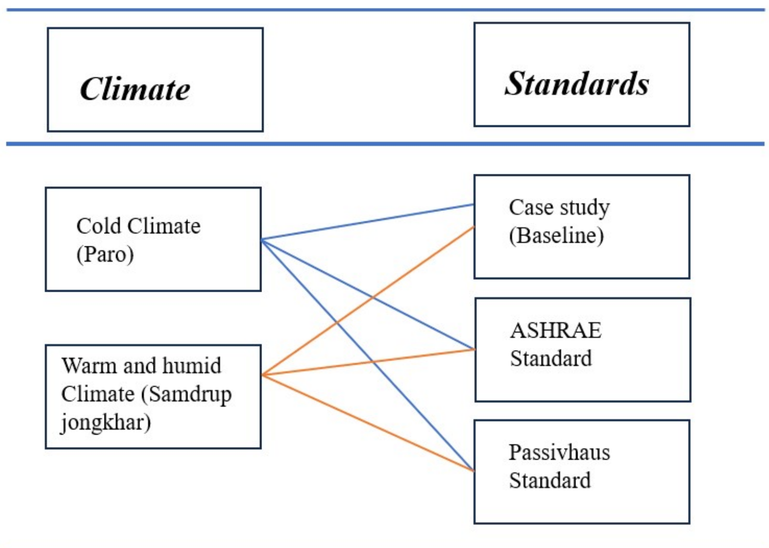


Figure 22. variables identified for energy efficiency analysis

Energy Efficiency Analysis

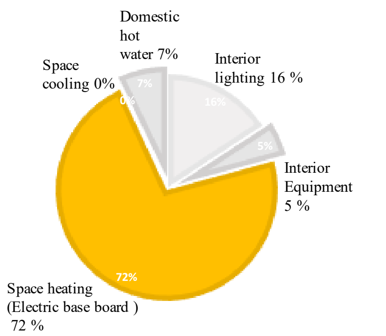
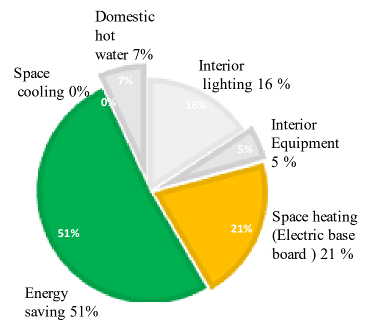
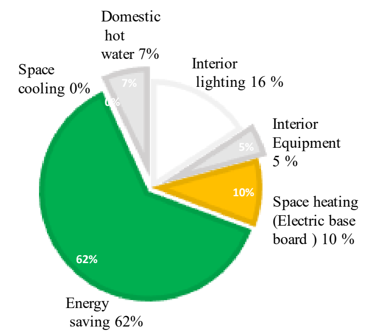
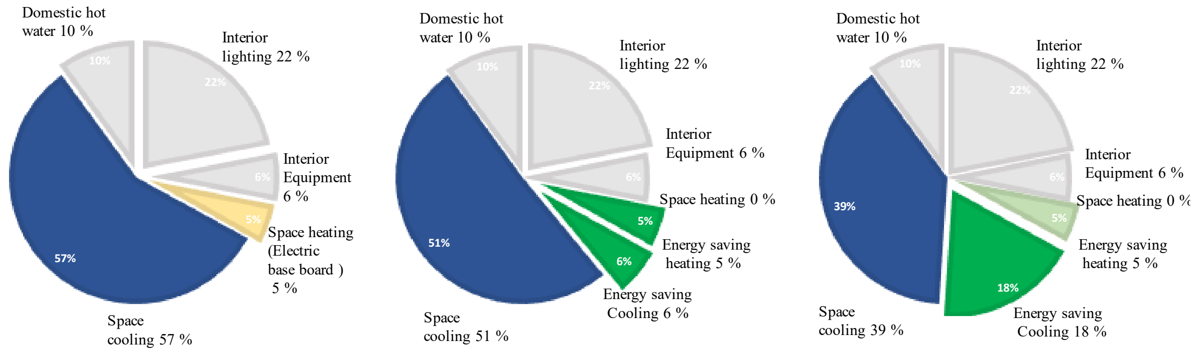
Baseline building Paro, Bhutan 269.5KWh/m2a	ASHRAE building Paro, Bhutan 93.75 KWh/m2a	Passivhaus building Paro, Bhutan 85.81KWh/m2a
		
Energy demand for a Baseline building in Paro, Bhutan (cold climate, heating only). Total 269.50 KWh/m2a (Uvalue 2.164 w/m2k for walls, Uvalue 4.996 w/m2k for roof, U factor 4.52 w/m2k for windows, 5 ACH50 and with 27.5 % glazing ratio.	Energy demand for a ASHRAE standard building in Paro, Bhutan (cold climate, heating only). Total 93.75 KWh/m2a (Uvalue 0.365 w/m2k for walls, Uvalue 0.273 w/m2k for roof, U factor 2.27 w/m2k for windows, 2 ACH50 and with 27.5 % glazing ratio.	Energy demand for a Passivhaus standard building in Paro, Bhutan (cold climate, heating only). Total 85.81 KWh/m2a (Uvalue 0.15 w/m2k for walls, Uvalue 0.15 w/m2k for roof, U factor 1.45 w/m2k for windows, 0.6 ACH50 and with 27.5 % glazing ratio.

Figure 23. energy demand distribution for cold climate paro, Bhutan.

In the first scenario (Baseline, left), space heating consumes 194.0 KWh/m^{2}a, 72% of the total demand. For Domestic hot water, lighting, and interior equipment, the energy consumed by the building is 7%,16%, and 5%, respectively. These energy demands are kept constant, and only building envelope and airtightness is varied for the other scenario. In the second scenario (ASHRAE standard, middle), the energy saving is 137.4 kWh/m^{2}a, 51 % of the total energy profile. Moreover, for the third scenario (Passivhaus standard, right), energy saving on space heating is 167.1 kWh/m^{2}a, 62% of the energy consumed by the same building.

Energy Efficiency Analysis

Baseline building SamdrupJonkhar, Bhutan 193.00 KWh/m2a	ASHRAE building SamdrupJongkhar, Bhutan 168.77 KWh/m2a	Passivhaus building SamdrupJongkhar, Bhutan 151.24 KWh/m2a



Energy Demand for a Baseline building in Samdrup Jongkhar, Bhutan (warm and humid climate, Cooling dominated) Total 193.00 KWh/m2a (Uvalue 2.164 w/m2k for walls, Uvalue 4.996 w/m2k for roof, U factor 4.52 w/m2k for windows, 5 ACH50 and with 27.5 % glazing ratio.	Energy demand for a ASHRAE building in Samdrup Jongkhar, Bhutan (warm and humid climate, Cooling dominated) Total 168.77 KWh/m2a (Uvalue 0.504 w/m2k for walls, Uvalue 0.273 w/m2k for roof, U factor 4.26 w/m2k for windows, 2 ACH50 and with 27.5 % glazing ratio.	Energy demand for a Passivehaus standard building in Samdrup Jongkhar, Bhutan (warm and humid climate, Cooling dominated) Total 151.24 KWh/m2a (Uvalue 0.15 w/m2k for walls, Uvalue 0.15 w/m2k for roof, U factor 1.45 w/m2k for windows, 0.6 ACH50 and with 27.5 % glazing ratio.

Figure 24. energy demand distribution for warm and humid climate Samdrup Jongkhar, Bhutan

In the first scenario (Baseline, left), space cooling demand is 110.0 KWh/m^{2}a, 57% of the total demand. For Domestic hot water, lighting, and interior equipment, the energy demand for the building is 10%, 22%, and 6%, respectively. These energy demands are kept constant, and only building envelope and airtightness is varied for the other scenario. In the second scenario (ASHRAE standard, middle), the energy saving in space heating and cooling is 21.2 kWh/m^{2}a, 11 % of the total energy profile. Moreover, for the third scenario (Passivhaus standard, right), energy saving on space heating and cooling is 44.4 kWh/m^{2}a, 23% of the energy consumed by the same building. The energy demand distribution plots highlight the relative improvements in energy efficiency that can be made by using more energy-efficient building enclosure assemblies. In general, heating-dominated colder climate zones benefit more from higher effective R-values than cooling-dominated hotter climate zones. Buildings in cooling-dominated climate zones benefit more from other strategies to reduce solar heating, which is beyond the scope of this research.

Comparing these two results in both climates, a significant amount of energy saving is noticed in ASHRAE standard. For the Passivhaus standard building envelope, it does not have huge energy savings in warm and humid climate, therefore for the durability analysis the PH standard wall assembly is simulated only for the cold climate.

4.2 Durability Analysis

4.2.1 Wood Frame Wall Configuration (WFW)

There are two types of timber building envelope being studied. One with wood frame wall (WFW) and other with the CLT as a structural wall assembly. WFW configuration has been shown in Figure 25 with its variables (V) and constants (C).

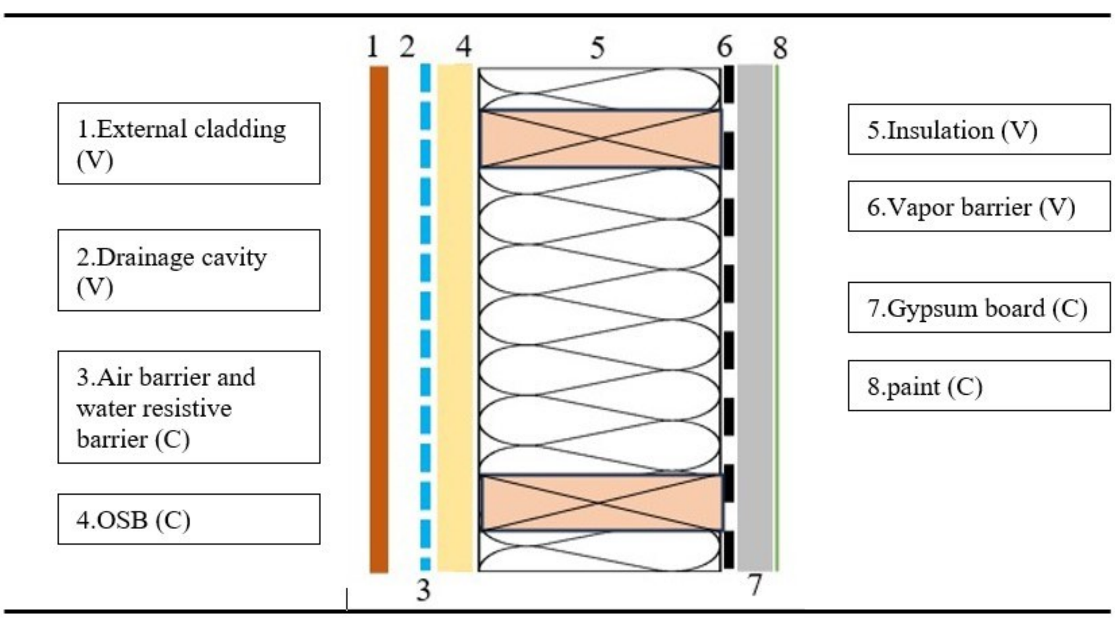


Figure 25. WFW configuration: (V) denotes varies and (C) denotes constant. 1. external cladding varies with wood siding and stucco siding, 2. drainage cavity varies with vented with 50 ACH and non-vented. 5. insulation varies with 4" 6" and 12" for different climate investigated, 6. vapor barrier varies with class I vapor barrier and no vapor barrier.

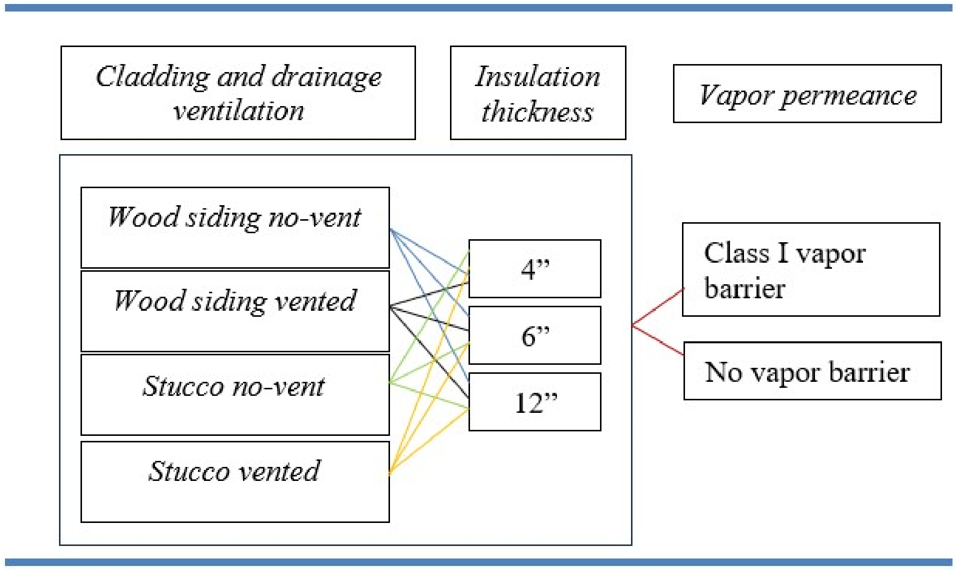


Figure 26. variables identified for WFW to optimize wall assembly for mold growth performance.

Figure 26 represents the variables identified for wood frame wall assembly (WFW). There are three variables. First variable (cladding and ventilation drainage) has 4 elements such as wood siding no-vent, wood siding vent, stucco no-vent, and stucco vented. The second variable (insulation thickness) has 3 elements, which are 4”,6” and 12 “ thick insulation with thermal conductivity 0.04w/m2k. The insulation thickness differs to meet the thermal performance required for each climate as well as for passivhaus standard. This leads to 12 simulation results which are further simulated with third variable (vapor permeance) which has 2 elements such as class I vapor barrier and no vapor barrier. Therefore, the total simulation is 24 for the WFW assembly.

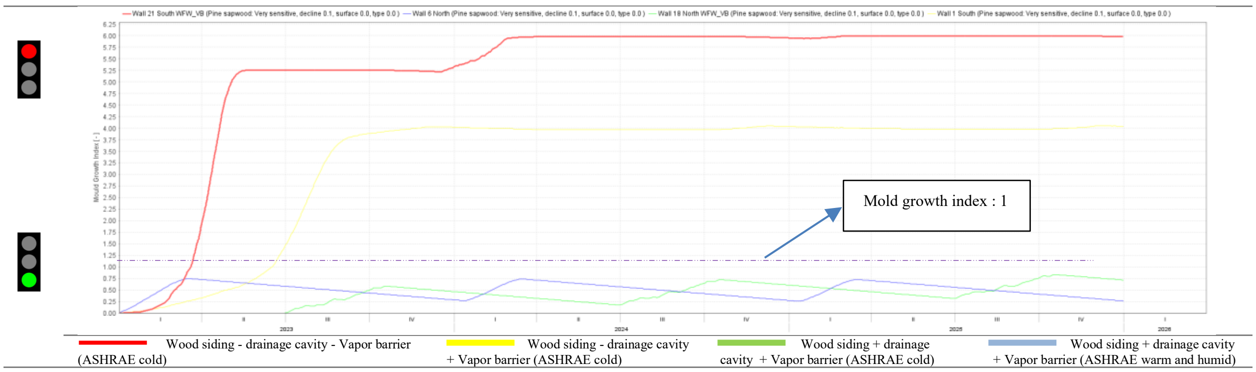


Figure 27. mold growth index and traffic signal representation

Figure 27 represents the mold growth index (MI) of OSB of the wall configurations simulated, the red traffic signal indicates that wall assembly will fail due to mold growth. And it is recommended to make the changes in wall design. The details of the wall configuration and MI is given in Table 12.

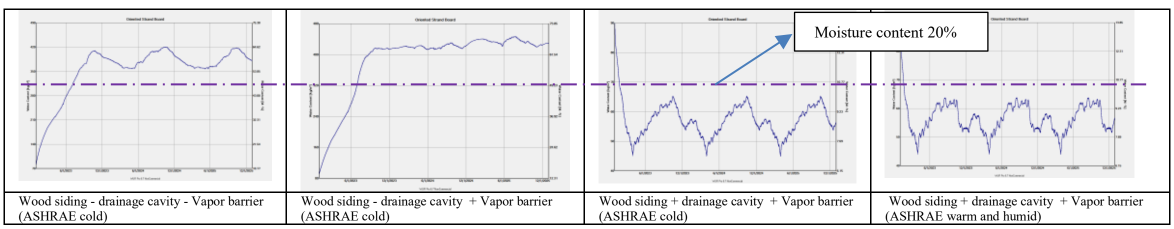
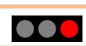


Figure 28. wall configuration with moisture content above and below 20 %

Figure 28 represents the moisture content of the OSB from the wall assemblies simulated for the MI. for wall configuration whose moisture content of the OSB is above 20% shows a MI of more than 3 which means that envelope is not safe. And for the wall assembly whose moisture content is below 20 % will have the MI less than 1, which is shown by the green traffic light, thereby making the wall assembly safe for construction. The details of the result for WFW configuration are given in Table 12.

	Wood Frame wall (WFW) configuration	**Climate**	**Mold Growth Index**
1	Wood siding - drainage cavity - Vapor barrier	ASHRAE cold	
2	Wood siding - drainage cavity + vapor barrier	ASHRAE cold	
3	Wood siding + drainage cavity - vapor barrier	ASHRAE cold	

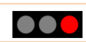
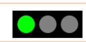
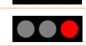
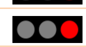
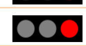
4	Wood siding + drainage cavity + vapor barrier	ASHRAE cold	
5	Stucco siding - drainage cavity - Vapor barrier	ASHRAE cold	
6	Stucco siding - drainage cavity + vapor barrier	ASHRAE cold	
7	Stucco siding + drainage cavity - vapor barrier	ASHRAE cold	
8	Stucco siding + drainage cavity + vapor barrier	ASHRAE cold	
9	Wood siding - drainage cavity - Vapor barrier	ASHRAE warm and humid	
10	Wood siding - drainage cavity + vapor barrier	ASHRAE warm and humid	
11	Wood siding + drainage cavity - vapor barrier	ASHRAE warm and humid	
12	Wood siding + drainage cavity + vapor barrier	ASHRAE warm and humid	
13	Stucco siding - drainage cavity - Vapor barrier	ASHRAE warm and humid	
14	Stucco siding - drainage cavity + vapor barrier	ASHRAE warm and humid	
15	Stucco siding + drainage cavity - vapor barrier	ASHRAE warm and humid	
16	Stucco siding + drainage cavity + vapor barrier	ASHRAE warm and humid	
17	Wood siding - drainage cavity - Vapor barrier	Passivhaus cold	
18	Wood siding - drainage cavity + vapor barrier	Passivhaus cold	
19	Wood siding + drainage cavity - vapor barrier	Passivhaus cold	
20	Wood siding + drainage cavity + vapor barrier	Passivhaus cold	
21	Stucco siding - drainage cavity - Vapor barrier	Passivhaus cold	
22	Stucco siding - drainage cavity + vapor barrier	Passivhaus cold	
23	Stucco siding + drainage cavity - vapor barrier	Passivhaus cold	
24	Stucco siding + drainage cavity + vapor barrier	Passivhaus cold	

Table 12. durability result for wood frame wall (WFW), (-) represents absence (+) represents presence.

Table 12 is the summary of the result obtained from WUFI pro 6.7 on durability analysis of wood frame wall (WFW) studied for the research. The result shows that 88% of the wall configurations investigated are not safe for construction in Paro which has a cold climate. This is true for both ASHRAE and Passivhaus standard insulation which is 6" and 12 " respectively. Only those wall assemblies which have both drainage cavity with vented air ACH50 and a Class I vapor barrier have a moisture content below 20 % and mold growth index below 1. All other combinations like drainage without vapor barrier or vapor barrier without drainage fail for wood siding as a cladding. But for the stucco siding even wall with both vented and vapor barrier fails to maintain mold growth index below 1 and moisture content below 20%. This indicates that of the two claddings, only wood siding is suitable for paro. When it comes to warm and humid climate 100 % of the wall configuration is without moisture problem, even wall cladding stucco without vented cavity and vapor barrier can be moisture safe for construction. This concludes that location in Bhutan plays a huge role in durability of WFW assembly in Bhutanese climate.

4.2.2 Cross Laminated Wall Configuration

The second wall assembly which is CLT configuration, the details of the wall assembly and its components are given in the Figure 29.

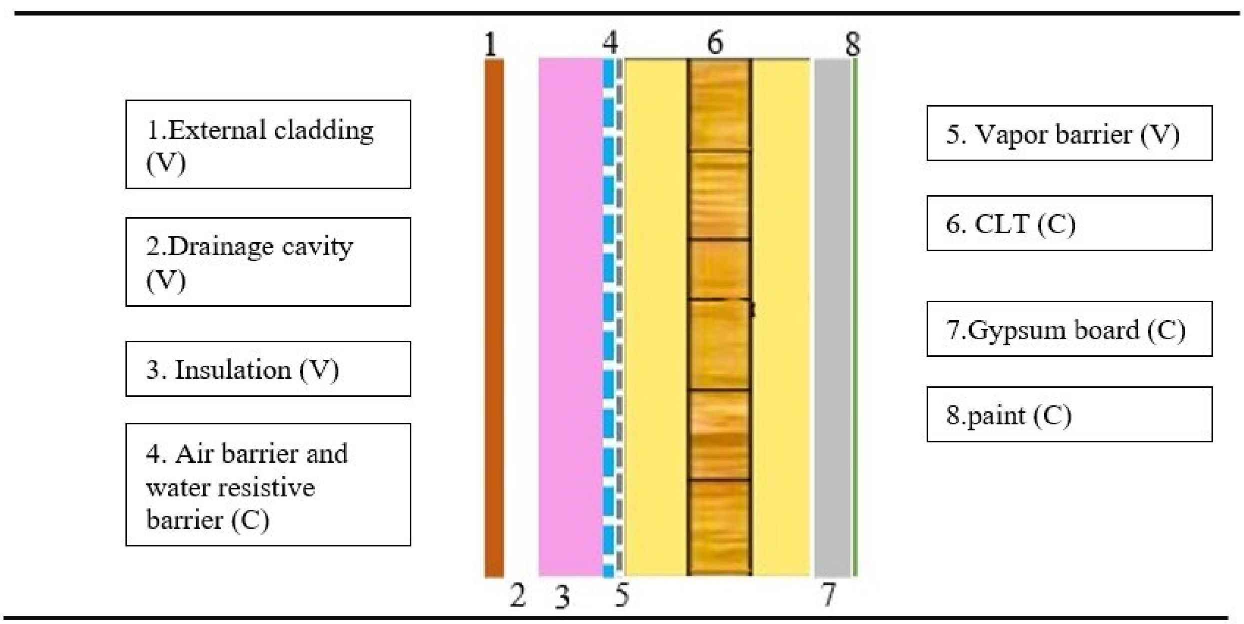


Figure 29. CLT configuration; (V) denotes varies and (C) denotes constant. 1. external cladding varies with wood siding and stucco siding, 2. drainage cavity varies with vented with 50 ACH and

non-vented. 3. insulation varies with 1" 2" and 10" for different climate investigated, 5. vapor barrier varies with class I vapor barrier and no vapor barrier and location of vapor barrier is always on the warm side.

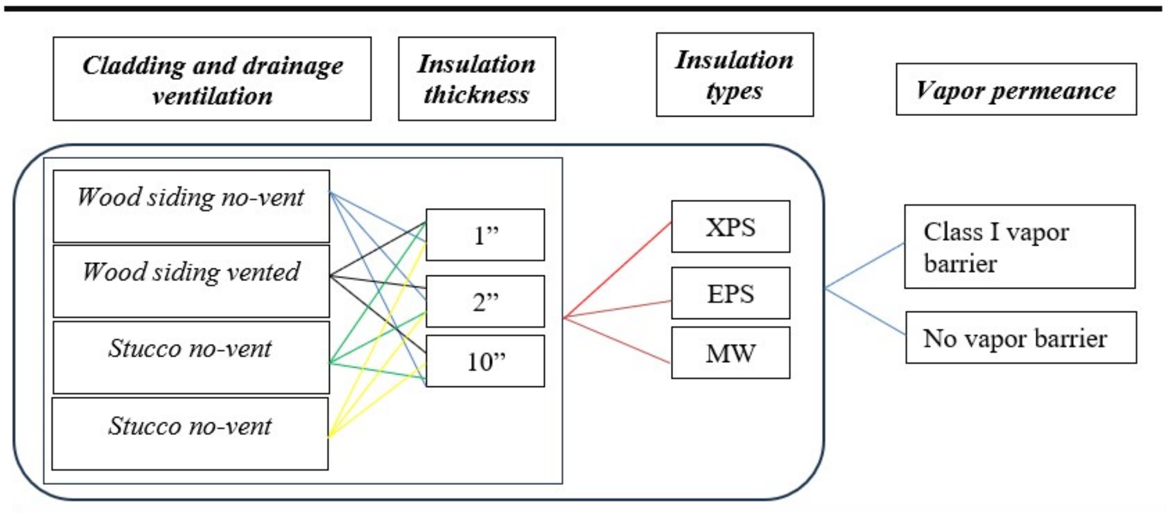


Figure 30. variables identified for CLT to optimize wall assembly for mold growth performance.

Figure 30 represents the variables identified for CLT wall assembly. There are four variables. First variable (cladding and ventilation drainage) has 4 elements such as wood siding no-vent, wood siding vented, stucco no-vent, and stucco vented. The second variable (insulation thickness) has 3 elements, which are 1",2" and 10 " thick insulation with thermal conductivity 0.04w/m2k. The insulation thickness differs to meet the thermal performance required for each climate as well as for passivhaus standard. This leads to 12 simulation results which are further simulated with third variable (insulation types) which has 3 elements namely extruded polystyrene XPS, expanded polystyrene EPS, and mineral wool MW. This results in 36 wall configurations. The last and fourth variable is the (vapor permeance) of the vapor barrier which has 2 elements such as class I vapor barrier and no vapor barrier. Therefore, the total simulation is 72 for the CLT wall assembly.

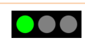
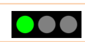
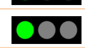
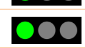
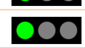
	Cross laminated timber (CLT) with (XPS,EPS and MW insulation)	Climate	Mold Growth Index
1	Wood siding - drainage cavity - Vapor barrier	ASHRAE cold	
2	Wood siding - drainage cavity + vapor barrier	ASHRAE cold	
3	Wood siding + drainage cavity - vapor barrier	ASHRAE cold	
4	Wood siding + drainage cavity + vapor barrier	ASHRAE cold	
.	Stucco siding - drainage cavity - Vapor barrier	ASHRAE cold	
.	Stucco siding - drainage cavity + vapor barrier	ASHRAE cold	
.	Stucco siding + drainage cavity - vapor barrier	ASHRAE cold	
.	Stucco siding + drainage cavity + vapor barrier	ASHRAE cold	
.			
.	Wood siding - drainage cavity - Vapor barrier	ASHRAE warm and humid	
.	Wood siding - drainage cavity + vapor barrier	ASHRAE warm and humid	
.	Wood siding + drainage cavity - vapor barrier	ASHRAE warm and humid	
.	Wood siding + drainage cavity + vapor barrier	ASHRAE warm and humid	
.	Stucco siding - drainage cavity - Vapor barrier	ASHRAE warm and humid	
.	Stucco siding - drainage cavity + vapor barrier	ASHRAE warm and humid	
.	Stucco siding + drainage cavity - vapor barrier	ASHRAE warm and humid	
.	Stucco siding + drainage cavity + vapor barrier	ASHRAE warm and humid	
.			
.	Wood siding - drainage cavity - Vapor barrier	Passivhaus cold	
.	Wood siding - drainage cavity + vapor barrier	Passivhaus cold	
.	Wood siding + drainage cavity - vapor barrier	Passivhaus cold	
.	Wood siding + drainage cavity + vapor barrier	Passivhaus cold	
.	Stucco siding - drainage cavity - Vapor barrier	Passivhaus cold	
70	Stucco siding - drainage cavity + vapor barrier	Passivhaus cold	
71	Stucco siding + drainage cavity - vapor barrier	Passivhaus cold	
72	Stucco siding + drainage cavity + vapor barrier	Passivhaus cold	

Table 13. durability result for wood frame wall (CLT) with (XPS,EPS, and MW), (-) represents absence (+) represents presence.

The parameter investigated is the cross laminated timber (CLT) for mold growth index and moisture content. The result from Table 13 indicates that CLT is a superior material than WFW in terms of durability. Because in all 72 configurations with various combinations mentioned in Figure 30, it all passes the mold growth index test with green traffic signal with the moisture content in CLT below 20 %. In many research concerning CLT wall configuration, the (XPS) combination has caused least envelope failure due to condensation and mold growth, followed by (EPS), and (MW) having cased more failures in hot and humid climates when passivhaus standard insulation thickness is modeled. In this research passivhaus insulation thickness was only modeled for cold climate and neglected for warm and humidity due to less energy savings potential concluded from energy efficiency analysis.

Chapter 5: Conclusion

By adopting a case study of an existing building typology of modern construction in Bhutan, this study investigated the feasibility of energy-efficient wood frame and CLT buildings in the Bhutanese climate. The main findings of this study through Design Builder and WUFI Pro analysis indicate that wood frame and CLT building envelope built to the ASHRAE and PH standard can provide excellent performance in the Bhutanese climate. The case study building in a cold climate (Paro) has an energy demand of 269.5 kWh/m^{2}a and 193.0 kwh/m^{2}a for warm and humid climates (Samdrup Jongkhar). There is an improvement of energy saving from space heating by 51% for the ASHRAE standard building envelope, whose energy demand is 93.7 kwh/m^{2}a. And improvement of 62% for the Passivhaus standard building envelope with 85.8 kwh/m^{2}a energy demand. For the proposed building envelope in Samdrup Jongkhar, the energy efficiency for space cooling is 11 % for ASHRAE standard building envelope with an energy demand of 168.7 kwh/m^{2}a. And improvement of 23% for the Passivhaus standard building envelope with 151.2 kwh/m^{2}a. The result shows that energy saving as a function of thermal envelope is more in the cold than in warm and humid climates.

The hygrothermal analysis is done for 24 WFW and 72 CLT wall assemblies. One out of eight wall configurations investigated are not safe for construction in Paro which has a cold climate. Only those wall assemblies which have both drainage cavity with vented air ACH50 and a Class I vapor barrier have a moisture content below 20 % and mold growth index below 1. But for the stucco siding even wall with both vented and vapor barrier fails. This indicates that of the two claddings, only wood siding is suitable for paro. When it comes to warm and humid climate 100 % of the wall configuration is without moisture problem, even wall cladding stucco without vented cavity and vapor barrier can be moisture safe for construction. On the contrary CLT can be constructed in both Paro and Samdrup Jongkhar with following any standard from ASHRAE and Passivhaus. And all combination 72 combination is safe for the construction. However, these recommendations are purely based on numerical analysis and simulations which are dependent upon certain assumptions that has been mentioned in the analysis and therefore on-site validation must be opted before it can be adopted for construction practices.

Bhutan being on the developing side of the economy, has seen less technological advancement in terms of adapting modern construction using WFW and CLT. Although cost benefit analysis is not made in this research, it has a potential to be a lot cheaper than the conventional material such as steel, brick, and concrete, because timber is produced in the country whereas most of the modern material is imported. As the government of Bhutan is trying to develop energy efficiency codes, and promoting timber architecture to conserve traditional architecture, more thermal insulation will need to be introduced in the building envelope to have better thermal comfort. With increase in thermal performance the risk of condensation and mold growth is inevitable. Through this research, a framework is laid in which more research can be done with field experiments and lab tests to confirm the simulated results. Further research can be done on sensitivity analysis of different claddings not limited to wood siding and stucco, and on the classes of vapor barriers different thickness of drainage gaps. This research contributes not to the theoretical knowledge of the existing literature but it’s a good ground for the practical solutions to improve thermal comfort, energy efficiency and durability of timber buildings in Bhutan.

Appendix 1 Building Physics of Heat, Air, and Moisture Transfer

1.1 Hygrothermal Load and Driving Forces.

The hygrothermal loads which act on the building envelope are used to predict the influence on the hygrothermal behavior of building assemblies as a basis for design recommendations and moisture control measures [9], [10] (Künzel et al., 2005). The hygrothermal loads include Ambient temperature and humidity, indoor temperature and humidity, solar radiation, exterior condensation, wind-driven rain, construction moisture, ground and surface water, and air pressure differentials. Ambient temperature and humidity, represented by the partial water vapor pressure, are the boundary conditions that always affect both sides of the building envelope. The climate-dependent exterior conditions may show significant diurnal and seasonal variations. Therefore, at least hourly data are needed for detailed building simulations. However, indoor humidity conditions in residential buildings are often influenced by the outdoor climate and occupant behavior. That water vapor must be removed by ventilation or air conditioning. The presence of spas or swimming pools increases the load substantially. (*ASHRAE Handbook Fundamentals*, 2017)(Glass et al., 2013) loads from occupant behavior show a primarily transient pattern: they are characterized by peak. Humidity buffering envelope materials, partition wall materials, and furniture help to dampen indoor humidity peaks, but they also reduce the moisture removal efficiency of intermittent ventilation (e.g., periodically opening windows, operating ventilation fans). Incident solar radiation is the major thermal load at the building exterior. For direct solar radiation, the resultant irradiation depends on the angle between the sun and the normal on the exposed surface and on its color. For moisture control, solar radiation is usually considered beneficial. However, in some cases solar radiation combined with water from precipitation or other sources (e.g., construction moisture) can lead to severe moisture problems by solar driven vapor flow(Lstiburek, 2009) (Straube & Finch, 2009a). For example, if the water-absorbing exterior layer of an assembly (e.g., brick veneer, a typical example of "reservoir "cladding) has been wetted by wind-driven rain, solar irradiation creates such high vapor pressure that, in addition to vapor diffusion toward the outdoors, part of the evaporating water diffuses inwards, leading to condensation on and in material layers within the assembly (e.g., sheathing boards, insulation layers, vapor retarders). Adapting the permeance of vapor retarders and weather-resistive barriers (WRB) to the potential loads may improve the situation.(Hartwig M. Künzel, n.d.) Depending on the building assembly's thermal properties, this may lead to a drop in the envelope's outdoor surface temperature below the ambient air temperature (undercooling). If this surface temperature reaches the air's dew point, condensation occurs on that exterior surface. Many modern building assemblies, such as lightweight roofs or exterior insulation finish systems (EIFSs), have little thermal inertia in their exterior surface layers and are subject to considerable amounts of exterior condensation. Exterior condensation can also occur on poorly insulated assemblies in cooling climates because of the operation of air-conditioning systems. Repeated exterior condensation or long-lasting, high relative humidity often provides the basis for soiling or microbial growth (fungi or algae). The load from rain, especially wind-driven rain, is the main reason for moisture-related building failure. [9], It is estimated from the average rain RN and the wind velocity component v parallel to the considered orientation.

$$RD = fvRN \qquad 1$$

Where,

RD = wind-driven rain intensity, $\frac{kg}{s.m^2}$

f = empirical factor = approximately 0.2 $\frac{s}{m}$

v = mean wind velocity, $\frac{m}{s}$

RN = rain intensity on a horizontal surface in an open field, $\frac{kg}{s.m^2}$

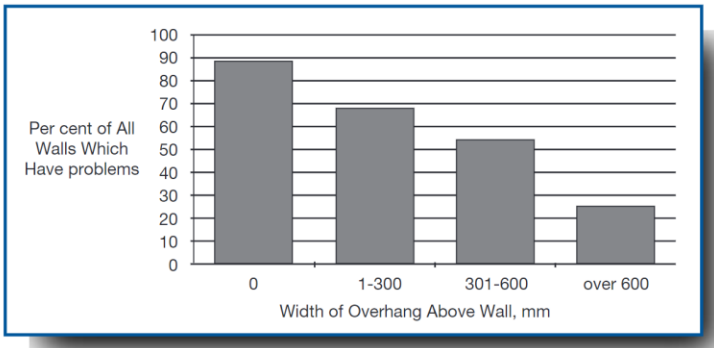


Figure 31. effect of overhang on wall performance

The frequency and intensity of wind-driven rain determines the amount of water potentially entering the enclosure from outside. The difference between indoor and outdoor temperatures determines whether, how much, and where condensation may form inside the enclosure assembly. The combination of temperature, humidity, and sunshine determines the rate and direction of vapor diffusion and, therefore, the drying potential. The outdoor temperature determines the temperature of materials in the outer part of an assembly (e.g., wood sheathing). Fungal decay of wood will only progress if the temperature and the moisture content of the materials are within certain ranges.

1.2 Heat Transfer

Heat transfer in a solid is governed by Fourier's law of conduction [9](Kumaran, 2009c).

$$q = -k\,grad(t) = -\left(k_x \frac{dt}{dx} + k_y \frac{dt}{dy} + k_z \frac{dt}{dz}\right) \quad (1)$$

where

q = heat flux ($\frac{w}{m^2}$)

T = temperature. °C

k_x, k_y, k_z = apparent thermal conductivity in direction of x,y,z axes. $(\frac{w}{mk})$

Grad(t) = gradient of temperature

(Kumaran, 2009c)

$\frac{dt}{dy}$= gradient of temperature along y-axis, k/m

$\frac{dt}{dz}$= gradient of temperature along z-axis, k/m

If the steady-state heat flux is only in one direction (e.g., perpendicular to the building envelope) and materials are assuming to be isotropic, equation (1) can be rewritten for each material layer within the building envelope as

$$q = -k_m \frac{\Delta t}{\Delta x} = -C\Delta t = -\frac{1}{R}\Delta t \qquad (2)$$

Where

Δt = temperature difference between two interfaces of one material layer, K

Δx = layer thickness, m

k_m mean thermal conductivity of material layer with thickness Δx , $\frac{w}{mk}$

C = thermal conductance of layer with thickness Δx , $\frac{w}{m^2 k}$

R = thermal resistance of layer with thickness Δx, $\frac{m^2 k}{w}$

1.3 Air Flow

Convection transfers energy by moving fluid, such as air. Convective heat transfer for building enclosures has two primary mechanisms: air convective flow within assemblies or spaces and convective flow through assemblies from interior to exterior or exterior to interior. This latter form of convection is generally referred to as air leakage. Convection within the airspaces of enclosure assemblies can reduce the effectiveness of low-density insulation by the movement of air (i.e., convective loops between hot and cold surfaces). Convection currents can be resisted by installing insulation to fill cavities and be in intimate contact with the air barrier. Convection due to air movement through assemblies, or air leakage, is a significant portion of the heat loss in a building. Depending on the airtightness of a building, up to 50% of the total heat loss could occur by air leakage. Airtight building-enclosure assemblies, components, and details control convection in energy-efficient wood-frame buildings(FPInnovations, 2013).

Airflow through and within building components is driven by stack pressure, wind pressure, and pressure differentials induced by mechanical. In calculating air flux in buildings, a distinction must be made between flow through open porous materials and open orifices, such as layers composed of small elements, cavities, cracks, leaks, and intentional vents. Air flux through an open porous material is given by (*ASHRAE Handbook Fundamentals*, 2017; Kumaran, 2009c)

$$m_a = -k_a grad(p_a) \quad (5)$$

Where,

m_a= air flux, $\frac{kg}{s.m^2}$

k_a= air permeability of open porous material, $\frac{kg}{pa.s.m}$

$grad(P_a)$ = gradient in total air pressure (stack, wind, and mechanical systems), $(\frac{Pa}{m})$

The air flux or air transfer equation for flow through the various orifice types is

$$m_a = C(\Delta P_a)^n$$

Where the flow coefficient C and flow exponent n are determined experimentally.

1.4 Moisture Transfer

Water vapor and liquid water migrate by a variety of transport mechanisms, such as Water vapor diffusion by partial water vapor pressure gradients, Displacement of water vapor by air movement, Surface diffusion, and capillary suction of liquid water in porous building materials, Liquid flow by gravity or water and air pressure gradients (*ASHRAE Handbook Fundamentals*, 2017),(Kumaran, 2009c),(Künzel et al., 2005)The equation used to calculate water vapor flux by diffusion through materials is based on Fick's law for the diffusion of a very dilute gas (water vapor) in a binary system (water vapor and dry air):

$$m_v = -\mu_p \, grad(p) \quad (6)$$

Where

m_v= water vapour flux

$grad(p)$= gradient of partial vapor pressure, pa

μ_p= water vapor permeability of porous material, $\frac{kg}{pa.s.m}$

Air transport not only enthalpy but also the water vapor it contains. Related water vapor flux is represented by

$$m_v = Wm_a = \frac{0.62}{p_a} m_a \, p \quad (7)$$

Where

W = humidity ratio of moving air

m_a= air flux, $\frac{kg}{s.m^2}$

P = partial water vapor pressure in air, Pa

P_a= atmospheric air pressure, pa

Even small air fluxes can carry much larger volumes of water vapor than vapor diffusion. However, potentially damaging airflow mostly occurs through cracks and leaky joints rather than through the entire area of a building component. (*ASHRAE Handbook Fundamentals*, 2017) Within tiny pores of an equivalent diameter of less than 0.1 mm, molecular attraction between the pore wall and the water molecules causes capillary suction is given by

$$s = \frac{2\sigma cos\theta}{r} \qquad (8)$$

Where

s = capillary suction, Pa

σ = surface tension of water, $\frac{N}{m}$

r = equivalent radius of capillary, m

θ = contact wetting angle, degrees

The gradient governs capillary water movement in capillary suction s:

$$m_l = -k_m grad(s) \qquad (9)$$

m_l= liquid flux, $\frac{kg}{s.m^2}$

k_m= water permeability, $\frac{kg}{pa.s.m}$

Alternatively, with relative humidity as the driving force

$$m_l = -\beta_\phi \; grad\;(\phi) \qquad (10)$$

Where

β_ϕ= liquid transport coefficient (relative humidity as driving potential) $\frac{kg}{m.s}$

Capillary suction is greater in smaller capillaries, so water moves from larger to smaller capillaries. In pores with constant equivalent radii, water moves toward zones with smaller contact angles. Although surface tension is a decreasing function of temperature (the higher the temperature, the lower the surface tension) and water moves toward zones with lower temperature, that effect is small compared to the effect of equivalent pore diameter and contact angle. Capillary suction increases linearly with the inverse of the radius [see Equation (8)], but the flow resistance increases proportionally to the fourth power of the inverse radius. Therefore, larger ones have a much greater liquid transport capacity than smaller ones. Furthermore, because larger pores can only be filled with water once the smaller pores are saturated, the liquid transport capacity is a function of moisture content [9]. Thus, water permeability k_m and liquid transport coefficient are also functions of water content. Transient water content profiles recorded from the tests serve to determine the liquid diffusivity D_w of the examined material, which is defined by

$$m_l = \; - D_w \, grad(w) \qquad (11)$$

Where

w = moisture content, $\frac{kg}{m^3}$

D_w= liquid diffusivity, $\frac{m2}{s}$

Although Equation (11), which resembles Fick's law for diffusion, would seem a natural choice for calculating liquid flow, its use is not recommended because the water content is not a continuous potential in building envelopes of different materials [9]. Using Equation (9) or (10) is recommended because the relative humidity ϕ and capillary suction s are considered to have continuous potential (no jumps at material interfaces). Where diffusivity functions are available, the liquid transport coefficient β_ϕ in Equation (10) can be determined by

$$\beta_\phi = \; D_w \frac{d_w}{d_\phi} \qquad (12)$$

Where

$\frac{d_w}{d_\phi}$= is the slope of the moisture retention curve, in $\frac{kg}{m^3}$

Liquid flow at low moisture content in porous materials with a fixed pore structure, the apparent increase in vapor permeability is because of liquid transport phenomena and to shorter diffusion paths among water islands in the porous system formed by capillary condensation. The driving potential of surface diffusion is the mobility of the molecules, which depends on the relative humidity in the pores (i.e., the adsorbed water migrates from zones of high to low relative humidity). If present low moisture content, liquid flow can be described by Equations (10) or (11), as capillary flow. Under isothermal conditions, it is impossible to differentiate between vapor and liquid flow at low moisture content. However, in the presence of a temperature gradient, both transport processes may oppose each other in a pore; the fluxes may go in opposite directions (Künzel, 1995). For heating climates in winter, the indoor vapor pressure is usually higher than outdoors, while the indoor humidity is lower than outdoors. Therefore, the partial vapor pressure gradient is opposed to the relative humidity gradient over the cross-section of an exterior wall. The only moisture transport mechanism is vapor diffusion, and the total flux is directed toward the exterior. Suppose the average humidity in the wall rises to 50 to 80% RH. In that case, liquid water moves in the opposite direction by surface diffusion or capillary suction in the nanopores. Under these conditions, the total moisture flux may go to zero if both fluxes are of the same magnitude (*Krus 1996 - Moisture Transport and Storage Coefficients*, n.d.). When conditions are very wet (e.g., wind-driven rain), most of the capillary pores are filled with water, and the dominant transport mechanism flows by capillary suction.

1.5 Transient Moisture Flow

It is difficult to experimentally distinguish between liquid flow by suction and water vapor flow by diffusion in porous, hygroscopic materials. However, because these materials have a very complex porous system and each surface is transverse by liquid-filled pore fractions and vapor-filled pore fractions, vapor and liquid flow are often treated as parallel processes (*ASHRAE Handbook Fundamentals*, 2017), (Kumaran, 2009c; Künzel et al., 2005). This allows the expression of moisture flow as the summation of the two transport equations, one using.

$$\frac{dw}{dt} = -div(m_w + m_v) + S_w \quad (13)$$

Where

w = moisture content of building materials, $\frac{kg}{m^3}$

m_v= water vapor flux, $\frac{kg}{m^2.s}$

m_w= liquid water flu, $\frac{kg}{m^2.s}$

s_w= moisture source or sink, $\frac{kg}{m^3.s}$

div = divergence (resulting inflow or outflow per unit volume of solid), m^{-1}

Equations give vapor and liquid fluxes (9) and (10), which may be rewritten in terms of only two driving forces, capillary suction pressure s and partial vapor pressure p

$$\frac{dw}{ds} \times \frac{ds}{dt} = div\left[k_m\, grad(s) + \mu_p\, grad(p)\right] + S_w \quad (14)$$

Where

s = capillary suction pressure, Pa

p = partial vapor pressure, pa

μ_p= vapor permeability (related to partial vapor pressure), $\frac{kg}{pa.s.m}$

k_m= water permeability (related to partial suction pressure), $\frac{kg}{pa.s.m}$

S_w= moisture source or sink, $\frac{kg}{m^3.s}$

Alternatively, capillary suction pressure s in Equation (14) can be replaced by relative humidity as the sole variable, with saturation pressures at only a function of temperature:

$$\frac{dw}{d_\phi} \times \frac{d\phi}{dt} = div\left[\beta_\phi grad(\phi) + \mu_p\, grad(\phi p_{sat})\right] + S_w \quad (15)$$

Where

ϕ = relative humidity, %

p_{sat}= saturation vapor pressure, Pa

μ_p= vapor permeability (related to partial vapor pressure), $\frac{kg}{pa.s.m}$

β_ϕ= liquid transport coefficient (related to relative humidity), $\frac{kg}{s,m}$

1.6 Controlling HAM Transfer.

1.6.1 Heat Transfer

The primary purpose of thermal insulation materials is to reduce conductive, convective, and radiant heat flows.(*ASHRAE Handbook Fundamentals*, 2017; Sandberg, 2009) When applied correctly in building envelopes, insulating materials can increase energy efficiency by reducing the building's heat loss or gain, control surface temperatures for occupant comfort, help to control temperatures within an assembly to reduce the potential for condensation, modulate temperature fluctuations in unconditioned or partly conditioned spaces. While heat flow through the building enclosure cannot be prevented, it can be controlled to reduce the total energy consumption and improve comfort. This is achieved by constructing a thermally insulated and airtight building enclosure, which is a fundamental strategy for achieving an energy-efficient building (FPInnovations, 2013).

Interior Insulated: Insulating layer is located on the interior side of the water-resistive barrier. For walls, this typically means that the insulation is located within the stud space. For roofs, the interior insulation may be located above the sheathing. However, both are interior insulated' under the roof membrane or below the sheathing within the roof framing.

Exterior-insulated: Insulating layer is located on the exterior of the water-resistive barrier, i.e., the likely wet zone. For walls, this means that the insulation is located within the drained cavity space. In contrast, for roofs, the insulation is located above the membrane (i.e., an inverted roof or protected membrane assembly). This is the preferred insulation strategy for mass timber, such as

CLT walls, to protect the wood from moisture accumulation. Exterior insulation materials must be resistant to the effects of moisture.

Split Insulation: More than one insulating layer is provided, typically with one layer to the interior and one layer to the exterior of the water-resistive barrier.

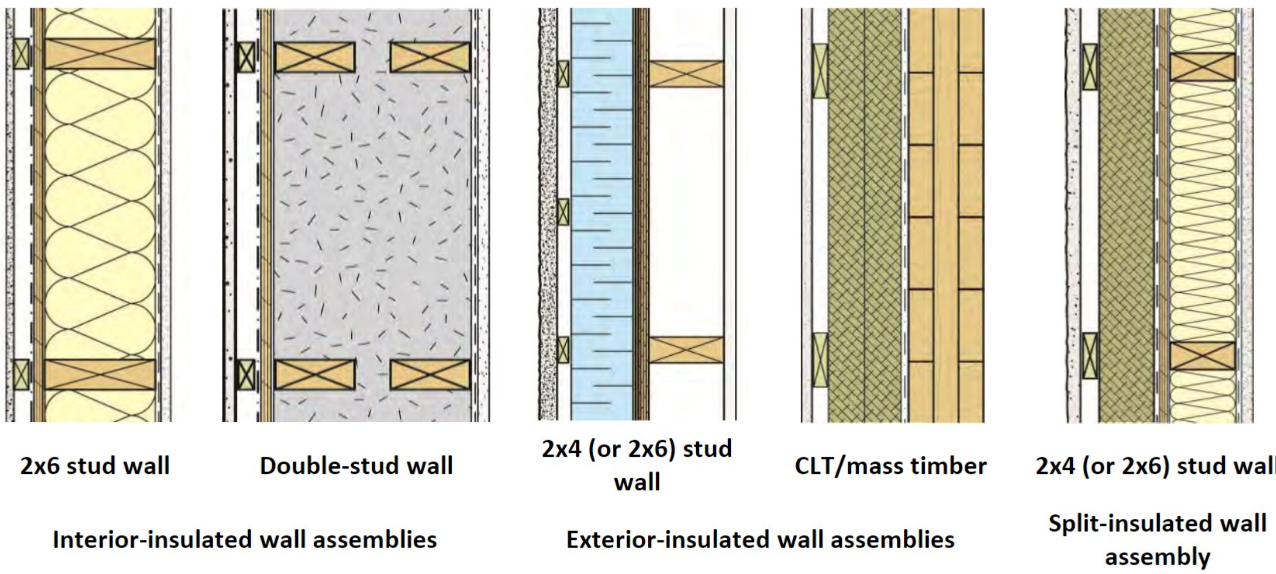


Figure 32. Options for placement of insulation within thermally efficient above-grade wood-frame wall assemblies @ (FPInnovations, 2013)

1.6.2 Air Barrier

Air barriers are generally located on the interior or exterior of the wood-frame portion of the wall assembly. In general, in hot and humid climates, the air barrier is installed on the exterior side of the wall to limit air infiltration and wind washing from the exterior and to prevent warm moist air from contacting cold interior surfaces. In mixed climates, the air barrier may be installed on the interior or exterior of the wall, or both, to limit air movement from the interior and exterior. In cold climates, the air barrier is generally installed on the interior to limit air exfiltration into the assembly and convective looping within fibrous insulations and to prevent moist indoor air from contacting cold exterior surfaces. In cold climates, an air-barrier material may also be installed on the exterior side of the wall to prevent wind washing. Unlike vapor barriers, there is little to no downside of redundancy in the air barrier, provided that the materials used for the air barrier do not negatively affect vapor flow (FPInnovations, 2013)(Lstiburek, 2002).

Air barriers may control both vapor and airflow (i.e., they may act as an air/vapor retarder), depending on the materials' characteristics. Many designs are based on this idea, with measures taken to ensure that the layer with vapor-retarding properties is continuous to control airflow. Some designs treat airflow and vapor retarders as separate entities. Still, an airflow retarder should not be where it can cause moisture to condense if it also has vapor retarding properties [9], [12](Canada Mortgage and Housing Corporation., 1999). Building assemblies are constructed, and the various air barrier assemblies are connected to form an air barrier system for the whole building. The building's air leakage characteristics can be determined with the ASTM Standard E779 test method. A 2008 addendum to ASHRAE Standard 90.1 requires 2.0 L/ (s · m2) at75 Pa pressure difference. Air leakage through building envelopes is not confined to doors and windows. Although 6 to 22% of air leakage occurs there, 18 to 50% typically occurs through walls and 3 to 30% through the ceiling. Leakage often occurs between the sill plate and foundation through interior walls, electrical outlets, plumbing penetrations, and cracks at the top and bottom of exterior walls. Not all cracks and openings can be sealed in existing buildings, nor can tight construction be achieved in new buildings. Provide as tight an enclosure as possible to reduce leakage, minimize potential condensation within the envelope, and reduce energy loss. However, the project team must also recognize the impact of airtightness.

Canadian construction codes, including the 2012 interim update of the 2010 National Building Code and 2011 National Energy Code for Buildings have general air-barrier continuity requirements. Materials used as part of the air-barrier systems must be air impermeable (less than 0.004 cfm/ft2 (0.02 L/s·m2) at 75 Pa), free of holes and cracks, and compatible with adjoining materials. Prescriptive air-sealing measures are included to ensure air-barrier continuity. In addition to opaque enclosure assemblies, the airtightness of manufactured fenestration must meet specific testing requirements as tested to AAMA/WDMA/ASTM/CSA requirements (range of 0.04 cfm/ft2 (0.2 L/s·m2) at 75 Pa to 0.1 cfm/ft2 (0.5 L/s·m2) at 75 Pa) and air-barrier continuity between opaque assemblies and fenestration must be maintained (FPInnovations, 2013).

IECC Airtightness Requirements, for residential buildings, MURB's Section R402.4 states that "the building envelope shall be constructed to limit air leakage" and includes performance-based requirements for whole-building air-leakage testing. A requirement for a whole-house or dwelling unit fan-door test to meet an air-leakage rate of 5 ACH@50 Pa or less is required in Climate Zones 1 to 3, and a rate of 3 ACH@50Pa or less is required in Climate Zones 4 to 8 (FPInnovations, 2013).

Managing airflow across the building enclosure is a key element in reducing energy consumption, increasing thermal comfort, and minimizing the movement of water vapor through the assembly. An air barrier system has five basic requirements: these requirements, with a specific focus on CLT wall, roof, and floor assemblies (FPInnovations, 2019).

1.6.3 Vapor Barrier

Water vapor retarders demand consideration in every building design. The need for any system depends on the climate zone, construction type, building usage, and moisture sources other than indoor water vapor to be considered (*ASHRAE Handbook Fundamentals*, 2017),(Bomberg & Shirtliffe, 2009). Water vapor retarders were initially designed to protect building elements from water vapor diffusing through building materials and condensing against and in layers at the cold side of the thermal insulation (Lstiburek, 2002). Now it is asserted as essential to allow a building assembly to dry as it is to keep the building assembly from getting wet by vapor diffusion. In some cases, to allow the building assembly to dry, a water vapor retarder may not be needed or should be semi-permeable. In other cases, the environmental conditions, building construction, and building usage may dictate that a material with extremely low water vapor permeance should be installed to protect building components. Therefore, a balanced design approach is needed: a vapor retarder can reduce the potential for an assembly to dry but can also reduce the potential for the assembly to get wet. ASHRAE Standard 160 should be followed to decide the need for and placement of a vapor retarder. The 2007 supplement to the International Codes (ICC 2007) lists three water vapor retarder classes:

Class I: 5.7 $\frac{ng}{Pa.sm^2}$ or less

Class II: more than 5.7 $\frac{ng}{Pa.sm^2}$ but less than or equal to 57 $\frac{ng}{Pa.sm^2}$

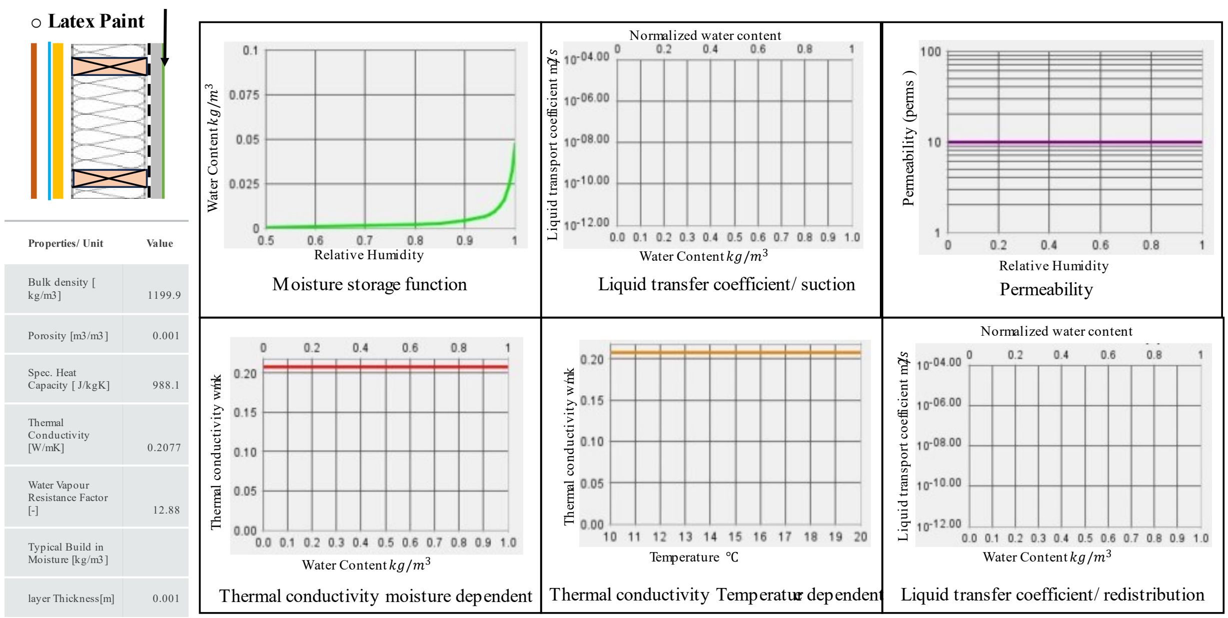
Class III: more than 57 $\frac{ng}{Pa.sm^2}$but less than or equal to$\frac{ng}{Pa.sm^2}$

Condensation occurs whenever air contacts a surface at a temperature below the dew point of the air. In heating climates, it is often thought of as a phenomenon resulting from the outward migration of water vapor during the heating season. This occurs because the warmer indoor air is at a higher dew point or vapor pressure than the colder exterior due to indoor moisture generation. Vapor-control layers installed at the interior side of the insulation, or insulation on the exterior of moisture-sensitive components (as discussed later in this chapter), are typically used to control this vapor flow and the potential for condensation in heating climates (FPInnovations, 2013)(Canada Mortgage and Housing Corporation., 1999).

A vapor retarder typically slows the water vapor diffusion rate but does not prevent it. In most cases, requirements for vapor retarders in envelope assemblies are relatively relaxed (*ASHRAE Handbook Fundamentals*, 2017). Because conditions on the inside and outside of buildings vary continually, air movement and ventilation can provide wetting and drying at various times. Water vapor entering one side of an envelope assembly can be stored temporarily as hygroscopic moisture and released later. (Bomberg & Shirtliffe, 2009)(Lstiburek, 2002)A vapor barrier is often used to stop water vapor transport when the real problem is water vapor transport by air transport. This needs to be clarified between the use and function of vapor barriers/retarders and those of air barriers. However, if conditions are conducive to excessive humidification, water vapor retarders help to (1) keep the thermal insulation dry; (2) prevent structural damage from rot, corrosion, freeze/thaw, and other environmental actions; and (3) reduce paint problems on exterior walls (although rain absorption through cracks in the paint may be a more probable cause of paint problems) (ASTM Standard C755). Judicious placement of a vapor retarder may also help an assembly today out. The vapor retarder's effectiveness depends on its vapor permeance, installation, and location in the insulation—the retarder should be at or near the surface exposed to higher water vapor pressure and higher temperature. In heating climates, this is usually the winter-warm side. In highly insulated building-enclosure assemblies, the potential for interstitial vapor condensation becomes a significant consideration in terms of durability. In heating-dominated climates, condensation most often results from the outward migration of water vapour because the warmer indoor air is at a higher dew point or vapor pressure than the colder exterior(FPInnovations, 2013)(Canada Mortgage and Housing Corporation., 1999). Vapor-control layers installed at the interior side of the insulation, or the use of insulation on the exterior of moisture-sensitive components to make them warmer and prevent moisture entrapment used to control this vapor flow and potential for condensation. In cooling-dominated climates, condensation typically results from the inward migration of water vapor during the cooling season (mainly when the indoors is air conditioned and has a lower dew point than the exterior). The use of vapor-control layers and or/exterior insulation on the exterior of assemblies or vapor-open assemblies are typically used to control vapor from the outside.

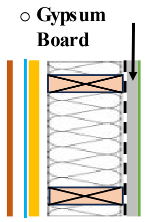
Appendix 2. Building Material Properties

2.1 WUFI Material Properties



Properties/ Unit	Value
Bulk density [kg/m3]	1199.9
Porosity [m3/m3]	0.001
Spec. Heat Capacity [J/kgK]	988.1
Thermal Conductivity [W/mK]	0.2077
Water Vapour Resistance Factor [-]	12.88
Typical Build in Moisture [kg/m3]	
layer Thickness[m]	0.001

Figure 33. material data for latex paint



Properties/ Unit	Value
Bulk density [kg/m3]	625
Porosity [m3/m3]	0.706
Spec. Heat Capacity [J/kgK]	870.02
Thermal Conductivity [W/mK]	0.16
Water Vapour Resistance Factor [-]	7.03
Typical Build in Moisture [kg/m3]	10
layer Thickness[m]	0.0125

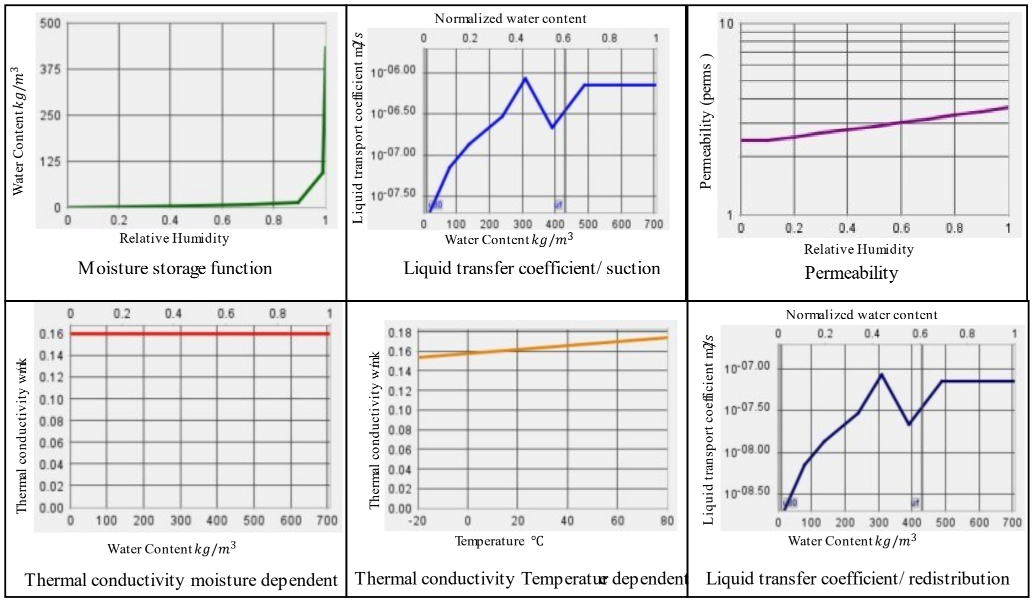
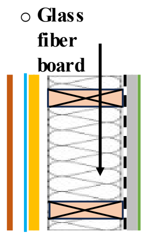


Figure 34. material data for gypsum board



Properties/ Unit	Value
Bulk density [kg/m3]	122
Porosity [m3/m3]	0.99
Spec. Heat Capacity [J/kgK]	839.06
Thermal Conductivity [W/mK]	0.035
Water Vapour Resistance Factor [-]	1.01
Typical Build in Moisture [kg/m3]	1.3407
layer Thickness[m]	0.1524

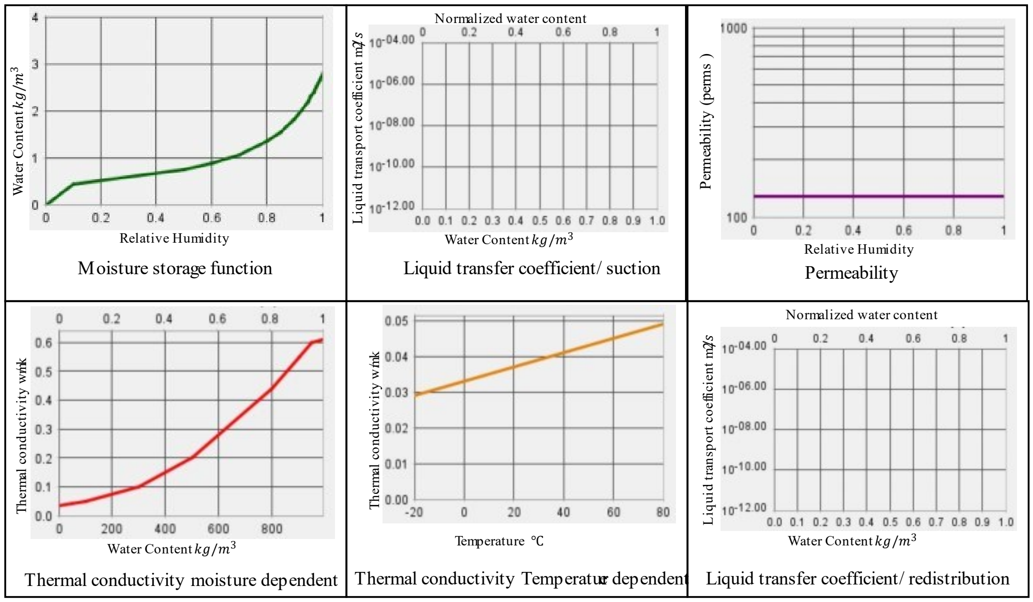
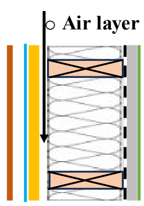


Figure 35. material data for glass fiber board insulation



Properties/ Unit	Value
Bulk density [kg/m3]	1.303
Porosity [m3/m3]	0.99
Spec. Heat Capacity [J/kgK]	999.82
Thermal Conductivity [W/mK]	0.13
Water Vapour Resistance Factor [-]	0.56
Typical Build in Moisture [kg/m3]	0.0091
layer Thickness[m]	0.005

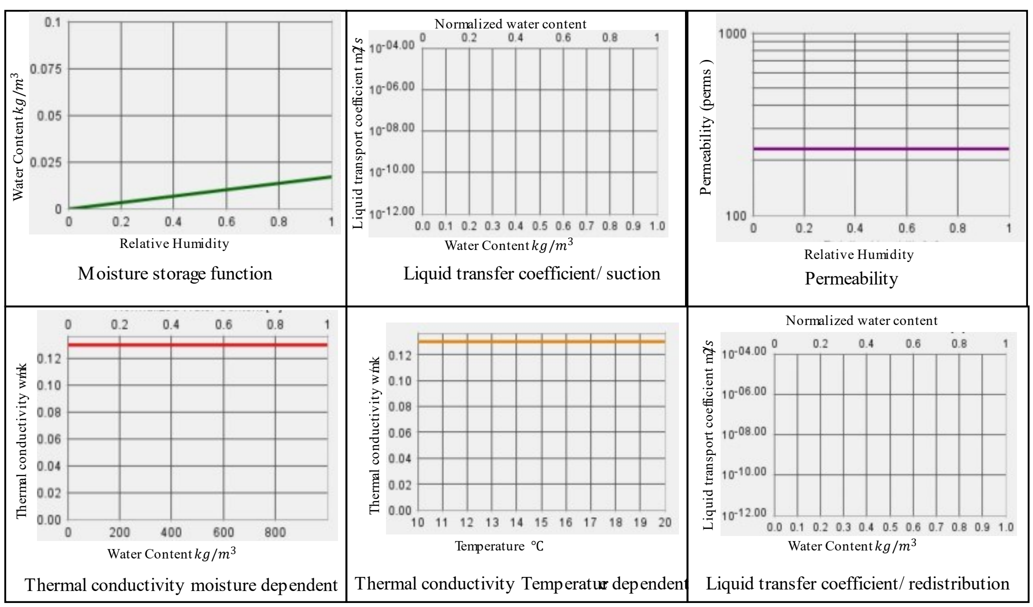
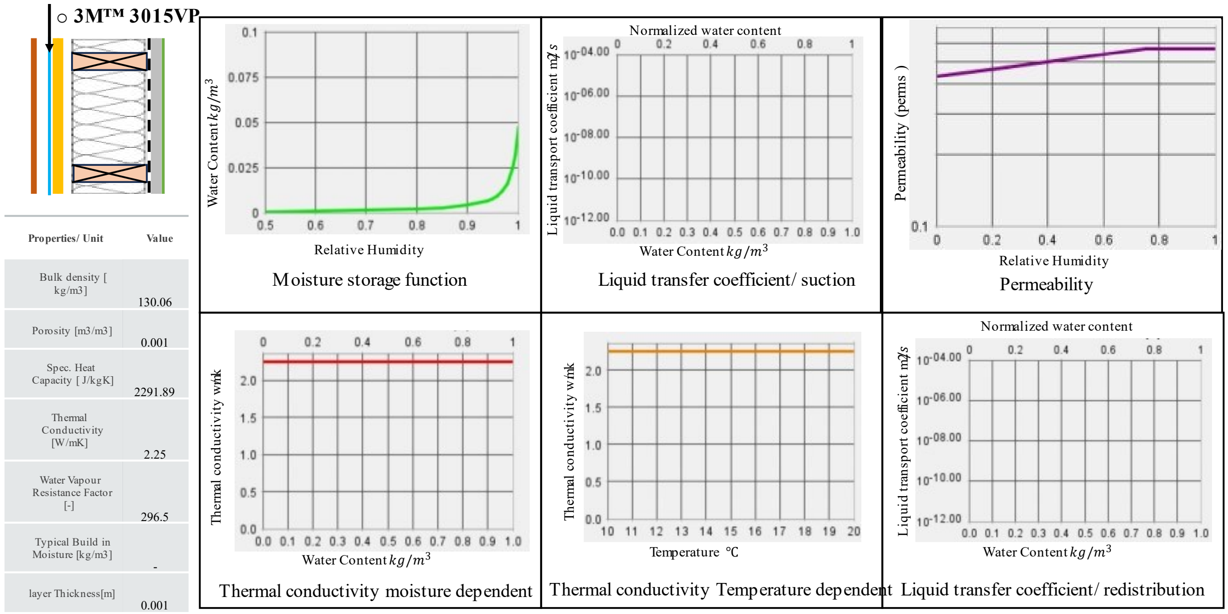
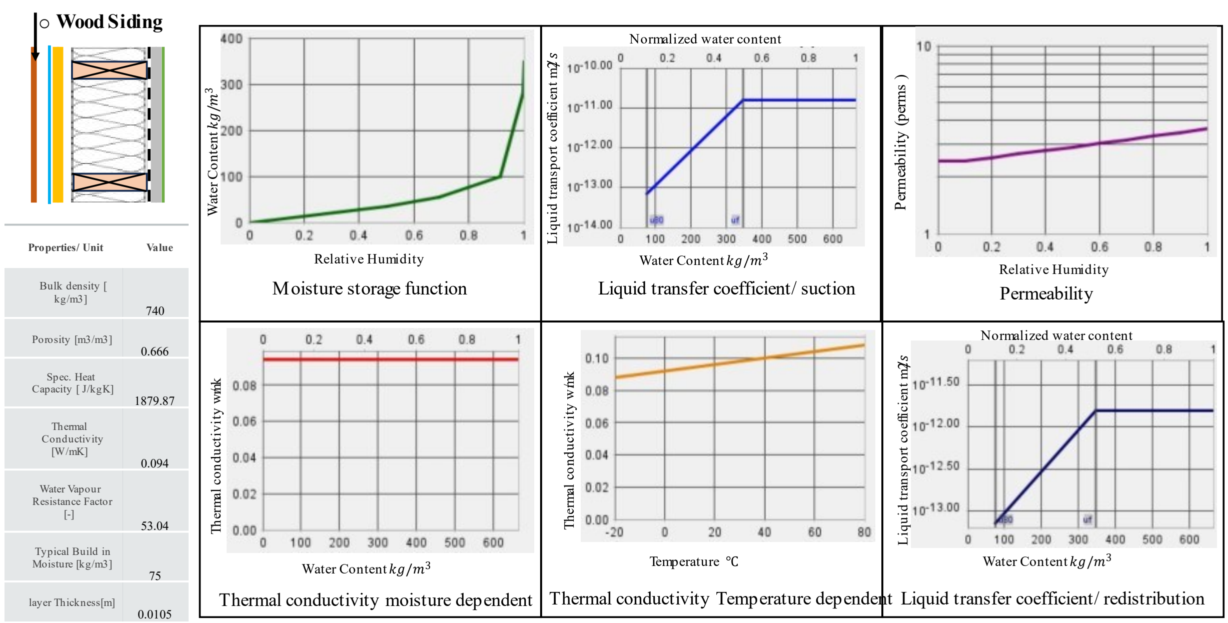


Figure 36. material data for air layer without additional moisture capacity



Properties/ Unit	Value
Bulk density [kg/m3]	130.06
Porosity [m3/m3]	0.001
Spec. Heat Capacity [J/kgK]	2291.89
Thermal Conductivity [W/mK]	2.25
Water Vapour Resistance Factor [-]	296.5
Typical Build in Moisture [kg/m3]	-
layer Thickness[m]	0.001

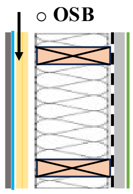
Figure 37. material data for 3M™ vapor permeable air barrier 3015VP. water resistive barrier and air control layer



Properties/ Unit	Value
Bulk density [kg/m3]	740
Porosity [m3/m3]	0.666
Spec. Heat Capacity [J/kgK]	1879.87
Thermal Conductivity [W/mK]	0.094
Water Vapour Resistance Factor [-]	53.04
Typical Build in Moisture [kg/m3]	75
layer Thickness[m]	0.0105

Figure 38. material data for wood siding

○ **OSB**



Properties/ Unit	Value
Bulk density [kg/m3]	650
Porosity [m3/m3]	0.95
Spec. Heat Capacity [J/kgK]	1879.87
Thermal Conductivity [W/mK]	0.094
Water Vapour Resistance Factor [-]	812.56
Typical Build in Moisture [kg/m3]	89.99
layer Thickness[m]	0.0125

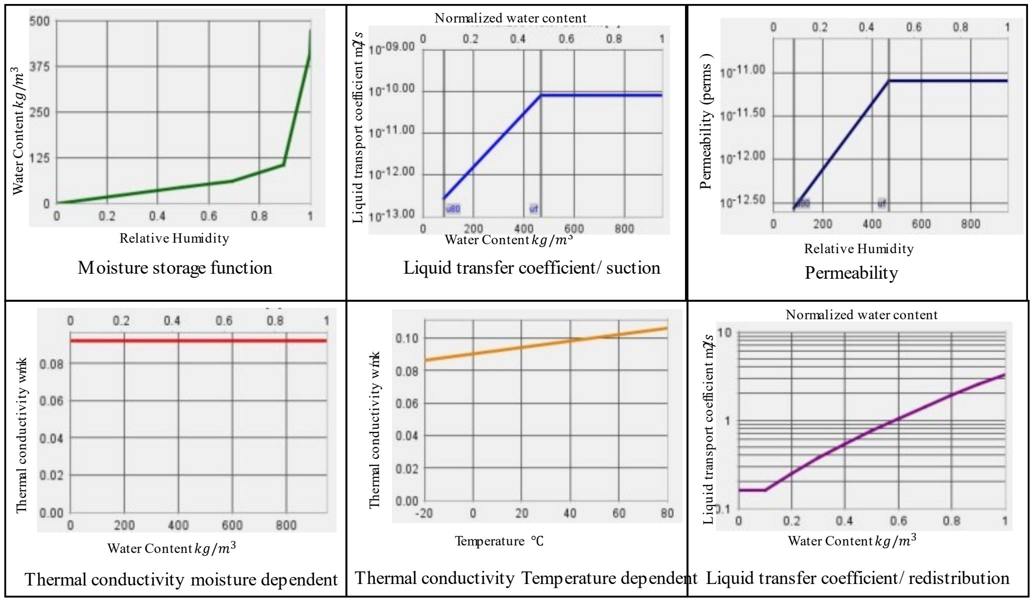
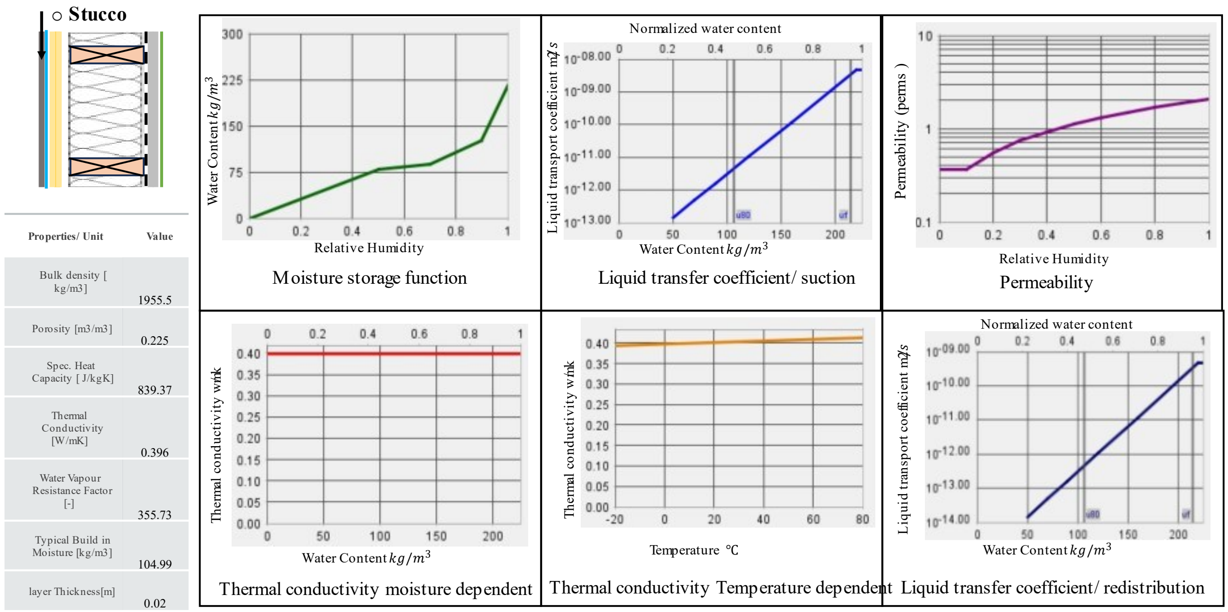
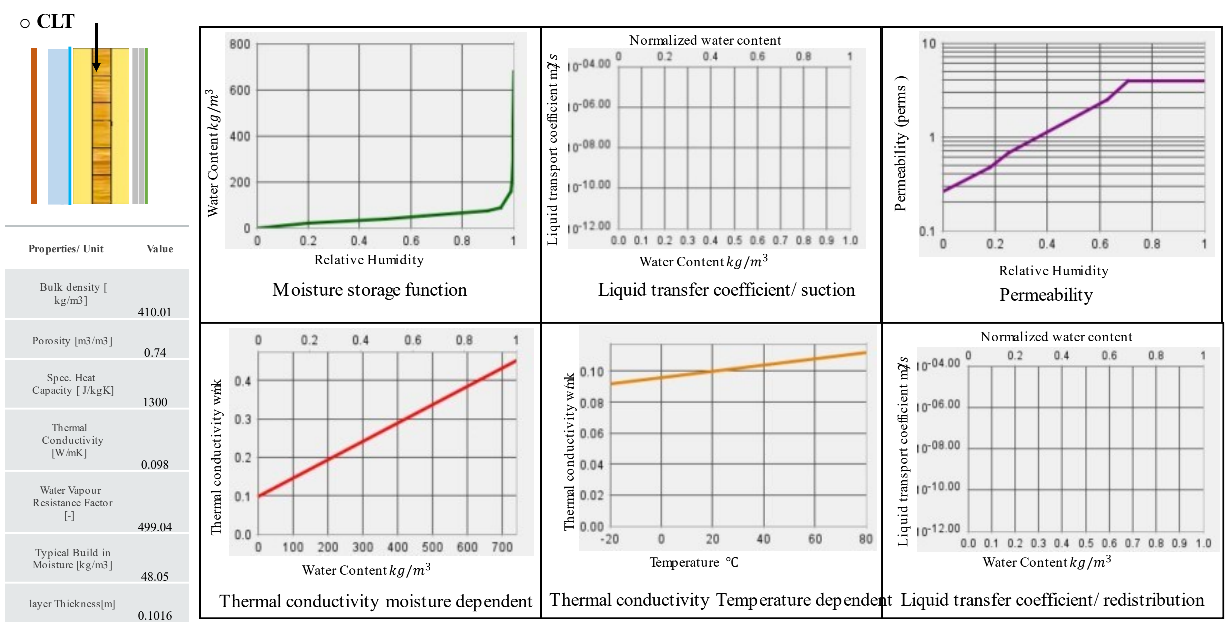


Figure 39. material data for oriented strand board



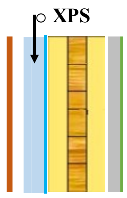
Properties/ Unit	Value
Bulk density [kg/m3]	1955.5
Porosity [m3/m3]	0.225
Spec. Heat Capacity [J/kgK]	839.37
Thermal Conductivity [W/mK]	0.396
Water Vapour Resistance Factor [-]	355.73
Typical Build in Moisture [kg/m3]	104.99
layer Thickness[m]	0.02

Figure 40. material data for ordinary portland cement stucco



Properties/ Unit	Value
Bulk density [kg/m3]	410.01
Porosity [m3/m3]	0.74
Spec. Heat Capacity [J/kgK]	1300
Thermal Conductivity [W/mK]	0.098
Water Vapour Resistance Factor [-]	499.04
Typical Build in Moisture [kg/m3]	48.05
layer Thickness[m]	0.1016

Figure 41. material data for cross laminated timber



Properties/ Unit	Value
Bulk density [kg/m3]	40.04
Porosity [m3/m3]	0.95
Spec. Heat Capacity [J/kgK]	1500.13
Thermal Conductivity [W/mK]	0.0299
Water Vapour Resistance Factor [-]	450.34
Typical Build in Moisture [kg/m3]	-
layer Thickness[m]	0.0381

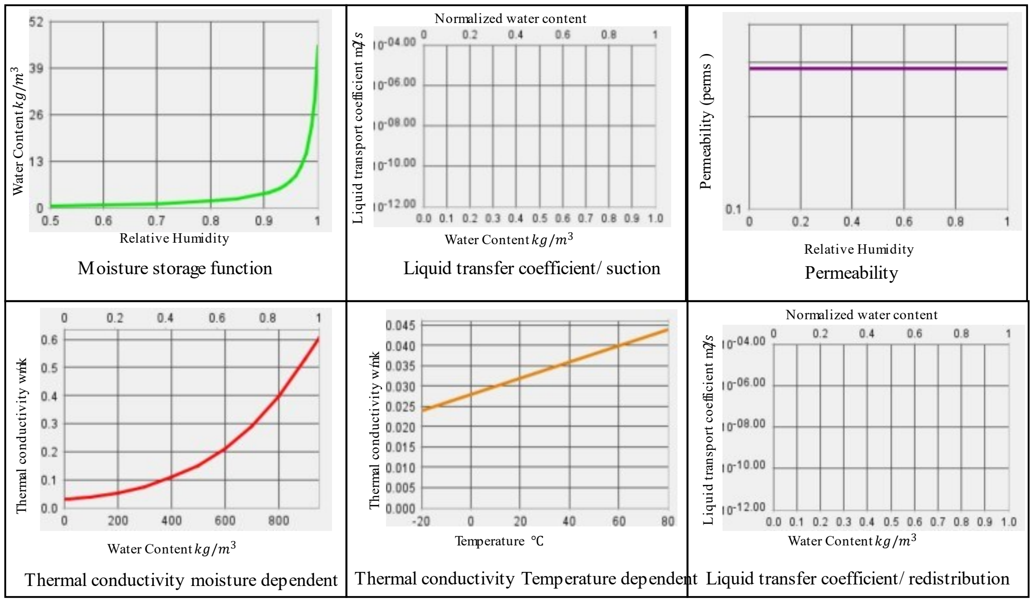
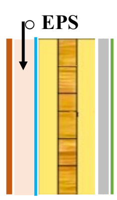


Figure 42. material data for extruded polystyrene, XPS



Properties/ Unit	Value
Bulk density [kg/m3]	14.99
Porosity [m3/m3]	0.95
Spec. Heat Capacity [J/kgK]	1500.13
Thermal Conductivity [W/mK]	0.04
Water Vapour Resistance Factor [-]	30.43
Typical Build in Moisture [kg/m3]	-
layer Thickness[m]	0.05

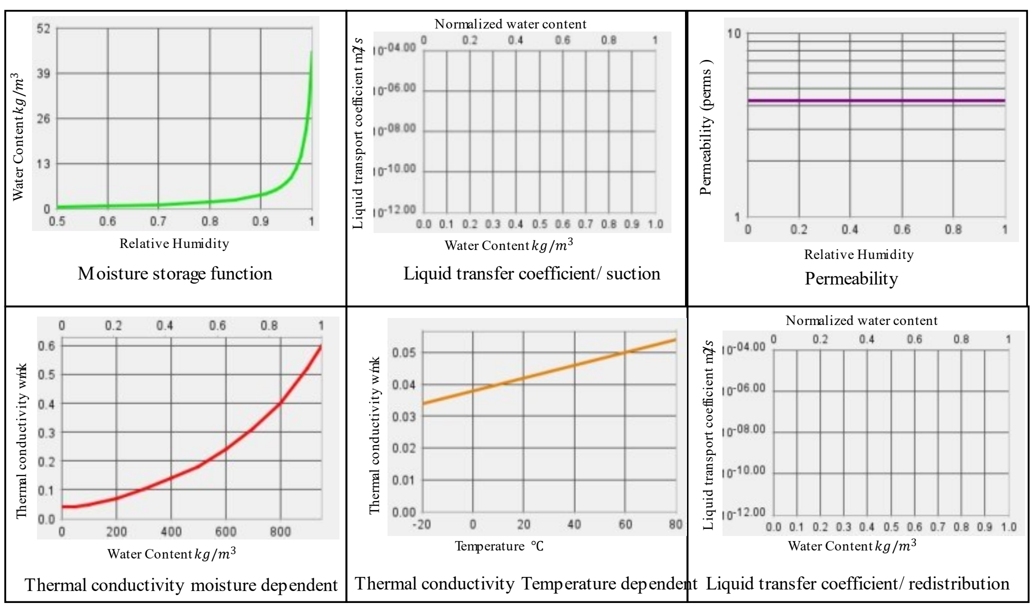
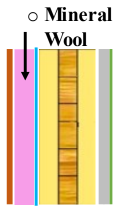


Figure 43. material data for expanded polystyrene, EPS



Properties/ Unit	Value
Bulk density [kg/m3]	60.009
Porosity [m3/m3]	0.95
Spec. Heat Capacity [J/kgK]	849.70
Thermal Conductivity [W/mK]	0.04
Water Vapour Resistance Factor [-]	1.3
Typical Build in Moisture [kg/m3]	-
layer Thickness[m]	0.05

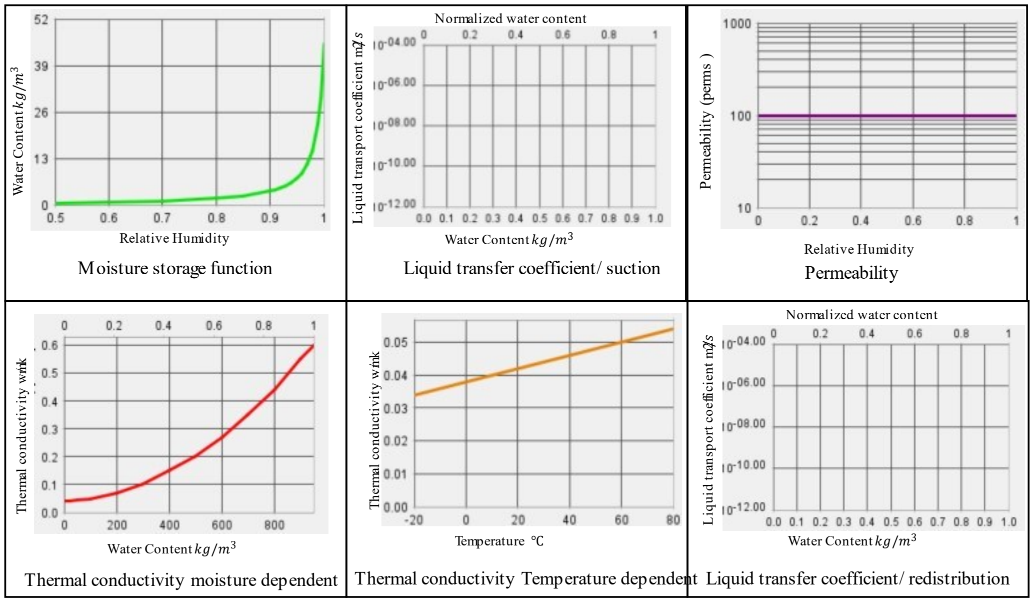


Figure 44. material data for expanded polystyrene EPS

Appendix 3. Building Wall Configuration

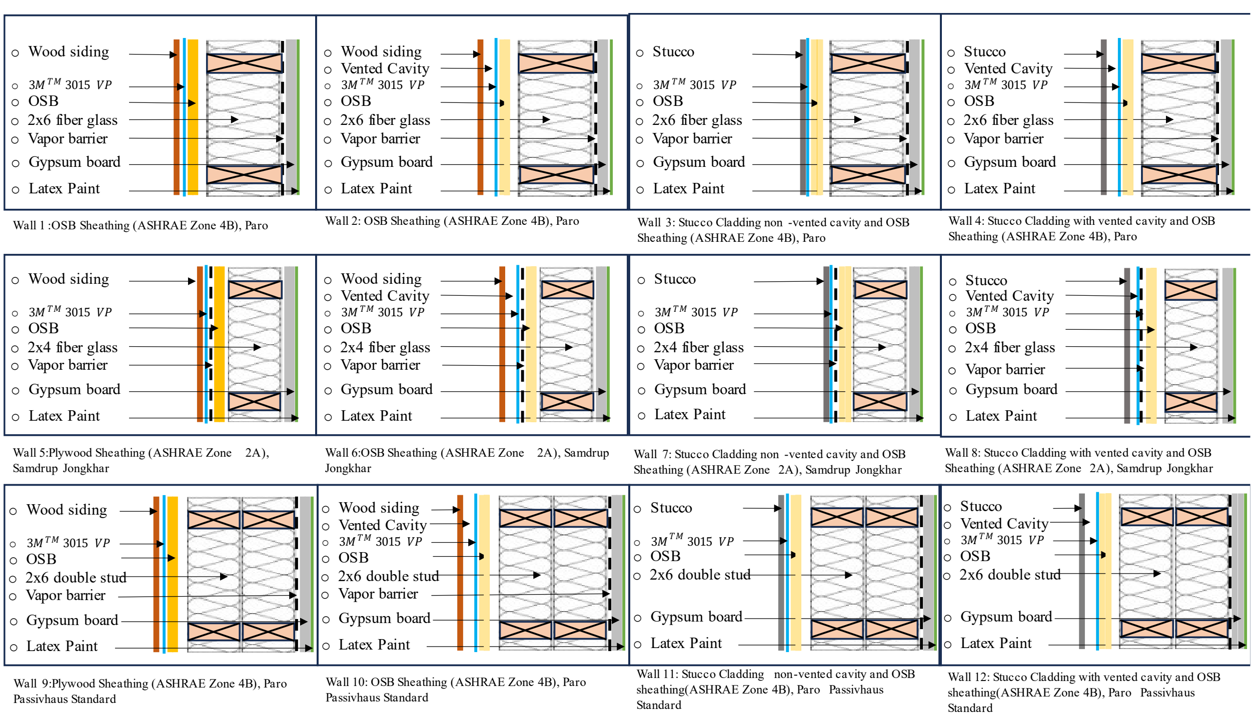


Figure 45. WFW configuration wall (1-12) with vapor barrier

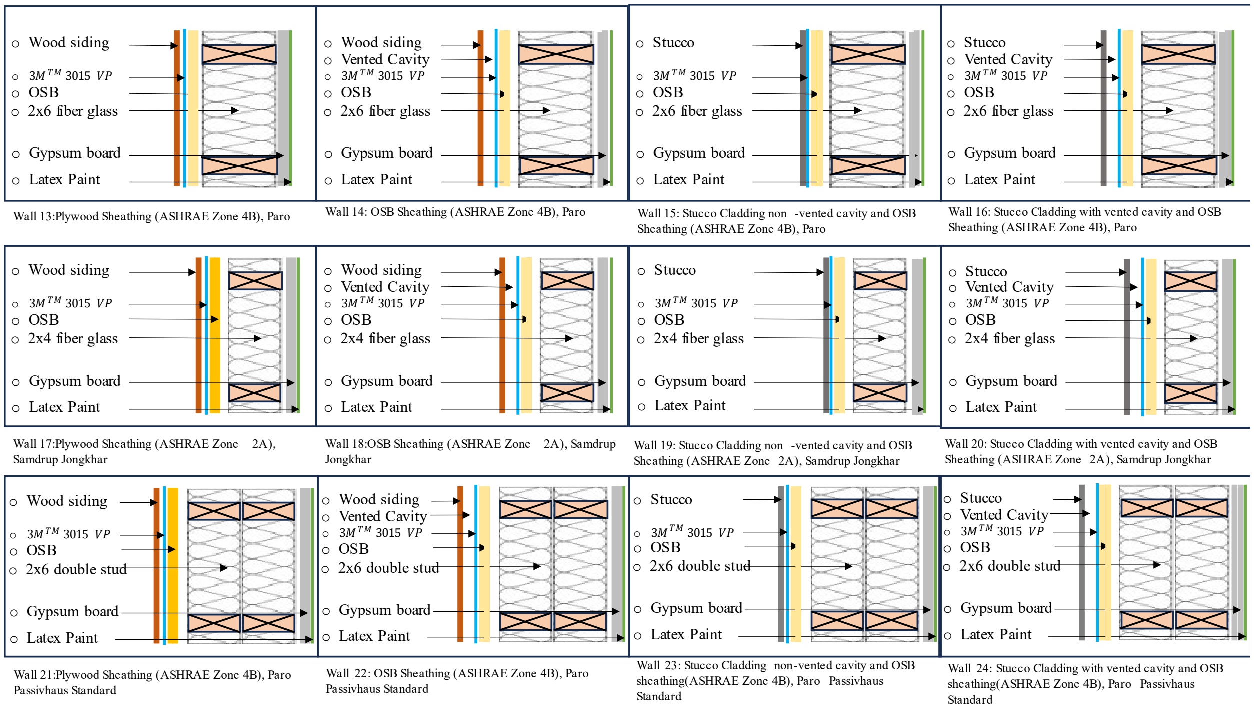


Figure 46. WFW configuration wall (13-24) without vapor barrier

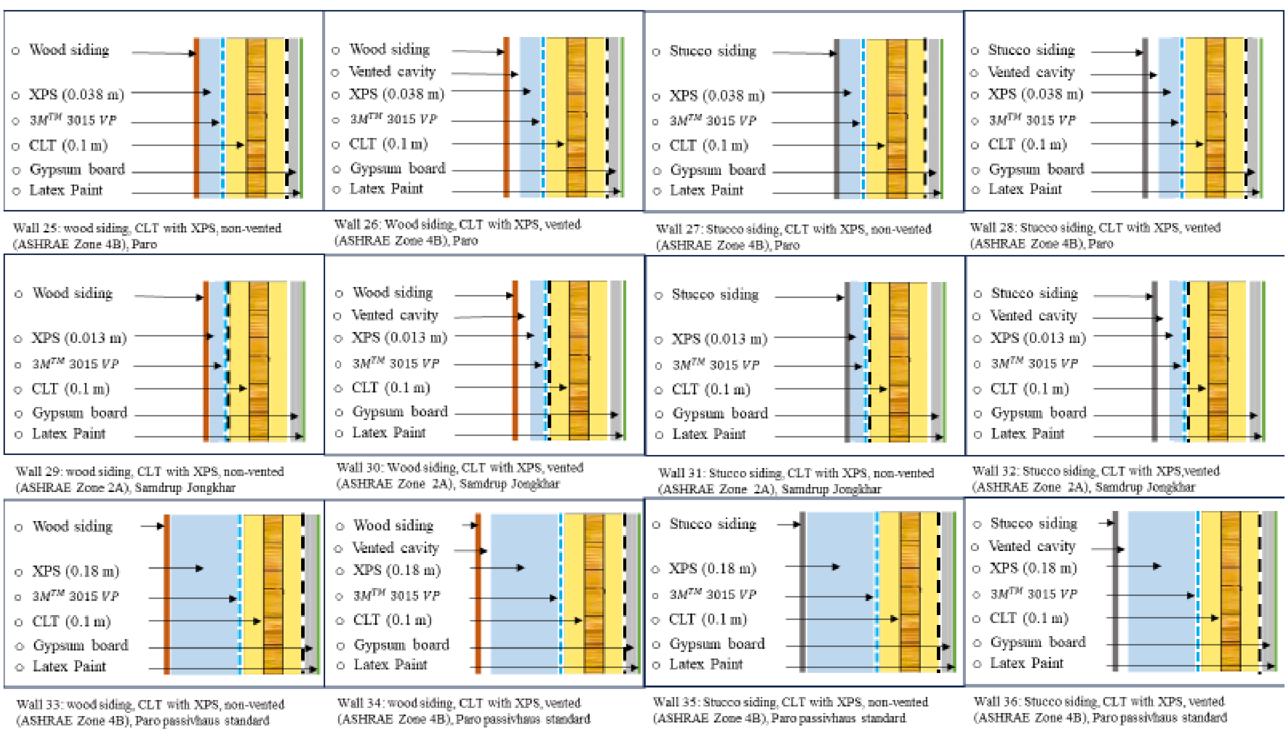


Figure 47. CLT configuration wall (25-36) with XPS insulation, with Vapor barrier

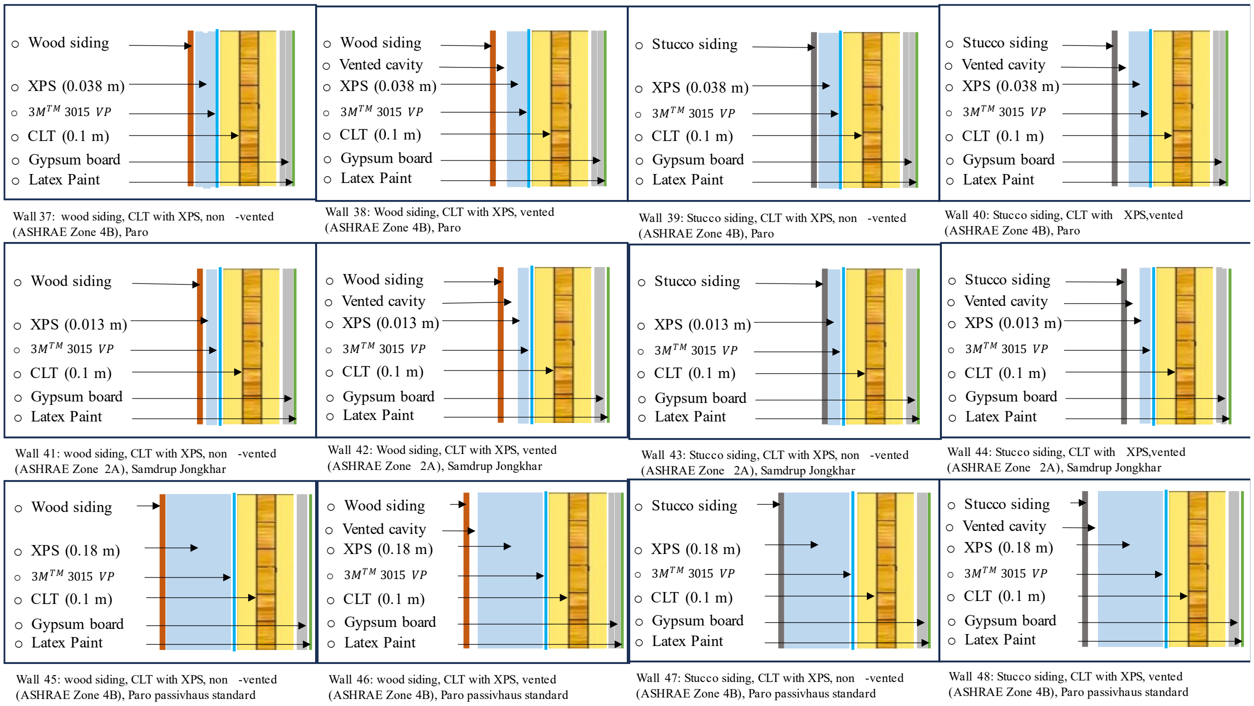


Figure 48. CLT configuration wall (37-48) with XPS, without vapor barrier

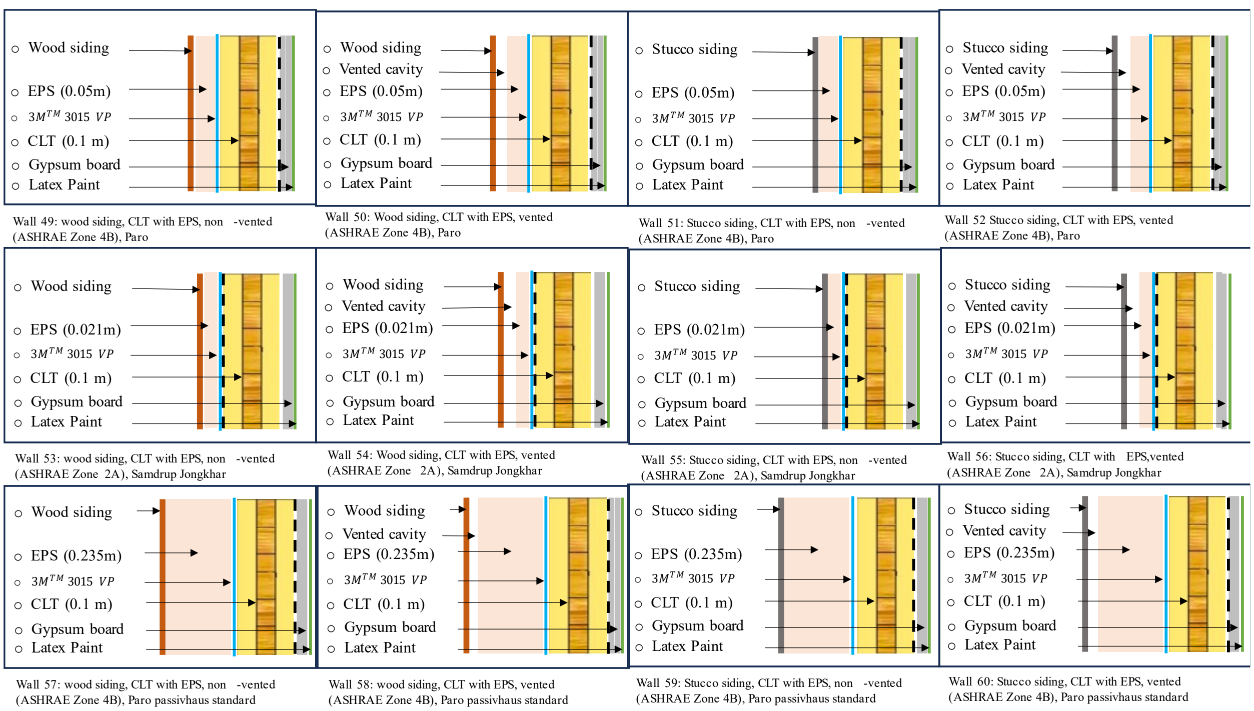


Figure 49. CLT configuration wall (49-60) with EPS insulation, with vapor barrier

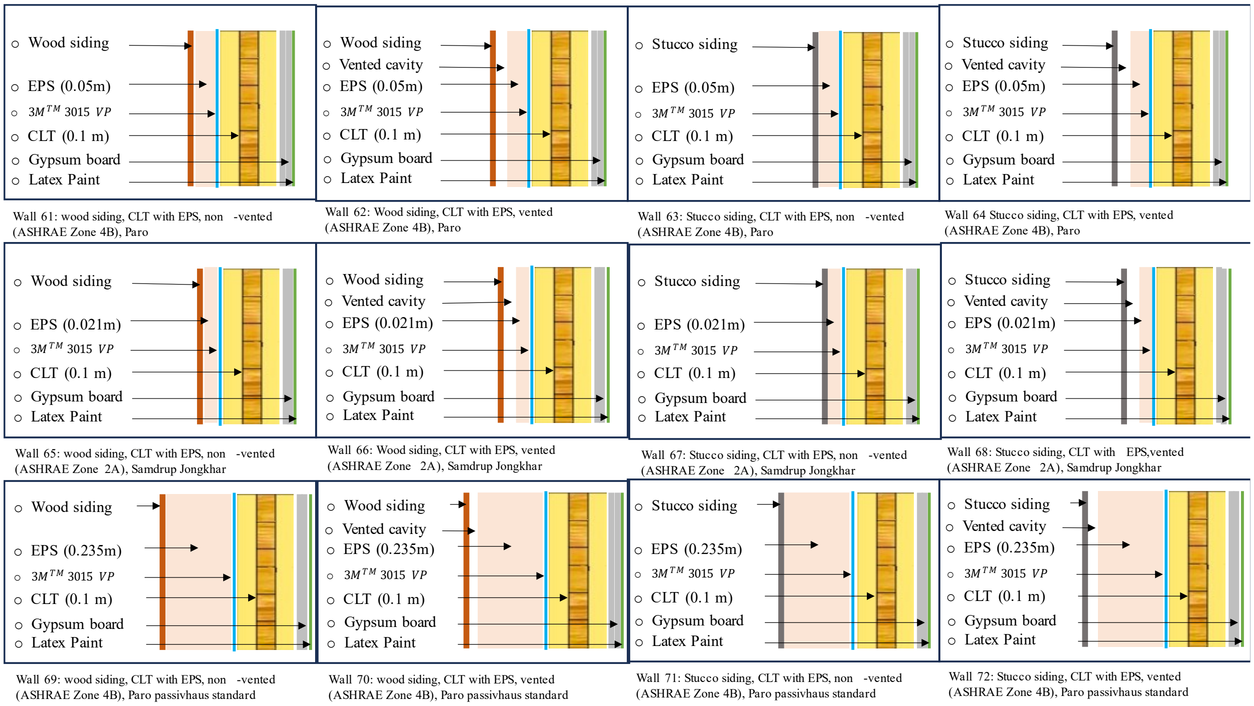


Figure 50. CLT configuration wall (61-72) with EPS insulation, without vapor barrier

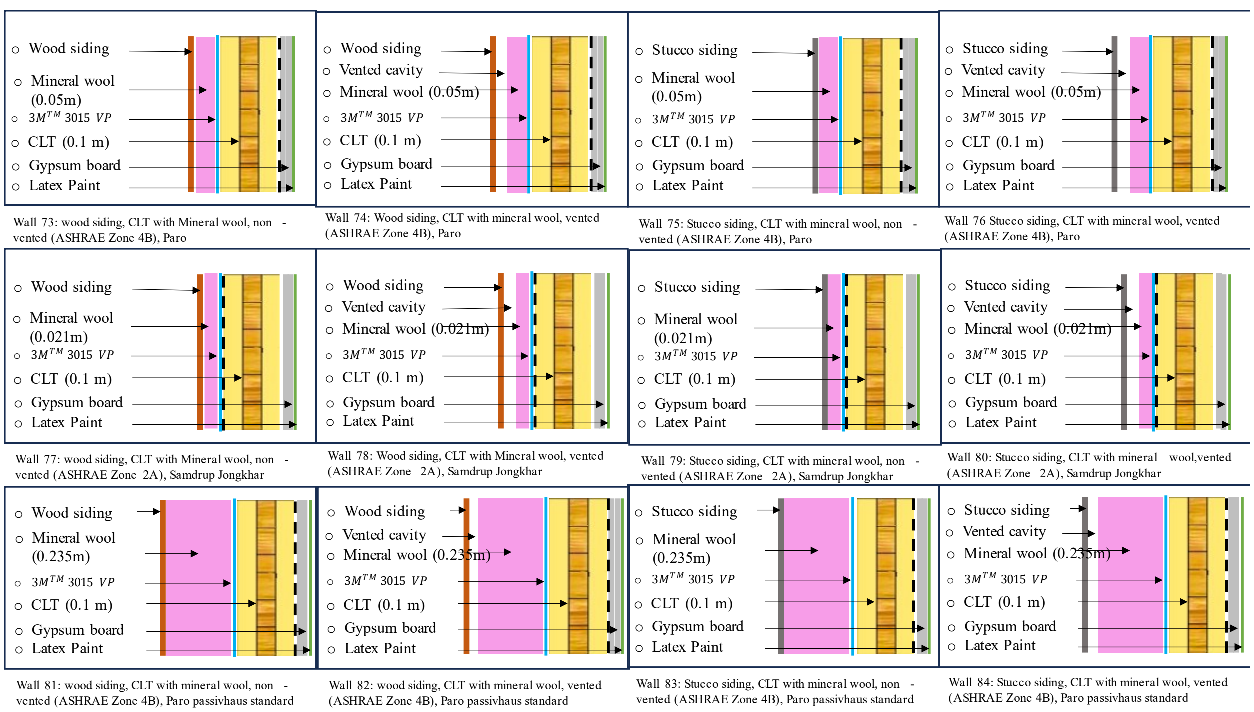


Figure 51. CLT configuration wall (73-84) with Mineral wool insulation, with vapor barrier

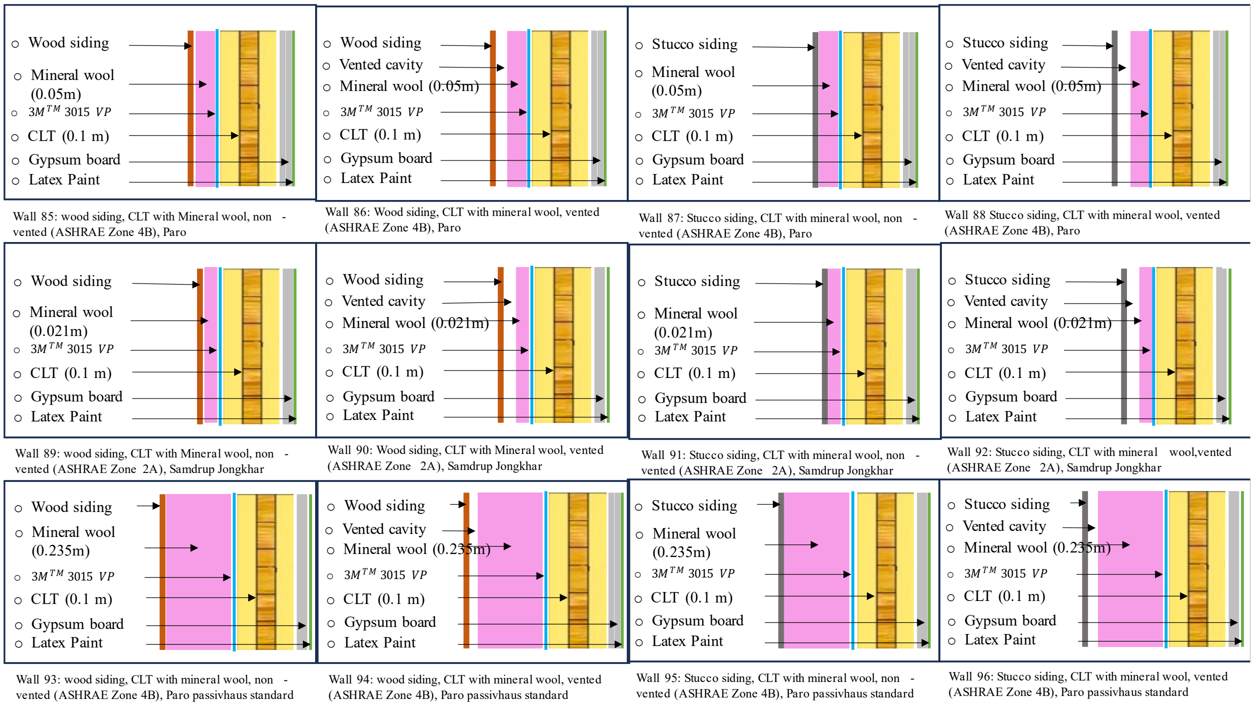


Figure 52. CLT configuration wall (85-96) with Mineral wool insulation, without vapor barrier

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