SUSTAINABLE ALTERNATIVE TO BHUTAN'S HOUSING CONSTRUCTION

JIGME THINLEY

A Thesis Submitted to the Graduate School of Naresuan University
in Partial Fulfillment of the Requirements
for the Master of Architecture Program in Architecture - (Type A 1)
2022

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Thesis entitled "Sustainable alternative to Bhutan's housing construction"
By Jigme Thinley

has been approved by the Graduate School as partial fulfillment of the requirements for the Master of Architecture Program in Architecture - (Type A 1) of Naresuan University

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ABSTRACT

The global construction industry lacks innovation and contributes substantially to world energy consumption and greenhouse gas (GHGs) emissions. The construction model in Thimphu, Bhutan, shares a similar narrative, plagued by inadequacies of conventional on-site practices using energy-intensive materials, often resonating implications to other sectors like housing construction and delivery. This study posits emerging mass timber construction (MTC) as an innovative alternative to Bhutan's archetype mid-rise residential structure, focusing on voluminous assemblages of wall and structural systems. Using an analytical approach, this study compared the existing concrete building's essential economic and environmental sustainability with its hypothetical MTC equivalent. The economics focused on the life-cycle cost analysis (LCCA), while the environment focused on the embodied energy and CO_2 emissions, estimated using the process-based method in a cradle-to-gate boundary limit. The environmental assessment unsurprisingly showed superior performances for the mass timber buildings relative to the conventional concrete ones.In contrast, the LCCA showed that mass timber buildings had material and built-up costs greater than concrete buildings by 30 and 38%, respectively, which is driven primarily by the high cost of timber in Bhutan. However, the scenario analyses regarding the end-of-life benefits and timber price reduction possibilities presented irrefutable evidence that the construction costs of MTC are cheaper or competitive with the concrete option. Integrating economics and environmental assessment establishes mass timber building as a viable innovative alternative, providing essential information to building developers and policymakers.

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Jigme Thinley

TABLE OF CONTENTS

LIST OF TABLES

Page

LIST OF FIGURES

Page

CHAPTER I

INTRODUCTION

1.1 Background and Rationale to the Thesis Topic

The building industry consumes 40% of global energy and contributes to about one-third of the overall carbon dioxide emission (Baek et al., 2013). By 2060, CO2 emission and energy demand will increase by 10% and 30%, respectively (Abed et al., 2022). The construction sector is increasingly encouraged to utilise renewable materials with low energy and less carbon-related emissions, thereby helping reduce global environmental impact. In addition, the construction industry drives the economic engine and subsequent national development (Alaloul et al., 2021; Khan et al., 2014; Ofori, 2015). Khan et al. (2014) illustrated the contribution to Malaysia's revenue generation, capital growth and employment creation, which eventually contributed to the GDP (Gross Domestic Product) and socioeconomic. Besides its direct involvement, the construction industry has substantial multiplier effects via forward and backward links with other economic sectors (Khan et al., 2014; Oladinrin et al., 2012; Ofori, 2015).

But the construction industry, particularly building construction, has been critiqued for lacklustre performance, such as low productivity and quality (Gibb, 1999; Windapo et al., 2021; Yusof et al., 2014) and for its inability to adopt sustainable technologies (Windapo et al., 2021). It prefers a conservative approach to developing and adopting new technologies, favouring well-established practices over innovative construction methods (Kulatunga et al., 2006; Rosenfeld, 1994).

The conventional construction practice in Bhutan depends mainly on mineral-based building materials and on-site construction. The 11th Five Year Plan (FYP) acknowledged the repercussions of the existing construction method incurring high construction costs, delivering poor quality of work, and requiring high maintenance costs. Bhutan's Ministry of Works and Human Settlement (MoWHS) suggested similar narratives. Currently, the majority of the Bhutanese population is faced with a moderate to severe rent burden, paying no less than 40% of their monthly household income, which is more than the international threshold of 30% (Ministry of Works & Human Settlement [MoWHS], 2019) According to the Royal Audit Authority [RAA] (2019), the primary reasons for poor delivery of affordable housing are the high cost of construction (labor and material) and lack of proper policies, institutional framework and poor implementation of effective strategies. Owing to the country's rising housing problems associated with unprecedented urban growth, sustainable housing development is a highly prioritised national policy objective. Besides the anecdotal criticism, scientific studies to recognise the possible causes or solutions to the apparent inadequacies in building construction are lacking.

The environmental sustainability of construction, another pertinent concern, has received less attention in the country. Dixit et al. (2010) reckon that until recently, only operating energy received attention due to its more significant fraction in the overall life cycle energy. Following substantial efforts in energy efficiency studies in recent years worldwide, the focus in current environmental studies has shifted to embodied energy and emissions (Dixit et al., 2010; Ibn-Mohammed et al., 2013; Kumanayake et al., 2018). Despite the growing significance of embodied impacts, efforts to lessen building's environmental footprints have primarily focused on their operating effects (Abed et al., 2022; Ajayi et al., 2019; Crawford & Cadorel, 2017). Developing countries such as Bhutan lack environmental assessment studies in buildings, although, from anecdotal evidence, they have proven unsustainable. Kumanayake et al. (2018) reiterated the significant gap in the current research on the environmental issues of buildings in developing countries.

This study appraises the current building construction method, focusing on the residential building contextualised to the capital, Thimphu Bhutan—and then proposes an innovative construction method recognised elsewhere (Prefabrication using mass timber construction)—by demonstrating the economic and environmental benefits attainable. This study is expected to promote the shortcomings and ramifications of the current construction practices and, as a result, provoke initiatives and studies for a productive and sustainable built environment from various industry practitioners.

1.2 Aim of the Research

Innovate housing/residential construction methods for sustainable transformation.

1.3 Objectives of the Research

- Appraise Bhutan’s housing construction method.
- Propose/recommend an applicable innovative construction method illustrating economic and environmental improvements.

1.4 Research Questions

The aim and objectives of the study are supported by three research questions as follows:

1. What are the current practices and characteristics of Bhutan’s housing construction in the country?
2. How can Bhutan innovate housing construction methods?
3. How does the selected innovation perform regarding economic and environmental sustainability compared with the conventional counterpart?

1.5 Scope of the Research

On a strategic level, this research considers innovation's technological (material/technique) aspect to augment the economic and environmental sustainability performance in Bhutan's residential/housing building construction sector. Further tactical level scope of the research is presented as per relevancy in the subsequent sections.

1.6 Key Assumptions

Improving the construction performance of economic and environmental sustainability requires multidimensional tasks involving diverse participants and tedious inter-related processes. Therefore, the core assumption of the research revolves around the standalone innovative construction model in an analytical setting.

Several assumptions regarding the innovative construction model are covered primarily in the methodology chapter.

1.7 Limitations

The research ventures into finding innovative technological construction solutions to solve the current inadequacies of economic and environmental sustainability plaguing building construction, mainly residential housing. Since the findings will be based on an analytical approach, any unaccounted practical-related dimensions which could affect the results are beyond the scope of this research.

This study focused on a single residential building in Bhutan. As this kind of building typified the buildings sector in the country, a residential building was considered appropriate for the study. The environmental assessment in this work is limited to the embodied impacts of energy and CO_2 emissions, while the economic assessment focuses only on the front-end construction costs. Only the voluminous building assemblages of walls and structural systems were considered for the study, assuming all other components and building processes, such as formwork, external works, materials, and components for building services, were considered constant.

1.8 Potential Outcomes and Importance

This study supplements the anecdotal criticism of on-site conventional construction practices of Bhutan with a scientific quantification of essential economic and environmental sustainability parameters. Alongside this, the possibilities of prefabrication using mass timber construction as an innovative solution will provide additional information to the decision-makers, such as building developers and policymakers, towards sustainable built environment transformation.

CHAPTER II

LITERATURE REVIEW

2.1 Introduction

This study aims to innovate Bhutan’s housing construction towards sustainable transformation and thus assumes the overarching theory of construction innovation framework of Xue et al. (2014) and Uusitalo & Lavikka's (2020) technology transfer model to realise the proposed aim. The innovation input influences innovation outcomes in a given innovation context (Figure 1). This framework provides structure to the literature chapter (Figure 2). As a result, the literature review comprises four distinct sections: Part A, innovation input; Part B, innovation outcome; Part C, innovation context and Part D, conceptual framework. The first part on innovation input discusses the prefabrication method using mass timber construction as an innovative model, which answers the second research question: How can Bhutan innovate the housing construction method? Part B then discusses the expected outcomes of innovation input to achieve sustainable housing. After that, Part C establishes the innovation context, which includes a comprehensive review of Bhutan’s housing construction, primarily based on multiple case studies, and thereby answers the first research question: What are the current practices and characteristics of Bhutan’s housing construction? Lastly, a conceptual framework summarises a working relationship between relevant variables to guide the subsequent analytical investigation.

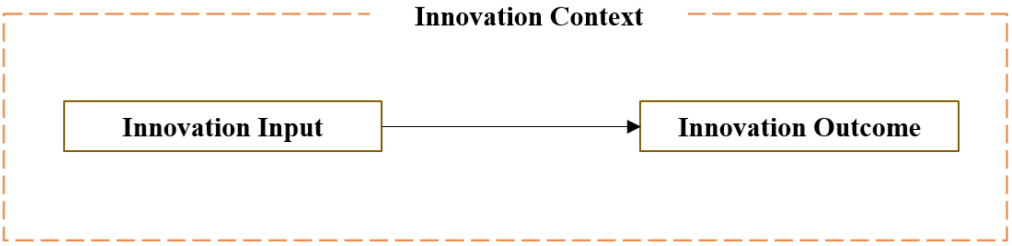


Figure 1: Relationship framework of construction innovation as a guide to literature sections.
Adapted from Xue et al. (2014) and Uusitalo & Lavikka (2020)

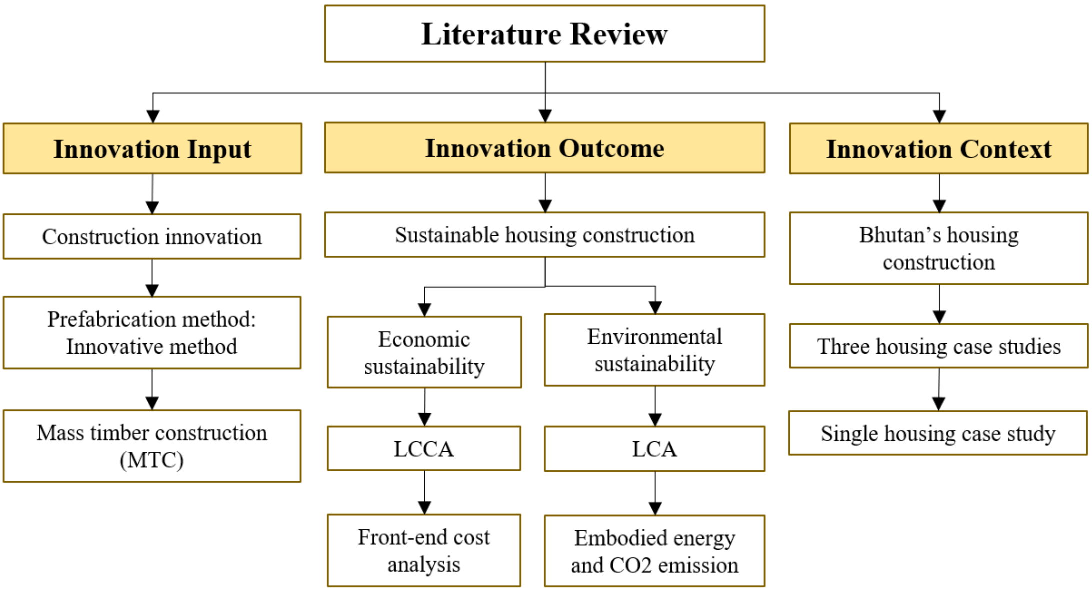


Figure 2: Overall structure of the literature review

Part A: Innovation Input

This work recognises construction innovation's importance in moving away from rudimentary to more productive and sustainable practices. In this regard, this section first discusses the broader theory of construction innovation concerning the challenges of the construction industry and some of the proven benefits, characteristics and adoption processes of innovation. This is followed by a comprehensive review of the prefabrication method, which ultimately narrows down to mass timber construction. Finally, the MTC postulates an appropriate innovation input for Bhutan. Figure 3 summarises the thought process of this section.

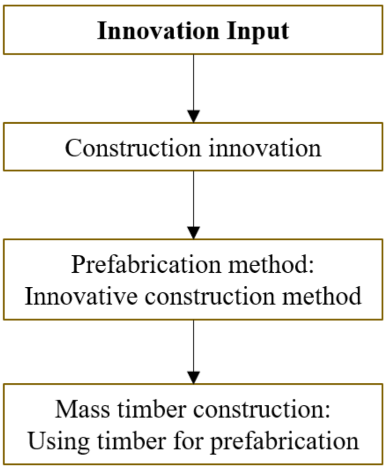


Figure 3: Summary of the innovation input section.

2.2 Construction innovation

The construction process is characterised by high complexity and variability (Bertelsen, 2005; Bildsten, 2011). Consequently, Bertelsen (2004) reckons improving productivity is a tremendous challenge for the construction industry. To reduce variability and complexity in construction projects, construction companies have an increasing demand for innovative component solutions (Bildsten, 2011). In response, Bertelsen (2004) and Bertelsen (2005) proposed two strategies; i) product strategy to reduce the complexity of the construction by the application of manufacturing principles (lean construction); ii) process strategy to better manage the complexity by developing new methods for the management and control of construction process. The lean construction concept stems from the manufacturing industry (Bertelsen, 2004; Bertelsen, 2005; Bildsten, 2011) and assumes a construction process similar to production, maximising the value for the client and minimising the waste (Bertelsen, 2004). Product strategy makes basic building materials such as cement, timber and bricks into components (offsite fabrication), making the construction's complexity less rigorous and thereby improving the construction productivity (Bertelsen, 2004). In addition, Bertelsen (2005) proposes modularisation as the third strategy to tackle the problems of construction, which would make the complexity easier to manage.

The construction industry is known for its conservative tendency towards developing and adopting new technologies and usually prefers well-established practices over innovative construction methods (Kulatunga et al., 2006; Rosenfeld, 1994). As a result, the construction industry has been outpaced by other industries for innovation and has been critiqued for low productivity and quality (Gibb, 1999; Yusof et al., 2014). In this regard, the construction sector has failed to effectively adopt innovative technologies to replace the traditional construction system, which has been lauded as a significant contributor to the low sustainability and poor cost-effectiveness of sustainable, affordable housing (Moghayedi et al., 2021). Though construction innovation is unique from generic innovation, there is no denying its contribution to reducing time and resources and improving quality (Xue et al., 2014). The developed nation of the UK faces similar reluctance; however, some projects in the country have already adopted modular construction as an innovative construction system and have demonstrated its superiority over the traditional construction system (Young et at., 2020).

In Hong Kong, by virtue of the construction process, public sector housing has demonstrated remarkable success in expediting the speed of construction while minimising the construction cost and quality (Chan & Chan, 2002). These strategies include standardising block designs and construction sequences, mandatory use of large panel steel formwork systems, precast concrete facade elements, semi-precast concrete floor slabs, and other standardised prefabricated building components (Chan & Chan, 2002). For a much simpler adoption, Wallbaum et al. (2012) demonstrated the number of most promising technologies for affordable housing projects that can be applied in a regional context by conducting a proper feasibility study of these technologies. Koebel (2008) suggests that innovation occurs across all components of homebuilding: foundations; floors; exterior walls; roofing; doors; windows; heating, ventilation, and air conditioning (HVAC); interior partitions and ceilings; landscaping; infrastructure; and site work. Moreover, the study by Slaughter (1998) emphasised five innovation models: incremental, modular, architectural, system and radical. Incremental innovation is more like a progressive change and is small in scale whereas system and radical innovation require major changes.

Tatum (1986) recognised technological innovation in the construction sector as an essential means for solving the issues of the construction industry. Advances in technological innovation, be it in new materials, new products, or new processes, is necessary to produce environmentally sensitive and sustainable residential development that utilises fewer resources (Koebel, 1999). Furthermore, Rosenfeld (1994) advocated positive aspects of innovative methods as better quality, higher efficiency and ultimately lower cost and higher value in the construction. On the contrary, the most significant barriers to innovation in construction methods can be associated with capital intensiveness limiting the people to stick with well-established and risk-aware methods, legal responsibilities and liability claims in case of failure of new techniques and imbalance of risk and profit between client and constructor of the construction industry (Rosenfeld, 1994).

2.2.1 Adoption of innovation

The previous section discussed the construction innovation theory, while this section will discuss the innovation adoption/diffusion process and characteristics. Research in the field of innovation diffusion has identified several factors of innovations that influence their adoption: relative advantage, compatibility, complexity, trialability, and observability (Koebel, 1999). In the built environment, the innovator can be a local government, a builder, or a consumer, with significant interdependencies among them (Koebel, 1999). However, based on the factors that influence the adoption of an innovation, the government has more capacity for innovation than the other two and is reconfirmed by Koebel (2008).

Koebel (2008) reckons planners are interested in promoting innovations that make housing, land development, and communities more sustainable, durable, and affordable. However, to achieve these goals, they will have to influence the firms that build our communities, particularly homebuilders. To successfully impact the home building industry to become more innovative, planners must understand the individual, firm, and industry characteristics that influence these companies to adopt new practices (Koebel, 2008). Koebel (2008) argues that although homebuilders have good reasons to avoid the risks associated with innovation, planners can promote innovation with greater knowledge of the factors that contribute to it.

Xue et al. (2014) developed the conceptual framework of the construction innovation process, including innovation input, drivers of innovation, and probable innovation outcomes (Figure 4). This framework proves essential as it allows the scope of the current investigation to include scientific and technological aspects as innovation input to target outcomes of sustainability and cost. Besides other construction parameters such as motivation and productivity, planning and scheduling techniques and managerial actions, technological improvements, be it in method, material, or tools, have been regarded as the most likely approach in addressing the common construction woes of cost, time and quality (Tam et al., 2002).

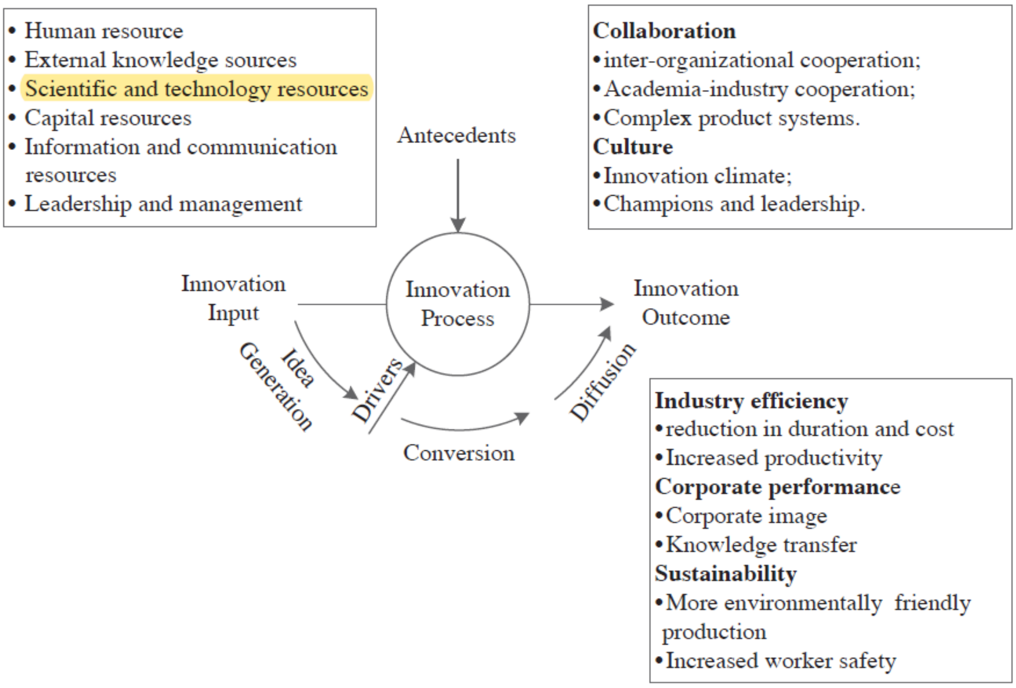


Figure 4: Conceptual framework of construction innovation.
Source: (Xue et al., 2014)

2.3 Prefabrication method: Innovative construction method

2.3.1 Overview

This work aims to innovate Bhutan's housing construction system towards sustainable transformation. The extant literature recognises prefabrication as an innovative construction method to induce sustainable housing. As a result, a comprehensive review of the prefabrication method is presented. The review touches on various aspects of prefabrication, such as definitions, benefits and hindrances, classifications systems, factors influencing prefabrication adoption and prefabrication of house components as appropriate levels of intervention (Figure 5). After that, building material in Bhutan is inventoried to identify the potential category to adopt the prefabrication method. Ultimately, prefabrication using wood, known as mass timber construction, was posited as an innovative construction method.

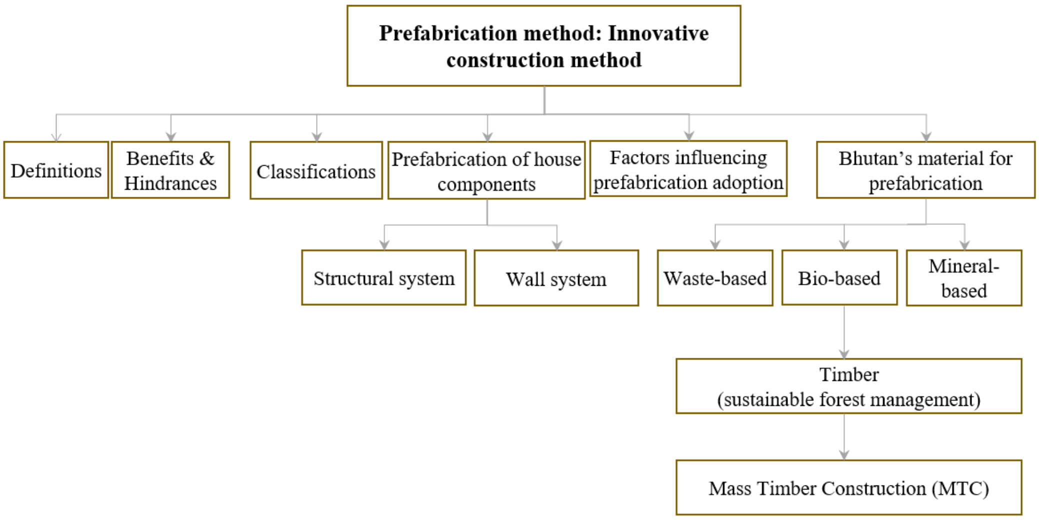


Figure 5: Flow chart overview of the prefabrication method

In general, Hashemi (2009) reiterated three primary construction methods depending on the fabrication level and machinery and labor use: traditional, post-traditional method (conventional method) and rationalised and industrialised systems. Traditional methods involve building from small components using intensive manual labor on-site. In contrast, the post-traditional or conventional method utilises newer machineries (excavation, concrete mixing and lifting) along with the traditional method to enhance the project productivity (Hashemi, 2009). Lastly, rationalised and industrialised systems include construction approaches that take advantage of manufacturing productivity (Hashemi, 2009).

Similarly, Tam et al. (2007) presented four significant construction systems: conventional, which utilises traditional in-situ construction activities; semi-prefabrication comprises both on-site activities and prefabricated components (e.g., system formwork and non-structural semi-prefabrication of the facade, curtain walls and drywall systems); comprehensive prefabrication includes structural parts (slabs, beams, columns) and pre-finished construction; and finally, volumetric off-site fabrication encompasses components that enclose usable space (e.g., washroom, plant room, lifts) but does not constitute the whole building (Tam et al., 2007).

Finally, Badir et al. (2002) also suggested that the construction methods can be categorised into four; conventional method; cast–situ; composite method; and fully prefabricated. The last three construction methods are considered nonconventional and all types of IBSs are categorised under them (Badir et al., 2002). The conventional method (RCC frame with brick infill) uses timber formwork; the cast-in-situ method uses lightweight prefabricated formwork (e.g., tunnel form) instead of timber and the composite construction method involves certain elements that can be standardised (e.g., floors, slabs, infill walls) and prefabricated in factories (Badir et al., 2002). In summary, apart from the conventional construction method, these three studies indicate the prefabrication method as an alternative construction method with varying degrees of application.

2.3.2 Prefabrication definition

The aftermath of World War I and II was accompanied by housing crises in the west, caused by the mass destruction of the public infrastructure and fueled by soldiers returning from the war (Ganiron Jr, 2016). In response, Ganiron Jr (2016) acknowledged the adoption of prefabrication technology at this time around to meet the explosive housing demand. Therefore, the concept of prefabrication is undoubtedly not new. However, its application in the building industry has gained renewed interest recently (Haas & Fagerlund, 2002). Moreover, prefabrication is acknowledged as an innovation in construction, not necessarily as an invention as per say, but in the acceptation and adoption of the technology (Kamar et al., 2011). For instance, the prefabrication concept preferred as IBS in Malaysia has been accepted as an innovation strategy to overcome critical housing problems.

Furthermore, Steinhardt and Manley (2016) recognised high application of prefabricated housing in Japan and Sweden, relatively high levels in countries like Germany and Netherlands and infrequent application of prefabricated housing technology in the case of the USA, UK and Australia. Moreover, a growing body of literature recognises prefabrication as an innovative solution for mass housing projects. Through the critical review, Li et al. (2014) identified researchers from developed countries, including the US, the UK, Hong Kong, Sweden, and Australia, who have made significant contributions to the development of the prefabrication domain. Similarly, those from developing countries, including China, Turkey, and Israel, where construction remains their main economic activity, have shown increasing interest in promoting prefabrication-related research.

The concept of prefabrication method is used interchangeably with other common terms (Table 1) like industrialised building system (IBS), offsite manufacturing (OSM), modern methods of construction (MMC), preassembly, modularisation and system building (Akmam Syed Zakaria et al., 2018; Correia Lopes et al., 2018; Gibb, 1999; Gibb, 2001; Gibb & Isack, 2003; Kadir et al., 2006; Kamar et al., 2011). However, their precise definition largely depends on the user's experience and understanding, which vary geographically (Gibb, 2001; Kamar et al., 2011). For instance, Gibb (2001) preferred pre-assembly over other terms, which meant to 'assemble before' either the building or parts of a building and then install on site.

Table 1: Synonyms of Industrialised Building System (IBS) and Prefabrication

Author	**Concepts**	**Remarks**
Gibb, 1999	Prefabrication and preassembly	Synonyms with Off-site fabrication
Gibb & Isack, 2003	Pre-assembly, prefabrication, modularisation, system building, and industrialised building	Synonyms with IBS and prefabrication
Kadir et al., 2006	Cast in-situ formwork, prefabricated system and composite system	Synonyms with IBS
Kamar et al., 2011	Pre-assembly, prefabrication, Modern Method of Construction (MMC), Offsite Manufacturing (OSM), Offsite Production (OSP) and Offsite Construction (OSC)	Synonyms with IBS and prefabrication
Akmam Syed Zakaria et al., 2018.	Off-site construction, off-site production, pre-assembled building, industrialised and automated construction, off-site manufacturing, prefabricated building, precast building, precast construction, non-traditional and the modern method of construction (MMC)	Synonyms with IBS
Correia Lopes et al., 2018	'Prefabrication', 'Pre-assembly', Modularisation', and 'Off-site Fabrication' (sometimes designated by PPMOF),	Synonyms with off-site fabrication (manufacture and pre-assembly)

In an attempt to unify and prevent misunderstandings due to multiple interpretations, Kamar et al. (2011) proposed a definition of IBS taking into consideration the previous literature; "An innovative process of building construction using the concept of mass-production of industrialised systems, produced at the factory or onsite within controlled environments, it includes the logistic and assembly aspect of it, done in proper coordination with thorough planning and integration." Likewise, Badir et al. (2002) defined IBS as the mass production of quality buildings involving building on-site with elements or components produced by series in plants.

Similarly, according to Tam et al. (1986) (as cited in Gibb, 199), “Prefabrication is a manufacturing process, generally taking place at a specialised facility, in which various materials are joined to form a part of the final installation.” In addition, through the literature, Kamar et al. (2011) classified IBS into two categories: IBS as a method, approach and process and IBS as a product, system and technology. ‘Modular housing’ has typically been synonymous with volumetric construction, while more inclusive terms such as ‘industrialised building systems’ and ‘modern methods of construction ‘have included volumetric and non-volumetric prefabrication (Steinhardt & Manley, 2016). The prefabricated system can be further subdivided into a frame system, panel system and block system (Kadir et al., 2006).

2.3.3 Benefits and hindrances of the prefabrication method

The most apparent advantage of off-site manufacturing/prefabrication is the shift from site-based activities to the factory (Correia Lopes et al., 2018; Gibb, 1999), making the construction activities relatively predictable and reliable (Gibb, 1999). For this reason, prefabrication is associated with several benefits in the extant literature, most notable being the reduction in construction time, comprehensive cost reduction and improved quality of the products (Badir et al., 2002; Correia Lopes et al., 2018; Gibb, 1999; Gibb & Isack, 2003; Navaratnam et al., 2019; Steinhardt & Manley, 2016; Zhang et al., 2014). Along a similar line, Bildsten (2011) illustrated that the prefabricated house components could curb inefficiencies related to the conventional construction system (Table 2). In a board sense, applying the IBS can also promote the development of the construction industry (Zhang et al., 2014).

The prefabrication method benefits from cost, time and quality due to the mass production of building components in a predictable factory setting, which replaces the unpredictable labour-intensive on-site wet construction activities (Gibb, 1999). For instance, cost savings up to 100% can be attained in the case of external scaffolding, more than 50% in material, 30% reduction for on-site labor, additional 4-5% savings from gross floor area exemption, and up to 100% saving on additional works for precast construction than traditional construction (Tam et al., 2015). Furthermore, the factory working environment improves safety and health, improving the labor's overall productivity (Akmam Syed Zakaria et al., 2018; Gibb, 1999; Gibb & Isack, 2003).

In a parallel study, a comparison of 100sq.m of the precast concrete wall panel with the traditional brick wall revealed that the total production cost of the PC wall panel is slighter higher than its conventional counterpart (material cost and machinery cost are higher while labor cost is less) (Zhang et al., 2014). In this regard, Zhang et al. (2014) recommended vigorous development of new technology and materials to reduce the cost of PC wall panels; thus, it can be widely accepted and recognised. For example, using locally available materials and waste materials from industrial and agriculture could serve the purpose.

Table 2: Opportunities in the use of prefabricated house components.

Opportunities	**Explanation**
Knowledge of costs	Buying products instead of services makes it easier to make a budget.
Lead-time reduction	Through the use of prefabricated components in tasks with long execution times, the lead-time can be reduced.
Securing availability of materials	The purchasing of materials and services is simplified through standardized work procedures and limited variety of components with long-term supplier contracts. This reduces the risk of standing without materials.
Reduced risk of production failures	The decreased complexity of coordinating people and materials through repetitive systems of house components reduces the risks of production failures.
Mass customisation	Exterior and interior design is handled systematically through professional designers in collaboration.
Delayed product differentiation	Modularisation could enable a delay of customisation to the end of the production process.
Improved quality	The delegated responsibility makes people concentrate on a particular activity, which they do well through repetitive experience. Also, the factory environment prevents exposure to bad weather that otherwise may destroy materials.
Moveable houses	Through modularisation, exterior and interior house components make it possible to move the house to a new location simply.

Source: Adapted from (Bildsten, 2011)

Likewise, prefabrication is strongly associated with environmental benefits (Akmam Syed Zakaria et al., 2018; Gibb, 1999; Steinhardt & Manley, 2016; Wu et al., 2019; Zhang et al., 2014). According to Gibb (1999), environmental benefits of off-site fabrication include reduced on-site work, material wastage, transportation, and pollution (noise, dust, air, etc.). Tam et al. (2005) encouraged replacing wet-trade construction activities with prefabrication as one of the waste minimisation strategies. Tam et al. (2007) established the advantages of prefabrication in decreasing order as; better supervision, frozen design at the early stage, reduced construction costs, shortened construction time, aesthetic issues, the integrity of the building and application of prefabrication.

Despite several opportunities attainable by the application of prefabricated construction, Wu et al. (2019) summarised the barriers, constraints, or limitations of prefabricated construction observed in literature as; 1) higher cost of construction or initial investment; 2) lack of adequate incentives and policy; 3) an inadequate level of standardisation; 4) incomplete industry chain; 5) poor labor quality (lack of skilled or experienced works and technicians) and; 6) negative perception of the public. Similarly, Tam showed the hindrances of prefabrication in the decreasing order as follows: Inflexible for design changes, lack of research information, higher initial construction cost, time-consuming, conventional method, limited site space, monotone in aesthetics, leakage problem, lack of experience and no demand for prefabrication.

Similarly, barriers to using house components for prefabrication include (Table 3): Tolerances, reduced living area through multiple layers, cost of development, dependency on suppliers, acceptance of the system by house buyers, price and supplier dominance (Bildsten, 2011).

Table 3: Barriers in the use of prefabricated house components.

Barriers	**Explanation**
Tolerances	To make all house components fit together, the house components require accurate sizes.
Reduced living area through multiple layers	The assembly of volume elements and interior components creates multiple layers of walls that reduce the living area.
Cost of development	Before the house components are ready to be disseminated into production, there is the initial cost of developing them.
Dependency on suppliers	Suppliers that offer customised products and services may become difficult to replace if, for some reason, they disappear.
Acceptance of the system by house buyers	Acceptance of innovative construction systems, e.g., timber volume elements, is sometimes tricky since customers often prefer traditional on-site constructions.
Price	The price is generally higher because a house component system is an “all-inclusive price” for services and materials. Therefore, prefabricated solutions are often rejected since other offers seem cheaper.
Supplier dominance	Construction material suppliers are generally a few prominent players that provide standard components and are reluctant to customise their products.

Source: Adapted from (Bildsten, 2011)

2.3.4 Classification of prefabrication system

The literature recognises multiple classifications of IBS under different synonyms (pre-assembly, prefabrication, etc.), as presented in Table 4. It is centered around various themes such as material, structural role, and, most commonly the level of prefabrication based on geometrical configuration. Kumar et al. (2011) suggested a generic IBS classification (Table 4) considering several others observed in the literature. However, it can be argued that the classification might generate misunderstanding since it includes multiple themes compared to others based on specific singular themes. Therefore, the following paragraph will compare various categories.

Firstly, based on geometrical configuration, Warszawski (2003) classified building systems as; linear or skeleton systems comprising primary structural elements such as columns, beams and frames, planar or panel systems employing panel-shaped elements like floor slabs, partitions and exterior walls and finally, three-dimensional or box systems. Another example of classification in terms of geometrical configuration has been established by Gibb (1999) in the increasing order of preassembly as non-volumetric off-site fabrication, volumetric off-site fabrication and modular building. Non-volumetric includes items that do not enclose usable spaces, such as structural frame parts, building cladding and internal partitions.

Table 4: Comparison of IBS/Prefabrication classification

Sl. No.	Author	Classification	Classification theme
1	Gibb (1999)	Classification of Off-site fabrication: • Modular building • Volumetric off-site fabrication • Non-volumetric off-site fabrication	Geometrical
2	Gibb (2001)	Classification of pre-assembly: • Modular building, • Volumetric pre-assembly • Non-volumetric pre-assembly • Component manufacture and sub-assembly	Geometrical
3	Badir et al (2002)	Classification of fully prefabricated construction: • Precast concrete (frame, panel and box) • Load bearing block • Sandwich panel • Steel frame	Structural and material
4	Gibb & Isack (2003)	Classification of pre-assembly: • Modular building, • Volumetric pre-assembly • Non-volumetric pre-assembly • Component manufacture and sub-assembly	Geometrical
5	Warszawski	Classification of IBS based on material:	Material

Sl. No.	Author	Classification	Classification theme
	(2003)	• Timber • Steel • Cast in situ concrete • Precast concrete	
6	Warszawski (2003)	Classification of IBS based on structural system: • Linear • Skeleton • Planar • Planar systems • Three dimensional box systems	Structural system
7	Kamar et al (2011)	Classification of IBS: • Frame System (pre-cast or steel) • Panelised System • Onsite fabrication • Sub-assembly and components • Block work system • Hybrid System • Volumetric and Modular System	Structural, material and geometrical

The volumetric category comprises units that encompass usable space but do not constitute the whole building (eg: lift, bathroom, plant room). Lastly, modular buildings include units that form a complete building or part of a building, including the structure and envelope. Examples of modular buildings include medium-rise office or hotel accommodation, stand-alone retail units, housing (in some countries), and a wide variety of temporary or relocatable solutions (Gibb, 1999). Subsequent research by Gibb (Gibb, 2001; Gibb & Isack, 2003) has reinforced the taxonomy above with the inclusion of an additional category of component manufacture/subassembly (eg: lintels) as the lowest level of preassembly (Figure 6). As a result, it is the most commonly adopted prefabrication taxonomy in the prefabrication domain and is validated by the Lu et al (2018). Lu et al. (2018) used this taxonomy to determine the optimal level of prefabrication adoption in a PEST setting of Hong Kong (political, environmental, social & technological). The study concluded that non-volumetric and volumetric assembly as the most suitable level of adoption in Hong Kong.

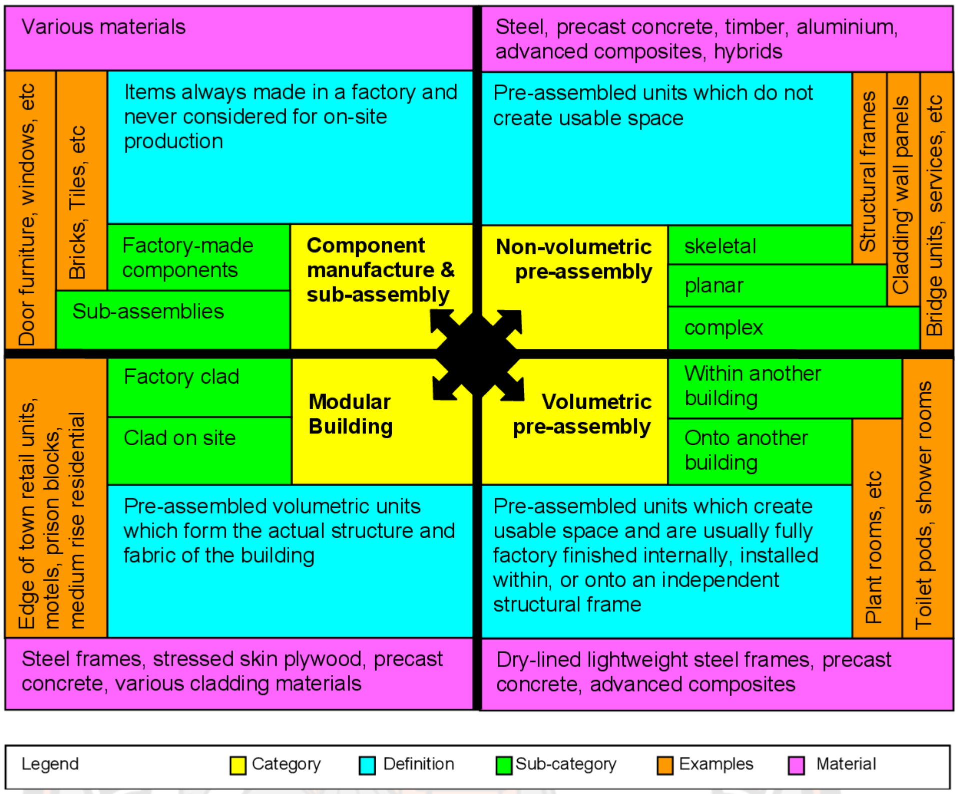


Figure 6: Classification of preassembly

Source: Gibb & Isack (2003)

Other classifications that reflect the taxonomy described above are also in use and have been tailored to suitability. For instance, prefabrication in Hong Kong can be broadly divided into non-structural, structural, and volumetric elements. Non-structural elements are mainly facades, dry wall internal partitions and cooking benches, while structural features include stairs, semi-precast slabs, curtain walls and decorative fins. Volumetric elements include water tanks and bathroom units (Tam et al., 2005).

The application of industrialisation of a linear system is characterised by its capacity to transfer heavy load over large spans and thus is used in the construction of bridges, parking lots, warehouses, industrial buildings, sports facilities, and so on (Warszawski, 2003). In contrast, the planar system is a widely prefabricated building component and thus finds its application in residential buildings, offices, schools, hotels and other similar structures with moderate loads and large amounts of finish works (Warszawski, 2003). A building system here would mean a set of interrelated elements that act together to enable the designated performance of a building (Warszawski, 2003).

2.3.5 Factors influencing the adoption of prefabrication.

For successful and appropriate adoption of the technology, the technology must be appraised with a multitude of parameters that define the recipient’s environment. In this regard, there are number of studies undertaken in the identification of these factors and are summarised in Table 5. First and foremost, through a comprehensive literature study, Akmam Syed Zakaria (2017) identified number of interrelated factors that influence IBS adoption into three categories of contextual factors (eg: economic conditions), structural factors (eg: decision-making style) and behavioral factors (eg: attitude) (Table 5). It can be argued that the comprehensive justification of all these factors in prefabrication adoption is nearly impossible. Hashemi (2009) suggests that some of these criteria are uncontrollable, some are absolute and some are unmeasurable.

Similarly, Wu et al. (2019) recognised 21 factors, grouped under five cluster in relative importance, with government factors (eg: incentive policies) as a dominant factor, followed by industry factors (eg: cost & labor quality), company factors (eg: organisational culture), technology factors (eg: technology lock-in) and market factors (eg: market demand). In addition, Wu et al. (2019) also established the top five factors influential in the promotion of prefabricated construction, at least in China, in decreasing order as technology lock-in (76.42%), incentive policies (75.91%), standardisation (73.70%), cost (73.70%) and entrepreneurial cognition (73.13%).

Table 5: Factors influencing the adoption of prefabrication construction.

Sl.No.	Author	Factors
1	Akmam Syed Zakaria (2017)	Factors that influence IBS adoption: (1) Contextual factors • Economic conditions • Government involvement • Stakeholder involvement • Sustainability features • Technology development (2) Structural factors: • communication process • decision-making style • project management approach • procurement (3) Behavioral factors • Experience • Attitude • Decision-maker awareness • bounded Rationality
2	Wu et al., 2019	Factors that influence the promotion of prefabrication

Sl.No.	Author	Factors
		technology: Government factors • incentive policies • standardization, • mandatory policies • government procurement Industry factors • Cost • labor quality • industry chain • Awareness of environmentally friendly development • supply chain coordination company factors • entrepreneurial cognition • organisational culture • company scale Technology factors • technology lock-in • relative superiority of technology • combination with other technologies and technology R&D, • technological achievement transformation Market factors • costumer acceptance • market structure • marketing strategies • market demand
3	Lu et al. (2018)	Political • Policy (18) • Standards, codes & guidelines (10) Economic • Supply (22) • Schedule (15) • Type and scope (11) • Repetitive components (10) Social • Labor (15) • Social attitude (9) • User acceptance (14) Technological • Resources (12) • Familiarity (15) • Construction tolerances (7) • Site logistics (12) Note: The number in parentheses represent the number of times the factors are mentioned in the literature.
4	Hashemi (2009)	Feasibility study of prefabrication technology in Iran based on the following factors: • Demand • Building regulations & standards, Practicality • Cost and economic issues • Cultural issues & public attitude, sustainability, policy & planning,

Sl.No.	Author	Factors
		• Early adopters & stakeholders • Construction industry, design & flexibility
5	Abdulla and Egbu (2010)	• Client's perspective • Cost • Design • Environment • Knowledge • Law, materials • Organisational issues • Quality • Risk • Time
6	Haas et al (2002)	Framework to determine prework feasibility for a particular project: • Schedule • Cost • Labor • Safety • Site attributes • Mechanical systems • Project & contract types • Quality • Design • Transportation • Supplier capability • Lifting requirements

In a more concise example, Lu et al. (2018) filtered thirteen influential factors affecting the prefabrication adoption spread across the theme of PEST (political, economic, social and technological). Likewise, Hashemi (2009) adopted nine variables to determine the feasibility and transferability of MMC to Iran, while Abdulla and Egbu (2010) considered eleven clusters in the adoption of IBS in the UK and the Malaysian construction industry.

They used these factors to determine the feasibility of the appropriate level of prefabrication technology in their respective context. Therefore, these studies provide valuable and relevant prefabrication adoption framework which can be adopted to determine the initial feasibility of the technology in Bhutan.

On the other hand, other studies have attempted to present the most critical or identified stimulators that greatly determine the success of prefabrication adoption (Table 5). For example, Haas & Fagerlund (2002) advocated the main drivers of prefabrication: cost, quality, schedule and safety, while secondary drivers supporting these themes include productivity, risk reduction and environmental factors.

Elsewhere, the main determinants of adoption are revealed to be (1) the annual number of housing completions, (2) rates of a new building versus renovation, (3) new housing ownership models, and (4) types of housing constructed (Steinhardt & Manley, 2016). Moreover, Tam et al. (2005) proposed three stimulators that would facilitate and encourage the adoption of prefabrication, including implementing more stringent environmental control and regulations, highlighting the savings resulting from the more productive lean construction methods, and granting government incentives such as relaxation to the gross floor area. In conclusion, these studies provide overview of various factors that influence the prefabrication adoption, and it can be adopted to perform feasibility of the prefabrication technology for a certain context.

2.4 Prefabrication of house components

The extant literature accentuates the adoption of the industrial building system as an innovative construction method that would resolve the woes of the conventional construction method. There is a growing demand for IBS technology adoption driven by its significant associated benefits (Akmam Syed Zakaria et al., 2018). For instance, Badir et al. (2002) suggested that the acute housing shortage in Malaysia cannot be achieved with the conventional construction system and emphasise d the need to adopt industrial building systems (IBSs). In the case of Hong Kong, the application of prefabrication technology is mainly adopted in the housing sector and has demonstrated positive results in terms of quality, time, and safety (Tam et al., 2005). Tam et al. (2005) identified these prefabricated elements, including pre-cast façade units, staircases, drywall, and semi-pre-cast floor planking, while the structural aspects remain cast-in-situ. In his later study (Tam et al., 2007), Tam recommended a conventional system for structural components for housing projects (both private and public), while comprehensive prefabrication was suggested for the wall (internal and external) for the same. It could be for this reason that Zhang et al. (2014) identified precast concrete wall panels as one of the frequently prefabricated components (Zhang et al., 2014).

Although mass production of houses is probably the fastest and cheapest way, Bildsten (2011) suggests it cannot be adopted owing to its failure to respond to the unique requirements of customers (mass customisation). In this response, Bildsten

(2011) proposes the prefabrication of house components rather than volumetric homes as a balanced solution towards mass production and mass customisation to reap the benefits of off-site construction. House components can range from the entire volume structure (bathroom pods) to smaller pieces such as pre-sawn timber board (Bildsten, 2011). Furthermore, house components reduce lead time, production cost, and operation complexity and can create a new product range of customised houses (Bildsten, 2011). In addition, turning raw materials into house components can make housing production more efficient. Therefore, Bildsten (2011) recommends most complex areas of the house be the most favorable to adopt the prefabrication technique.

The overview of prefabrication adoption emphasised non-volumetric building components as more appropriate than volumetric ones. Then came the question of which building components, as the exploration of prefabrication to every building component, would be beyond the scope of this thesis and might not even lead to significant outcomes. In this regard, the scope of the investigation contextualised to building components with significant mass-volume, complexity, and cost contribution in a typical residential building of Bhutan: Wall systems and structural systems. These building assemblages constitute the largest and most complex due to the many sub-processes associated with their assembly. Bhutan's MoWHS analysed the cost contribution of various components (Table 6) in a typical residential structure in Thimphu. They suggested that the RCC construction account for the highest cost contribution at about 43% (sum of concrete, rebar & shuttering), followed by the wall system at roughly 20% (sum of wall, plaster, wall tiling & painting). Subsequently, the related literature on the prefabrication of the wall and structural systems will be presented.

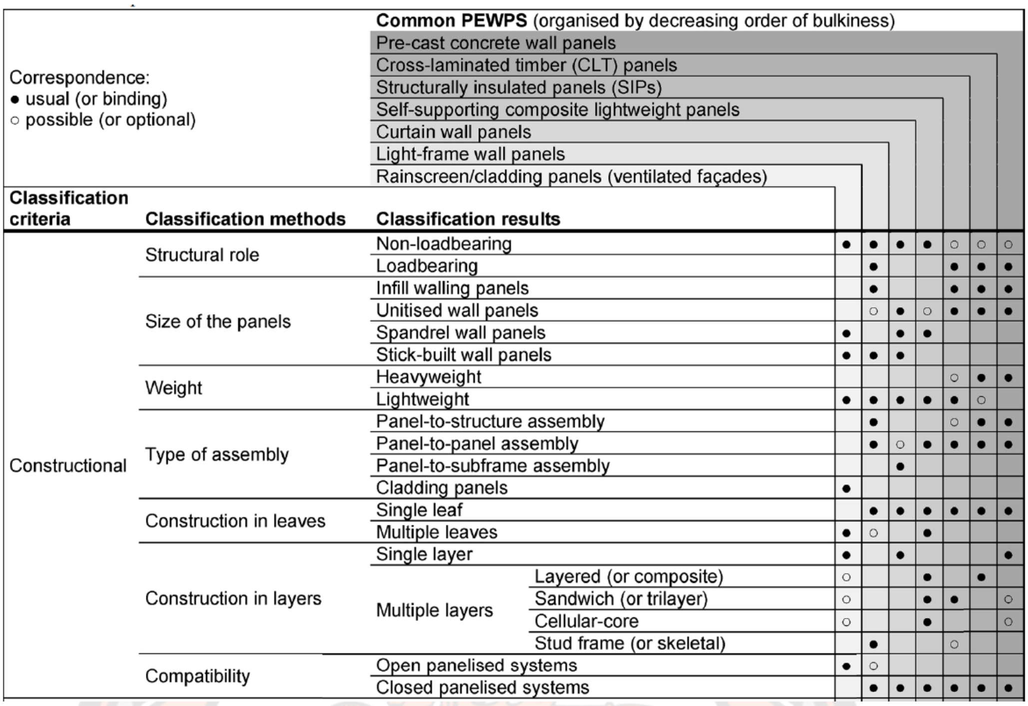
Table 6: Cost breakdown of the components of the residential construction in Bhutan.

Structure	Plinth area (Sq.m)	Concrete	Rebar	Shuttering	Wall	Plaster	Flooring	Windows & Doors	Wall tiling	Painting	Railing	Roofing	Plumbing& Sanitation	Plinth & drain	Foundation	Electrical
G+5	125.78	12.72	22.26	7.67	11.60	2.79	8.61	8.96	3.77	1.85	1.43	5.57	5.16	0.50	1.03	6.08
B+G+3	240.94	13.32	17.98	7.69	12.71	4.19	8.91	9.32	2.97	2.33	1.98	5.58	5.10	0.64	1.11	6.17
B+G+4	236.09	13.82	26.59	6.83	8.87	2.38	7.44	6.88	3.10	2.55	1.55	5.23	4.70	0.45	1.90	7.71
Weighted average		13.39	22.25	7.35	10.98	3.19	8.27	8.29	3.19	2.32	1.70	5.44	4.96	0.54	1.40	6.75

Source: (MoWHS, Bhutan)

2.4.1 Prefabrication of wall system

This section encompasses the possibilities of wall system prefabrication, covering various methods, materials, and case examples from the literature. In general, Correia lopes et al. (2018) classify different prefabricated enclosure wall panel systems (PEWPS) and categorises them as the sub-category of off-site manufacturing (OSM) construction system (Figure 7).



Correspondence:
● usual (or binding)
○ possible (or optional)

Common PEWPS (organised by decreasing order of bulkiness)

Classification criteria	Classification methods	Classification results		Rainscreen/cladding panels (ventilated façades)	Light-frame wall panels	Curtain wall panels	Self-supporting composite lightweight panels	Structurally insulated panels (SIPs)	Cross-laminated timber (CLT) panels	Pre-cast concrete wall panels
Constructional	Structural role	Non-loadbearing		●	●	●	●	○	○	○
		Loadbearing			●			●	●	●
	Size of the panels	Infill walling panels			●			●	●	●
		Unitised wall panels			○	●	○	●	●	●
		Spandrel wall panels		●		●	●			
		Stick-built wall panels		●	●	●				
	Weight	Heavyweight						○	●	●
		Lightweight		●	●	●	●	●	○	
	Type of assembly	Panel-to-structure assembly			●			○	●	●
		Panel-to-panel assembly			●	○	●	●	●	●
		Panel-to-subframe assembly				●				
		Cladding panels		●						
	Construction in leaves	Single leaf			●	●	●	●	●	●
		Multiple leaves		●	○		●			
	Construction in layers	Single layer		●		●				●
		Multiple layers	Layered (or composite)	○			●		●	
			Sandwich (or trilayer)	○			●	●		○
			Cellular-core	○			●			○
			Stud frame (or skeletal)		●			○		
	Compatibility	Open panelised systems		●	○					
		Closed panelised systems			●	●	●	●	●	●

Figure 7: Constructional criteria for the classification of PEWPS.

Source: Adapted from (Correia Lopes et al., 2018)

Figure 8 illustrates the various constructional criteria Correia Lopes et al. (2018) used for the PEWPS classification. Although these panels are designed for the external envelope, these systems can be adopted for an internal partition wall with less vigor to equally maximise the functional and constructional benefits. In addition, the panel system of non-volumetric prefabrication can lead to 20-30% time saving compared to the traditional construction system (Correia Lopes et al., 2018). Correia Lopes et al. (2018) organise PEWPS in their decreasing order of bulkiness as; precast concrete wall panels, cross-laminated timber (CLT) panels, structurally insulated panels (SIPs), self-supporting composite lightweight panels, curtain wall panels, curtain wall panels, light-frame wall panels and rain screen/cladding panels (ventilated facades). However, since this thesis ventures towards finding innovative and sustainable universal wall solution that includes both external and internal partition wall, the latter three typical cladding systems becomes irrelevant. Moreover, owing to the bulkiness and its regular usage as load bearing system, the former three also proves less applicable. Thus it can be theoretically hypothesised that the self-supporting composite lightweight panels which is commonly applied as non-load bearing wall as a potential answer. The following section discusses the related literature on wall prefabrication systems.

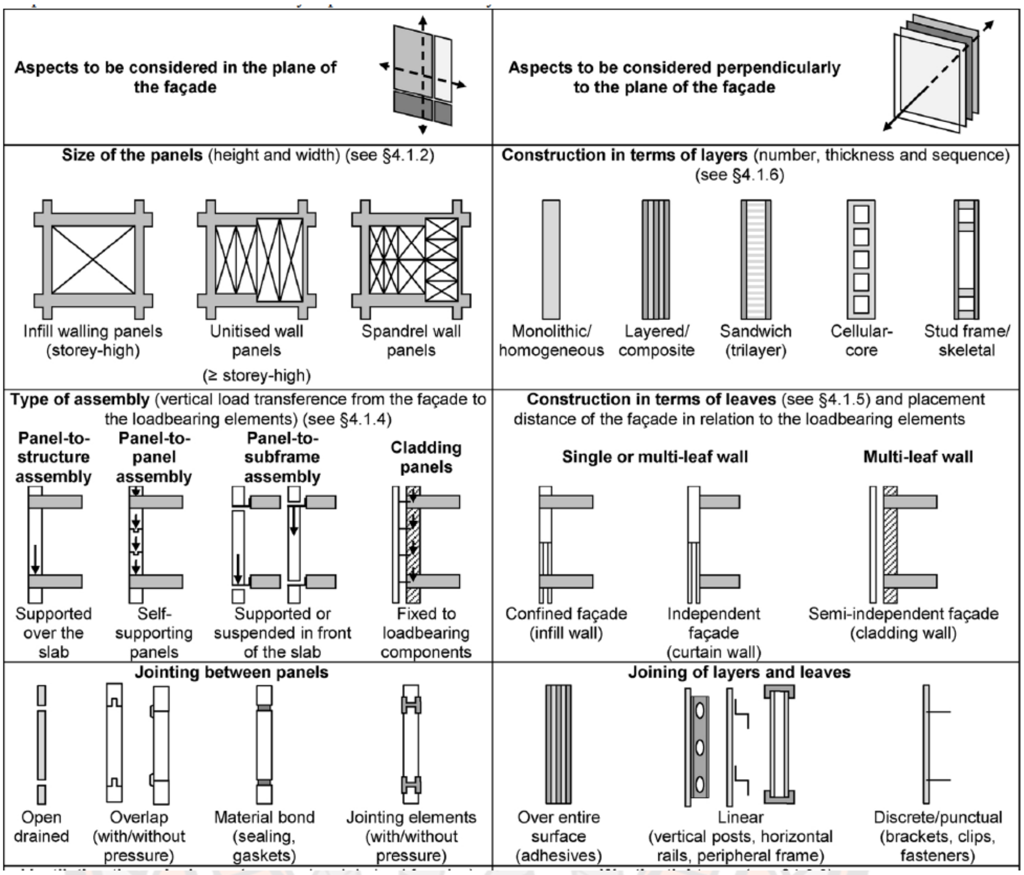


Figure 8: Graphical overview of the constructional criteria used to classify PEWPS.

Source: Adapted from (Correia Lopes et al., 2018)

Cherian et al. (2017) demonstrate the use of glass fiber-reinforced gypsum (GFRG) panels as an innovative and rapid solution for affordable housing in India. The prefab panels (12M X 3M X 124MM) made from the recycled industrial waste of gypsum can be used as load-bearing structures in 8-10 multi-storeyed buildings (Cherian et al., 2017). Likewise, Joseph (2020) advocates precast lightweight concrete sandwich panels (3M X 12.5M X 150MM) comprising concrete wythes, expanded polystyrene core, and truss shear connectors to replace the brick masonry walls to achieve the growing housing demand in India. The author points out that the conventional housing system of India using burnt bricks and hollow bricks consumes a significant amount of natural resources. The construction cost is primarily high due to its associated higher labour cost and time (Joseph, 2021). Bhandari (2016) concluded the application of ferrocement over the insulation core (thermocol) to produce lightweight structural panels is an ideal solution for housing production in

India. The proposed panels proved to be a cheaper method than conventional brick masonry in addition to being lightweight and structurally sound (Bhandari, 2016).

Sneha and Tezeswi (2016) analysed the comparison between the pre-cast sandwich composite panel (expanded polystyrene core with shotcrete cover) and RCC framed structure with brick infill for a single-storied building. The study indicated that the expanded polystyrene wall and slab panels are cost-effective and efficient, reaping time-saving of 50% and overall cost-saving of 30% compared with the conventional traditional RCC frame with brick infill walls (Sneha & Tezeswi, 2016)

Bras et al. (2020) concluded that India's current housing construction system needs improvement from a whole-life energy use perspective at a material and system level, service life improvement, and accurate monitoring of buildings and structures. In this regard, the author recommended replacing conventional materials with sustainable materials obtained by treating locally available wastes since it produces better environmental, economic, and social results. These sustainable materials can be combined with prefab technologies, which lead to the affordable and speedy construction of mass houses (Bras et al., 2020)

Puri et al. (2017) undertook a study to present an alternative sustainable building material in prefabricated bamboo reinforced wall panels beneficial for low-cost housing. In addition to the adequate strength, these panels were 56% lighter in weight and 40% cheaper as compared to partition brick walls (Puri et al., 2017)

Benayoune et al. (2004) demonstrate the potentiality of the precast concrete sandwich panel (PCSP) as an alternative (Industrial Building system) to conventional building systems to provide affordable quality housing in Malaysia. IBS is defined as building systems in which components, prefabricated at the site or in a factory and then assembled to form a complete structure with minimum in-situ construction, are destined to provide a solution to this multi-dimensional problem, primarily since the buildings constructed suing this method have a shorter construction time with additional benefits of strength, integrity, durability, indoor thermal comfort, and labour saving (Benayoune et al., 2004)

These studies suggest applying a prefabricated wall system that utilises local materials or industrial waste as an innovative, sustainable, and cost-effective solution.

2.4.1.1 Sandwich panels

Sandwich panels are a specific form of composite panels consisting of two high-strength skins (or facings) bonded to a foam insulation core (Correia Lopes et al., 2018). Ideally, structural insulated panels (SIPs) are produced by this method. However, according to Yeh et al. (2008), it can be defined as the product of securely bonding and pressing structural panel facings such as oriented strand board (engineered wood) with a foam plastic insulation core (generally EPS) with the help of an adhesive. Nevertheless, precast concrete wall panels and self-supporting composite lightweight panels can also be manufactured by adopting the sandwiching method. In contrast, cross-laminated timber panels are a high-strength prefabricated product produced by pressing cross-wise layering of single (finger-jointed) boards, often in odd numbers, which are bonded together with an adhesive (Brandner et al., 2016).

Precast Concrete Sandwich Panels (PCSPs) are a composite cladding type encompassing concrete wythes that embed a layer of thermal insulation and are prefabricated in factories (Al Kashif et al., 2012; O’Hegarty & Kinnane, 2020). Typically, PCSPs are heavy; thus, recent studies have attempted to make them thinner and lighter to increase their applicability to various projects. The manufacturing of PCSP begins by preparing timber/steel formwork, placing steel reinforcement and pouring the first layer of concrete, fixing connectors and insulation, and finally pouring the second layer of concrete. The PCSPs can be either load-bearing or non-load bearing, allowing for a much thinner and lighter section (O’Hegarty & Kinnane, 2020). Furthermore, ultra-high performance concrete such as fiber-reinforced and textile-reinforced concretes can enable thinner sections by replacing solid steel reinforcement. Likewise, high-performance insulation materials, such as vacuum insulation, have allowed a slimmer design (O’Hegarty & Kinnane, 2020).

Wang et al. (2018) noted the adoption of pultrusion or bonding processes to fabricate sandwich panels in most studies. In this response, to increase the choice in terms of the manufacturing process, the author proposed a simple and innovative sandwich panel (load bearing) comprising of glass fiber-reinforced polymer (GFRP) skin and GFRP foam core which was manufactured using a vacuum-assisted resin infusion process (Wang et al., 2018). This alternative allows slender structures with a high potential for economic savings in terms of materials and transport, as well as reduced time and effort during mounting (Shams et al., 2015). Furthermore, Shams et al. (2015) presented the possibility of achieving high bond strength using foaming core material between the precast facings in place of standard methods of using ready-made insulation material for gluing and pressing with the precast concrete layers (Figure 9 & Figure 10). This innovative production method can be used to produce load-bearing sandwich panels.

Thin precast concrete sandwich panels (<200mm) offer weight and material savings over standard reinforced concrete panels (>350mm), which enable manufacturing, transport, and onsite efficiencies, as well as reduced embodied energy. In this regard, thin PCSP was prefabricated using the fiber-reinforced concrete wythes, a combination of vacuum insulation panel (VIP) and phenolic foam, and Carbon fiber reinforced polymer shear connectors were chosen to connect the layers of concrete and insulation. However, the cost of producing one of these panels is significantly higher than that of making a standard (larger) precast concrete sandwich panel (O'Hegarty et al., 2021). In addition, these panels serve as thermally and structurally efficient elements for exterior walls and roofs (Al Kashif et al., 2012).

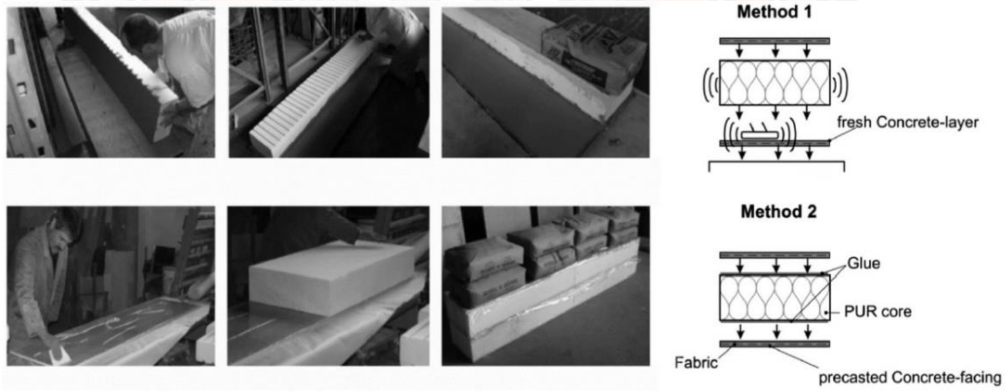


Figure 9: Conventional sandwich manufacturing process.
Method 1: Placing of insulation core in fresh concrete. Method 2: Placing and gluing insulation foam with the precast concrete facings.

Source: (Shams et al., 2015).

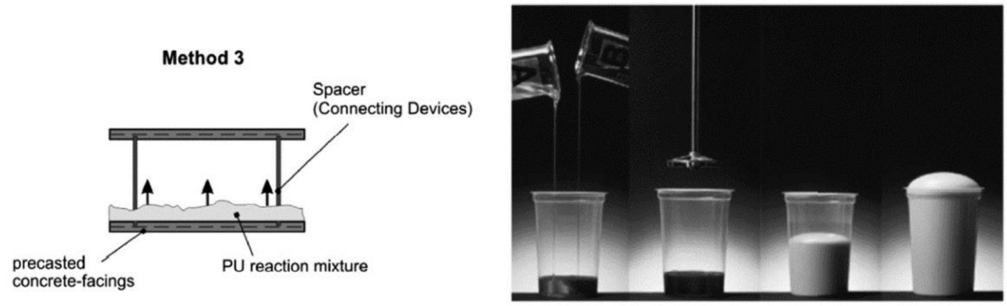


Figure 10: Foaming production method for sandwich panels (left). Expansion of insulation mixture (right).

Source: (Shams et al., 2015).

2.4.1.2 Other innovative construction material and method

This section includes using natural materials, agriculture waste, and recyclable materials to produce innovative and sustainable building material solutions. The implementation of innovative construction materials should be based on satisfying some of these requirements, such as sustainability, durability, reliability, safety, economy, improved quality, enhanced mechanical and physical characteristics, flexibility in extreme conditions and locations, simple assembly, and environmentally friendly (Bamigboye et al., 2019). From the literature review, Bamigboye et al. (2019) concluded that some of the innovative construction materials, including 3D printing, 3D printed ceramics, pollution-absorbing concrete, laminated timber, aluminum foam, bamboo reinforced concrete, bio-receptive concrete, bricks made from pollutants, plaited microbial cellulose, superplasticizers, etc.

Asdrubali et al. (2016) acknowledged the promises provided by natural and bio-based construction materials in optimising the environmental sustainability of buildings. In this view, he presented the use of reed as a filler material for sandwich building panels owing to its acceptable thermal and acoustic characteristics. Similarly, rice husk produced by gluing and pressing was proposed to be used for sound and thermal insulation applications (Buratti et al., 2018). Elsewhere, straw bale core caged between fir boards finished with natural plaster (cocciopesto plaster) was recommended as an innovative wall package with incredible energy and environmental performance (Cornaro et al., 2020). Likewise, Gonzalez et al. (2021) proposed innovative sandwich-like composite bio-panels comprising bamboo or melina facings with balsa core that performed better in every essence than conventional brick and concrete walls. The bidirectional bamboo veneers were glued with vinyl acrylic resin. At the same time, formaldehyde urea was used for Melina, followed by pressing at 300 psi under 100°C for 30 minutes for both panels (González et al., 2021). Given its excellent adherence capacity, a two-component Polyurethane adhesive (Pur2C) was then used to bind the bamboo and Melina facing boards with the core material. (González et al., 2021). These studies illustrate the acceptable thermal and acoustic characteristics of the natural materials and their proven possibility to be used as filler material in the sandwich panels. In addition, agriculture waste is another potential source of sustainable building materials (Barreca et al., 2019), and so is the case for recyclable products. Correspondingly, potential sources for building materials locally available in Bhutan were identified.

Barreca et al. (2019) presented local agricultural waste of giant reed and agglomerated cork as a cavity wall system as a sustainable walling solution. Similarly, several studies have been undertaken to determine the possibility of cardboard.

The current use of recycled cardboard in the building sector ranges from honeycomb cardboard as core material in sandwich panels, cellulose fibers and flocks in thermal and acoustic panels, and lastly, as cardboard tubes for structural systems or concrete formwork (Secchi et al., 2016). For instance, Secchi et al. (2016) presented a cardboard sandwich panel made of two panels of honeycomb cardboard panels filled with cellulose fibers (Thickness- ranging from 20mm -50mm) as a sustainable alternative to a gypsum panel for building acoustic. Similarly, Asdrubali et al. (2015) concluded the comparable thermal and acoustic properties of corrugated cardboard (waste from packaging) with other commercialised products, making them suitable to be used as light insulation solutions for wall panels. In addition, Betts et al. (2019) proposed a sandwich panel comprising a cardboard core with flax-reinforced polymer (FFRP) faces for building an envelope after experimenting with the impact behavior. In a more comprehensive example, recycled cardboard was used primarily as the primary structural (cardboard tubes) and cladding component (sandwiched panels) to build a prototype school in the UK. These sandwich panels comprised honeycomb lightweight cardboard core glued to the timber, easing the installation by conventional screwing process (Cripps, 2004). Cripps (2004) recommended mass production of the components to reduce the initial cost of producing such panels.

2.4.1.3 Autoclave aerated concrete (AAC) panels

The section on AAC is presented separately owing to its popularity and proven potentiality in the building industry as an innovative and sustainable material. AAC (autoclave aerated concrete) is produced by autoclaving (steam-based heat treatment) the mixture of sand, cement, lime, gypsum, water and a small amount of foaming agent, aluminum powder (El-Didamony et al., 2019; Kalpana & Mohith, 2020) or it can be zinc powder (Kalpana & Mohith, 2020). The resulting product is lightweight, primarily due to the 35-40% porosity (Raj et al., 2020) of the total volume. The popularity of AAC panels in building construction is increasing due to their unique material properties, such as being lightweight, sustainable, a good insulator, and fire resistant, combined with having a high speed of erection and ease of quality control (Taghipour et al., 2018; van Boggelen & van Boggelen, 2018). For instance, Raj et al. (2020) concluded that the AAC block is approximately 22.73% less than the wall system made up of ordinary burnt clay brick after performing a cost analysis in the locality of Guwahati (India), over 100 km from the nearest border town in Bhutan.

Van Boggelen & van Boggelen (2018) recognises the predominant application of AAC as a relatively simple-commodity-type wall-building material. Therefore, the author advocates a panel construction method using mid-size modular AAC to realise the added benefit of prefabrication and the traits mentioned above of the material. Several countries like Japan, Australia, China, and South East Asia are moving toward AAC wall panels for modular applications (van Boggelen & van Boggelen, 2018). The size of lightweight AAC wall panels used in the modular building system ranges from Height- 1200/2100/2400/2700/3000/3300, width- 300/400/600/750, and thickness- 150/200/250 (van Boggelen & van Boggelen, 2018). Taghipour et al. (2018) used the AAC panel locally available to assess the seismic behavior were 2400mm X 600mm X 200mm with 4mm reinforcement bars (Figure 11).

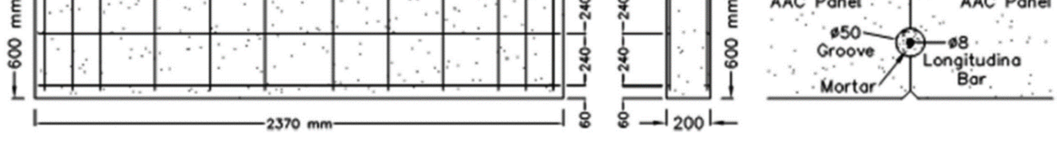


Figure 11: AAC panel detail.

Source: (Taghipour et al., 2018)

AAC, as a lightweight prefabricated product, can be used either as a block or as a panel for every building component. However, its application in the wall system is gaining prominence (Raj et al., 2020). The production of AAC block (Figure 12) or panel (Figure 13) involves five stages, namely, mixing of raw materials, casting, expansion or rising, wire cutting, and finally, autoclaving (Raj et al., 2020; Wahane, 2017).

In the AAC panel system, steel rebars are currently used as internal reinforcement (Mousa & Uddin, 2009). Nevertheless, fiber-reinforced polymer (FRP) can be used as a reinforcing fabric. FRP-AAC panels are lightweight and savings in time, material and labor could significantly reduce the cost compared to traditional construction (Mousa & Uddin, 2009). For example, Mousa & Uddin (2009) demonstrated using carbon fibers embedded in an epoxy resin matrix as laminates to reinforce the AAC panels. Moreover, E-glass fibers can be a cheaper alternative to carbon fibers. In such a panel production system, Vacuum Assisted Resin Transfer Molding (VARTM) could be adopted due to its high efficiency without requiring skilled labor in a short time (Mousa & Uddin, 2009).

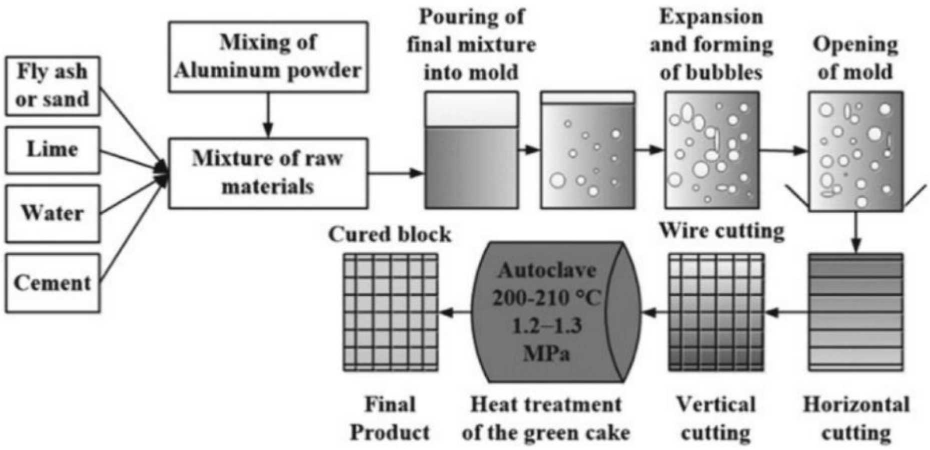


Figure 12: Manufacturing process of AAC blocks.
Source: (Raj et al., 2020)

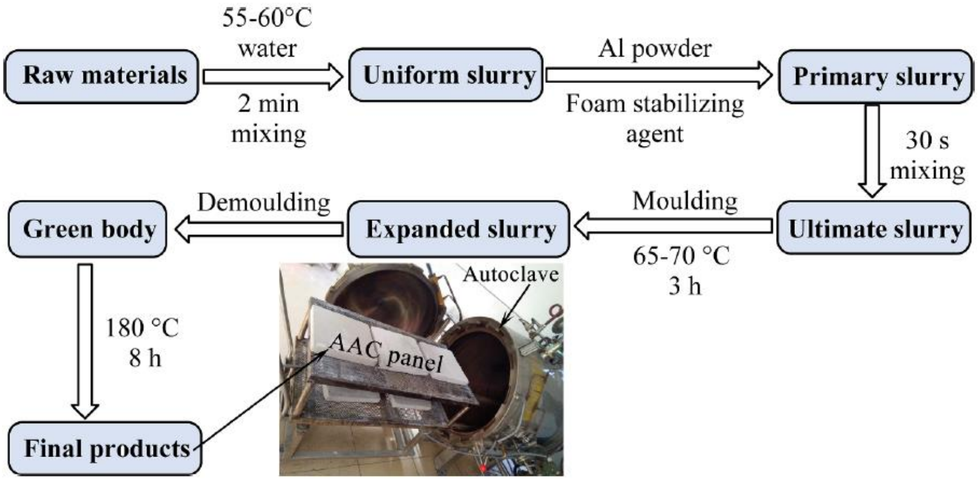


Figure 13: Manufacturing process of AAC panels.
Source: (Zhao et al., 2021)

2.4.2 Prefabrication of structural system

Regarding the structural system, the choice of material is traditionally limited to primarily concrete and steel. Based on the construction technology (main structural and space-enclosing), four central building systems can be distinguished: Timber, steel, cast in situ concrete, and precast concrete (Warszawski, 2003). Warszawski (2003) explicitly summarises different types of precast concrete prefabrication systems: Linear or skeleton (beams and columns) systems, Planar or panel systems and, finally, three-dimensional or box systems. Similarly, Gibb (1999) presents only multiple precast concrete prefabricated buildings across the globe. Precast concrete in housing projects in Hong Kong is limited to non-structural components as conventional cast in situ prevails for the structural elements (Tam et al., 2005; Tam et al., 2007).

Nevertheless, a growing body of literature highlights the potentiality of timber, regarded as mass timber construction as the new material for the 21st century—capable of prefabricating structural components. The 18-story student residence building, Brocks Commons Tallwood House, constructed in mass timber, stands testimonial. More on this is covered later in the mass timber construction section.

2.5 Bhutan's building material inventory.

This section presents a brief inventory of building materials in Bhutan, intending to identify the potential category for achieving prefabrication. Three broad types of waste, mineral-based and bio-based building materials, are inventoried and concluded for their prefabrication potentiality. Their potentiality was assessed based on their expected environmental sustainability and scalability for widespread adoption, at least in Bhutan.

2.5.1 Waste

The waste produced in the country can be categorised as general, industrial, and agricultural. According to the National Environment Commission 2019, household waste accounted for nearly 50% of the total solid waste production, followed by commercial waste at 40% (Figure 14). Similarly, the composition revealed food waste as the highest producer (46%), followed by plastic and paper waste at 33% (Figure 15). However, the survey collected only the solid general wastes from industries, not the toxic and hazardous ones like chemicals, slags, etc.; thus, it will be presented under the industrial waste section below.

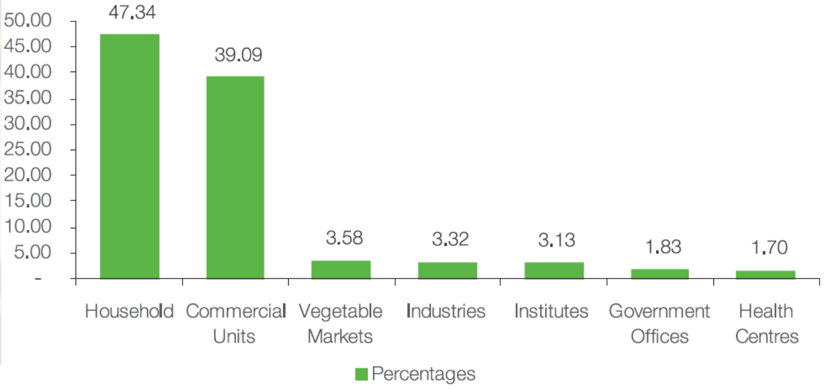


Figure 14: Proportion of wastes from different sectors in percentage.
Source: (National Environment Commission, 2019)

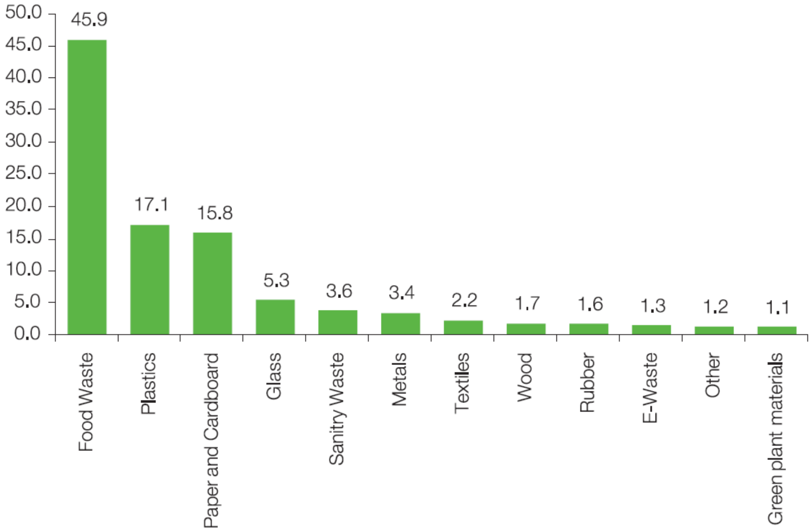


Figure 15: Waste composition in percentage.
Source: (National Environment Commission, 2019)

Significant industries in Bhutan comprise food and beverage, wood, metal, and mineral processing industries (Asian Development Bank, 2010). Waste generated from the wood processing factories includes sawdust, wood parts, metal waste, dust/ash, paper waste and sludge. These wastes are mainly disposed of by selling and open dumping. For example, while metal waste is sold to scrap dealers, dust, ash and sludge are disposed of through open disposal.

In the case of metal processing industries, waste generated is slag, sludge/slurry, metal waste and scrap, and metal dust (copper and carbide). A total of 28,626 slags are generated annually (70 tons per day), which is disposed by land filling within the compound, making it the most significant waste, followed by metal waste/scrap, sludge/slurry and metal dust.

Mineral processing industries produce metal scraps, slag/sludge, and textile waste comprising cotton and jute bags and filter fabrics and dust as the largest waste producer in this category. The wastes generated from mineral-based industries are disposed of either by selling to scrap dealers, dumping in designated areas, or burning.

According to the Land Use and Land Cover Assessment of Bhutan 2016, only 2.76% of Bhutan is under cultivated agriculture. Nevertheless, agriculture is the mainstay of the people, with an estimated 69% of the population engaged in farming and major cereals crops produced are rice, maize, wheat, barley, buckwheat, and millets (Katwal, 2013). Crop residue burning is the standard method of disposal of agriculture waste in Bhutan and has been validated by Dey et al. (2020).

2.5.2 Mineral-based

Table 7 highlights different types of Bhutan’s minerals, predominantly exported without value addition. As necessitated by the EDP 2016, for a synergistic environment-friendly industrial development in the country, a detailed feasibility study was undertaken to establish the mineral-based industrial cluster where it presented the strength and weaknesses, and the possible recommendations were provided to achieve the goal (Ministry of Economic Affairs, 2018).

Table 7: Export and domestic use of the mineral in Bhutan 2016.

Minerals	**Unit**	**Export**	**Export %**	**Domestic use**	**Domestic %**	**Total**
Dolomite	MT	2,283,723	96%	83,934	4%	2,367,657
Limestone	MT	1,244,999	99%	12,102	1%	1,257,101
Gypsum	MT	241,650	76%	75,948	24%	317,598
Marble	MT	36,358	48%	38,674	52%	75,032
Quartzite	MT	2,745	3%	90,025	97%	92,770
Granite boulders	MT	5,860,390	98%	96,827	2%	5,957,217
Total		**9,669,865**	96%	**397,510**	4%	**10,067,375**

Source: Adapted from (Ministry of Economic Affairs, 2018).

2.5.3 Bio-based

Timber reasoned as a renewable building material that can be grown. Bhutan’s forest cover stands at 71%, comparable to Sweden, although the latter is geographically roughly ten times bigger. Along with sustainable forestry practices (covered in greater detail in the MTC sub-section), the timber can be sustainably harvested without compromising the forest resources. Countries such as USA and Sweden have shown growth in their forest cover.

2.5.4 Summary

This section presented a high-level summary of possible different sources of sustainable building materials. Based on the selection criteria of scalability and environmental sustainability—along with the general acceptance of mass timber construction as an innovative construction method in the literature—timber was posited as more relevant and appropriate than the other two categories of waste and mineral resources. For instance, although reusing waste blends with sustainability concerns, it does not provide any potential for mass-scale adoption. Likewise, mineral resources are abundant but not sustainable as they are extracted, requiring high energy and carbon-intensive approaches. Therefore, the following section will dive deeper into mass timber construction technology.

2.6 Mass timber construction (MTC)

Buildings and construction account for nearly 40% of energy-related CO2 emissions (28% operational emissions, 11% embodied emissions) (Abergel et al., 2017; Abouhamad & Abu-Hamd, 2021). Considering the current pattern, by 2060, CO2 emission is expected to increase by 10% and energy demand by 30% (Abed et al., 2022). For this reason, the construction sector is increasingly encouraged to utilise renewable materials with less carbon-related emission and thereby help reduce global environmental impact (Figure 16). In recent years, there has been a conscious effort to improve the energy efficiency of buildings but limited focus on the use of sustainable materials, which is an essential step towards reducing building-related emissions (Abed et al., 2022; Crawford & Cadorel, 2017; Smith et al., 2015). Mass Timber Construction (MTC), owing to its low embodied energy, renewability and carbon sequester capability, is an attractive and viable construction material for this century (Smith et al., 2015).

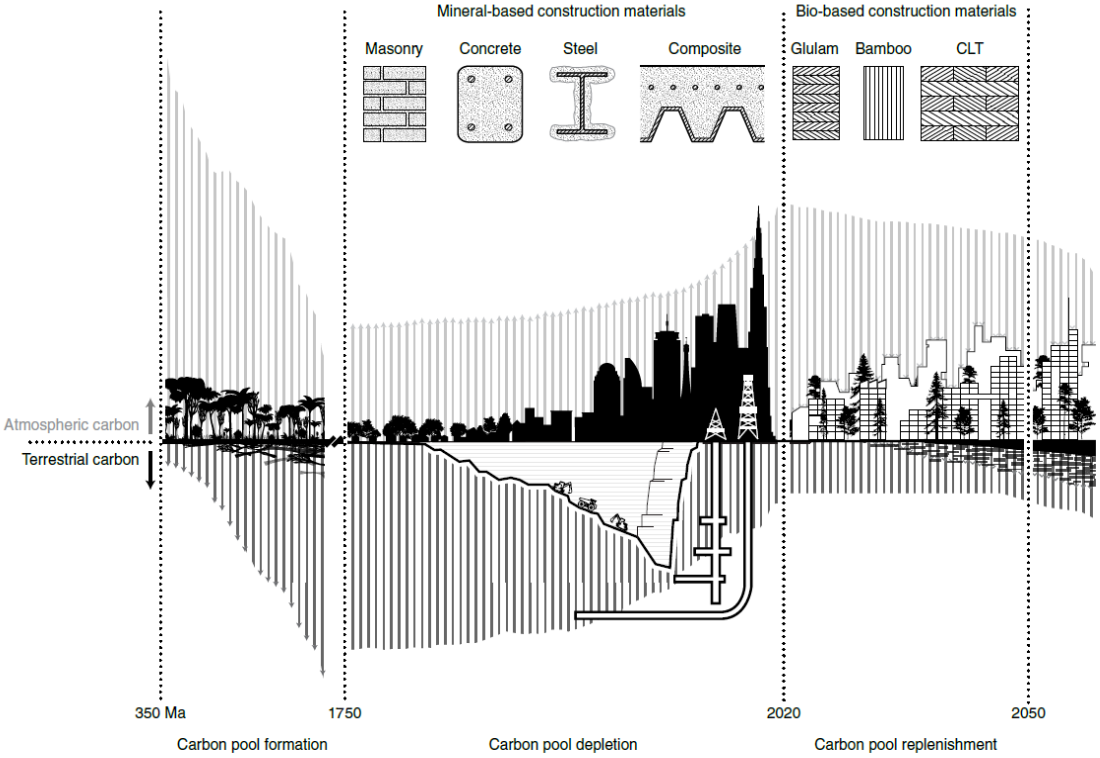


Figure 16: The processes that cause the production, depletion, and possible replenishment of the land carbon pool, as well as changes in atmospheric CO2 concentrations over time.
Source: (Churkina et al., 2020).

Mass timber construction (MTC) describes engineered wood products of large section sizes offering alternatives to steel and concrete (Abed et al., 2022; Harte, 2017). These mass timber products (Figure 17) are laminated from smaller boards or lamella into larger structural components (Churkina et al., 2020) using glue or non-glued methods like nails and dowels. Glued products include Glued laminated timber (Glulam or GLT), Laminated veneer lumber (LVL), Structural composite lumber (SCL), Parallel strand lumber (PSL) and Cross-laminated timber (CLT), while non-glued products include Dowel-laminated timber (DLT), Nail-laminated timber (NLT) and Interlocking cross-laminated timber (ICLT) (Abed et al., 2022; Smith et al., 2015). The current literature considers CLT (for walls and floors) and GLT (for structural framing) the most adopted products (Table 8). MTC comes as either a honeycomb system using primarily CLT or a post and beam system using a mix of CLT, glulam and LVL (Crawford & Cadorel, 2017). MTC is used synonymously with Solid Timber Construction (STC), as Smith et al. (2015) demonstrated. MTC or STC finds its application in a building's walls, floors, roofs, partitions and core elements (Smith et al., 2015).

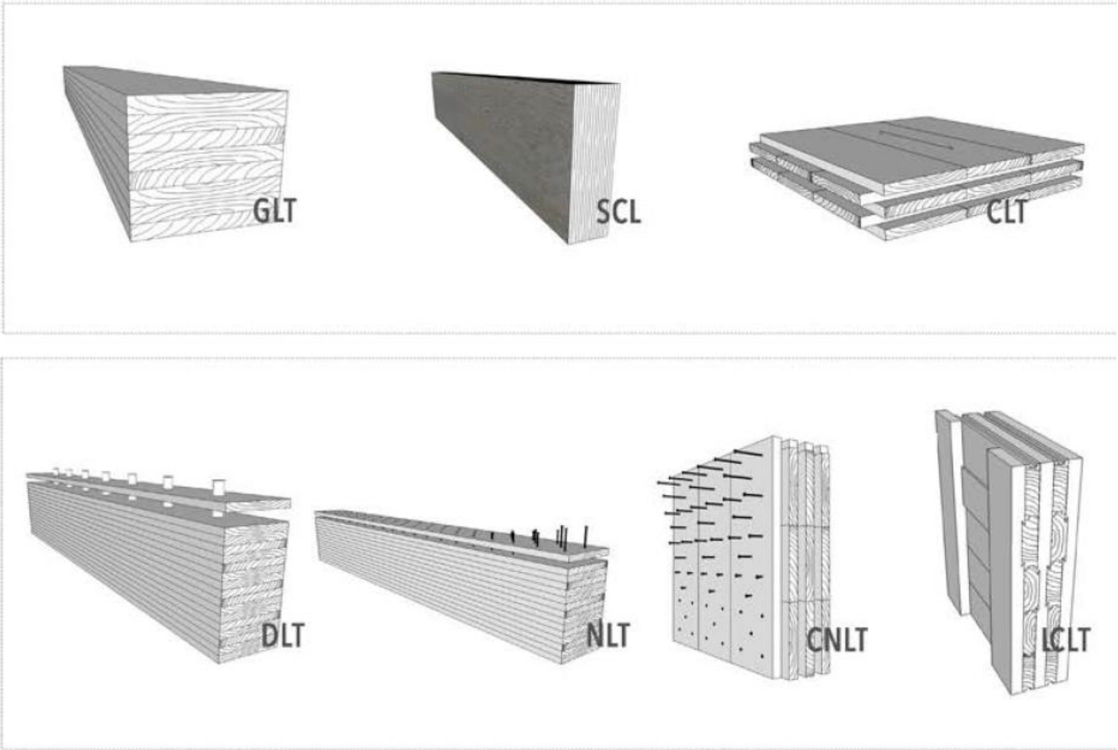


Figure 17: Types of Solid Timber products (Glued and Non-glued)
Source: (Smith et al., 2015)

Table 8: Summary of the relative advantages and disadvantages of using different mass timber products in construction.

Mass Timber Products	Applications	Advantages	Disadvantages
Cross Laminated Timber (CLT)	Floors, walls, roofs	• High dimension stability • High strength and stiffness • Easy to manufacture	• Higher cost
Glued Laminated Timber (Glulam)	Beams, Columns	• High strength and stiffness • Structurally efficient • Can be manufactured in complex shapes	• Higher cost
Nail Laminated Timber (NLT)	Floors, walls, roofs	• No specialised equipment required to manufacture. • Cost effective. • Fast procurement times	• Labour intensive • Greater chance of human error
Dowel Laminated Timber (DLT)	Floors, walls, roofs	• High dimensional stability • Easy and safe to manufacture. • No adhesives or metal fasteners required.	• Limited panel sizes • Limited thicknesses
Structural Composite Lumber (SCL)	Beams, columns, joists, studs, rafters	• Not prone to shrinking, splitting or warping. • Able to withstand greater loads than solid timber	• Limited panel sizes • Limited thicknesses • More suitable for low-rise buildings

Source: Adapted from (Abed et al., 2022)

Given their technical capabilities, cost competitiveness and environmental benefits, there has been a significant interest in these products and building systems (Harte, 2017). In addition, the recent development of these "mass timber" technologies and the supporting scientific research and legislative changes show that engineered wood products and structural systems can potentially replace many mineral-based materials used in the construction of urban structures. (Churkina et al., 2020).

MTC is being used in an increasing number of projects (e.g., only 1 CLT manufacturer in Europe in 2003, it increased to 50 globally by 2017) (Crawford & Cadorel, 2017). Europe, Canada and the United States of America are arguably the leaders in the MTC. For instance, in Canada, MTC, as of 2021, is dominated by the application of glulam (352 projects), followed by CLT (101), GLT (54) and NLT (53) (Natural Resources Canada, 2021). On the other hand, the least adopted category is DLT, LVL and PSL, with only ten projects (Natural Resources Canada, 2021). At the same time, other countries have also started to recognise the viability of MTC as a dependable construction method. For example, in Australia and New Zealand, mass timber building technology has progressed from being technically feasible to being established as a viable alternative to reinforced concrete and steel construction. Nevertheless, the adoption of MTC faces obstacles, such as building supply chains, gathering engineering and assembly knowledge, and necessitating a change in conventional marketing and sales processes. (Evison et al., 2018).

Quantifying the environmental benefit of MTC, which is its significant strength, can increase the diffusion of the construction system to a larger community (Crawford & Cadorel, 2017). In their review, Abed et al. (2022) concluded that when all performance parameters are considered, mass timber is superior to concrete and steel and suggests that the construction industry should switch to mass timber as the future's low-carbon, high-performance building material.

2.6.1 Benefits of Mass Timber

The environmental benefit is probably the most significant benefit of MTC. Alongside this, it does also have other benefits that make MTC attractive. The advantages of MTC include speed, weather versatility, raw material, carbon reduction, remote locations, labor costs, weight, precision and safety (Smith et al., 2015). Based on several MTC case studies, some of MTC's quantifiable benefits include 4% savings in cost, 20% savings in schedule, 3.7 average change orders (quality) and zero reported safety-related incidents. Project cost saving is tied to the reduction of the project schedule. A reduced construction schedule of STC can lead to project savings through construction interest savings and rental income (Smith et al., 2015).

In contrast, MTC's disadvantages include Knowledge and labour, research, logistics, planning, acoustics & vibration, job displacement, code permits, wind, and component flexibility (Smith et al., 2015). Nevertheless, no material is inherently more resistant to fire, potentially catastrophic earthquakes, or other weather-related catastrophes (e.g., RCC needs reinforcing as it is weak in tensile strength, and structural steel is strong but subject to corrosion) (Churkina et al., 2020). Moreover, since buildings are systems of materials and connections, they must be well-engineered to manage the anticipated stresses because, as history has shown, system engineering failure frequently occurs before material failure (Churkina et al., 2020).

Many of the current studies in the literature have attempted to demonstrate the viability of the MTC in comparison with the conventional construction material in steel and concrete. Figure 17 compares the physical dimensions, carbon emissions and carbon storage capacity of 1 t of cement, steel and timber material (Churkina et al., 2020). Although steel and concrete are widely used, owing to their favorable properties (structural, durability, performance and cost), they are highly energy intensive and result in significant GHG emissions. (Abed et al., 2022; Crawford & Cadorel, 2017). For example, it is estimated that for every ton of cement or steel produced, around 1 ton and 1.85 tons of CO2 are emitted, respectively (Abed et al., 2022).

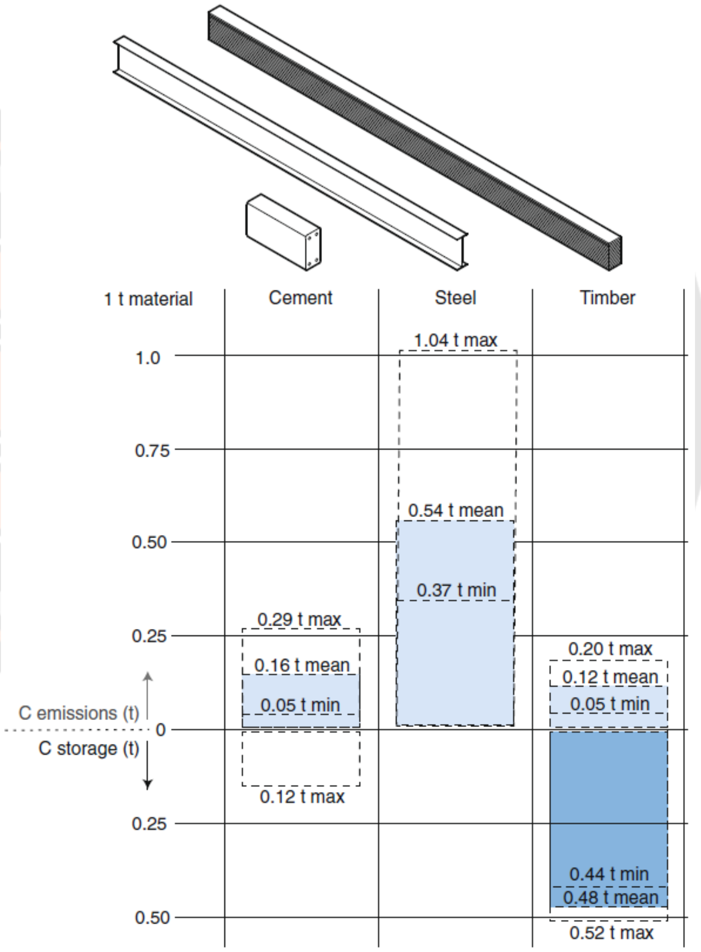


Figure 17: Physical dimensions, carbon emissions and carbon storage capacity of 1 t of cement, steel and timber materials
Source: (Churkina et al., 2020)

Moreover, in a case study in Minneapolis, USA, steel used 17% more embodied energy in manufacturing and construction (Falk, 2009; Lippke et al., 2004). Likewise, since 50% of the weight of wood is carbon, the carbon footprint of timber (framing lumber) is significantly lower when compared with other conventional building materials like concrete (8 times) and steel (21 times) (Falk, 2009). Falk (2009) concluded that embodied energy of solid wood products is even lesser than wood products (e.g., plywood) as it requires additional processing steps and much less than the non-wood counterparts. Along a similar line, after analysing 21 international studies, Sathre & O'Connor, 2010 concluded that each ton of carbon in wood products that is substituted in place of non-wood ones reduces greenhouse gas (GHG) emissions by 2.1 tons of carbon on average. Using wood to replace conventional construction materials globally could save 14-31% CO2 emissions (Oliver et al., 2014). Durlinger et al. (2013) demonstrated a reduction in global warming potential (GWP) of 13%-22% in a case study of the Australian CLT building, 'Forte,' compared to a structure of identical design using concrete. The houses built with wood-based systems required about 15% less operational energy and 20-50% lower GHG emissions when compared with comparable houses built with either steel or concrete-based building systems (Upton et al., 2008). These studies reflect MTC as a viable and sustainable building material/method alternative to conventional concrete and steel construction (Table 9).

Table 9: Performance of Mass Timber Construction (MTC) relative to conventional construction.

Performance Criteria	Performance Rating
Environmental	
Carbon emissions	Far better
Energy use	Far better
Water use	Far better
Seismic	
Seismic behavior	Better
Wind	
Wind performance	Undetermined
Fire	
Charring method	Similar
Encapsulation method	Better
Health	
Mental health	Far better
Physical health	Far better
Costs	
Material costs	Similar
Foundation and earthworks	Far better
Labour costs	Far better
Speed of construction	Far better
Economic growth potential	Far better

Source: (Abed et al., 2022)

2.6.2 Sustainable Forest Management

Bhutan is endowed with abundant natural resources. Forest resources are fundamental natural capital critical for the human population's sustenance (Department of Forests and Park Services, 2021). However, due to ever-increasing demand originating from the increasing urban population trend, not just in Bhutan, sustainable management of forests has become imperative. According to the Food and Agriculture Organisation of the United Nations, Sustainable Forest management (SFM) is the “dynamic and evolving concept, which aims to maintain and enhance the economic, social and environmental values of all types of forests, for the benefit of present and future generations.” Similarly, (MacDicken et al., 2015) pronounce the management of the forest’s regenerative capacity in reaping the benefits now without compromising the advantages and choices of future generations as the focal ideology of most SFMs. Throughout this thesis, it will adopt the principles above of SFM. Many criteria and indicators of SFM (e.g., Montreal Process) are developed to measure and report SFM (MacDicken et al., 2015); however, that is not the scope of this thesis.

The forest resource is renewable, and with proper management (sustainable forest management), a flow of wood products can be maintained forever (Churkina et al., 2020; Falk, 2009). MacDicken et al. (2015) found that progress in establishing the conditions for SFM is being achieved globally. For instance, he reported that SFM-related policies and regulations are in place in 97% of the global forest area (MacDicken et al., 2015). In addition, over the last decade, the number of countries with national forest inventories has increased from 48 to 112 (MacDicken et al., 2015). As for Bhutan, nearly thirty years after the Pre-Investment Survey (PIS) carried out from 1974-81, the National Forest Inventory (NFI) was launched with a preparatory phase in 2009 and actual fieldwork carried out between July 2012 - December 2015 (Department of Forests and Park Services, 2016). Such forest inventories establish a foundational setting to enable science-based forest management to achieve improved measurement and monitoring. The state of the enabling environment for SFM and progress made at the operational level demonstrates a commitment to sustainable forest management by governments, industry and communities (MacDicken et al., 2015).

Although using forest resources for the unlimited demand of humankind may seem impractical, which may ultimately lead to the exhaustion of natural resources, there are proven benefits with SFM balancing production and protection. Increased demand for timber in construction would have to be supported by a strong legal and political commitment to sustainable forest management, robust forest certification schemes, empowerment of people living in forests, efforts to curb illegal logging and exploring bamboo and other plant fibres as a replacement for timber in tropical and subtropical regions (Churkina et al., 2020). Managed forests, especially in the southern US, have demonstrated higher growth rates and production of higher quality wood. This helps reduce harvest pressures on the natural forests, providing better opportunities for their sustainable management (Siry et al., 2005). Shorter rotation harvests can sequester total carbon than more extended rotation harvests (Falk, 2009). Wood obtained through sustainable forestry practices in green building applications promotes a healthy environment and a strong economy (Ritter et al., 2011).

Bhutan has a great forest cover of 71% (Department of Forests and Park Services, 2021) and its constitution mandates a minimum coverage of 60% for all times to come. By land cover class, Broad-leaved Forest constitutes 1,927,913 ha (50%) and Coniferous Forest comprises 770,032 ha (20%) (Department of Forests and Park Services, 2016). The forest here would mean land with trees spanning more than 0.5 hectares with trees higher than 5 meters and a canopy cover of more than 10% (Ministry of Agriculture and Forests, 2011). Currently, the forest management regimes in Bhutan include Protected Areas, Community Forests, Forest Management Units & Local Forest Management Areas (Department of Forests and Park Services, 2021). Interestingly, 51% of the forest falls under the protected areas, which comprise parks, biological corridors and protected areas (Department of Forests and Park Services, 2021). According to the Department of Forests and Park Services (DoFPS), there are 21 FMUs in the country (70% coniferous, 30% broadleaf). FMUs in this context can be defined as forests designated under the Forest and Nature Conservation Rules of Bhutan for the scientific management of forests (Ministry of Agriculture and Forests, 2011).

Figure 19 presents the graphical overview of Bhutan’s area under sustainable forest management. Regarding sustainable forest management, 28% of the country’s geographical area (40% of total forest land) is potent, considering a slope less than or equal to 45 degrees. At the same time, it reduces to 23% (33% of total forest area) when considered a slope less than or equal to 35 degrees (Department of Forests and Park Services, 2013). Since the above figures include the protected areas, the actual area excluding the protected areas amounts to about 11.27% of the total geographical location, equivalent to 16% of the entire forest as having potential for sustainable forest management (Department of Forests and Park Services, 2013). However, according to the DoFPS, timber extraction is equivalent to 5% of the total forest area, predominantly (90%) conifer and only 10% broadleaves. In addition, nearly 78% of the timber extraction is from the FMUs in the country. Therefore, the country can sustainably triple (5% to 16%) its current timber extraction.

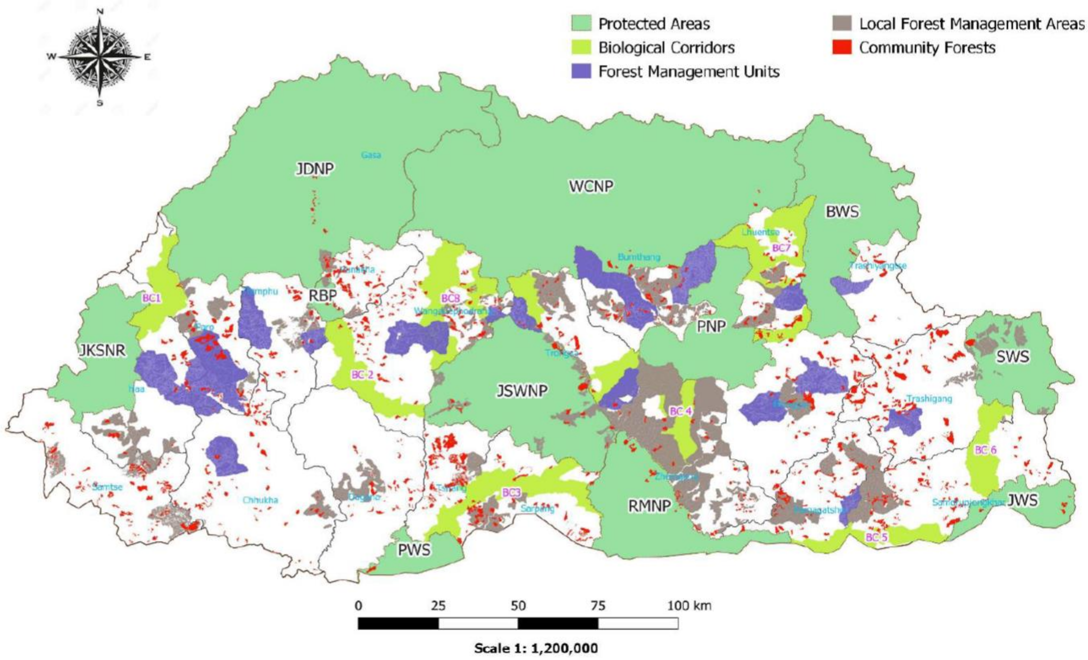


Figure 19: Bhutan’s area under sustainable forest management
Source: (Department of Forests and Park Services, 2021)

Part B: Innovation outcome

This thesis aimed to innovate the housing construction model for sustainable transformation. The previous section on *innovation input* identified the adoption of prefabrication construction using mass timber construction as an innovative housing construction method appropriate for Bhutan. This section (Figure 20) reviews several studies to develop an understanding and application of various project-related outcomes before narrowing the focus on the innovation outcome of sustainable housing construction, which represents the core focus of the thesis and is measured in terms of economic and environmental sustainability. The LCA methodology underpins this thesis to generate/target quantifiable variables for each of the above two domains of sustainability. As a result, the economic parameter focuses on the essential project performance criterion of cost in terms of LCCA, and environmental sustainability focuses on embodied energy and embodied CO_2. These decisions and the state-of-the-art current literature related to these variables are included in the subsequent paragraphs.

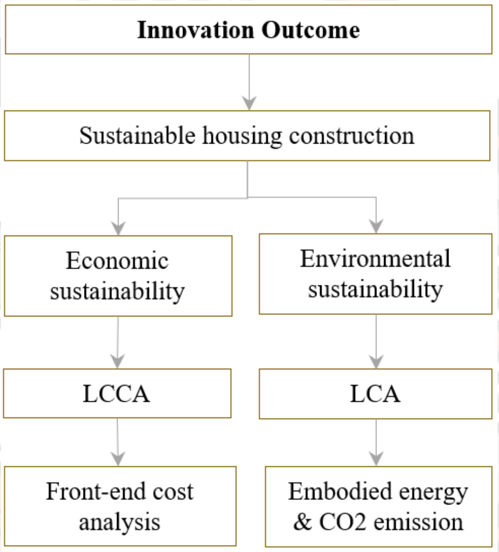


Figure 20: Summary of innovation outcome section

2.7 Review on construction innovation outcomes

Xue et al.(2014) exemplified innovation outcomes can include many attributes depending on the context of the study ranging from industry efficiency to corporate performance and sustainability. Therefore, this work postulates prefabrication as an innovative method to tackle current significant construction inadequacies of cost and environmental sustainability. Nonetheless, this section reviews many studies to develop relevancy and understanding of the above-stated attributes used for different purposes, such as selecting, assessing, and comparing construction methods.

Pasquire et al. (2005) arguably developed one of the earliest frameworks for comprehensively comparing the prefabrication construction method with the on-site construction. They established an elaborate list of 97 indicators under the six variables: cost, time, quality, health and safety, sustainability and site issues. Likewise, Moghayedi et al. (2021) consolidated extensive critical success factors (CSFs) in the implementation of sustainable, innovative and affordable housing (SIAH). These two studies certainly have many commonalities in indicators relevant to the assessment of construction methods and have attempted to describe appropriate comprehensive parameters. Further studies with less rigor and scope than the above two were reviewed. It was observed that Pasquire et al.'s indicators were influential to the subsequent studies, as illustrated by some of them presented hereafter.

In a recent study, for the selection of the best mass housing construction method, Noorzai et al. (2020) developed a selection framework comprising of 15 most critical indicators, which were under the category of cost, time, quality & environment concerns and safety. However, they argued that instead of including extensive criteria, the more efficient approach would be to adopt the Pareto principle to select the top 20% (the top 20% have 80% influence) with higher importance from an extensive list.

Few others validated the findings of Noorzai et al. (2020) from different geographical areas. For instance, from India, Nanyam et al. (2015) developed a multi-criteria evaluation framework that could be used to determine the most appropriate method from a pool of emerging technologies for residential building construction from the perspective of affordability and sustainability. The evaluation framework comprised 30 indicators assorted under six themes in decreasing order of economic viability (41%), sustainability (23%), constructability (12%), the functional requirement (11%), maintenance (9%) and finish quality (3%). Similarly, in the US, in an attempt to develop construction method assessment criteria from the sustainability perspective, Chen et al. (2010) reconfirmed the significance of the indicators, as mentioned earlier. Although the study proposed 33 sustainable performance criteria (SPC), construction time, initial construction cost, constructability, material cost and lead-time criteria were the most influential. For a more specific application, Moghayedi and Windapo (2018) concluded the critical performance criteria for the wall construction method as time (39.08%), cost (34.03%), quality (13.40%), ease of construction (7.25%) and availability of method & skill (6.25%).

All these studies reinforce the significant project objective of cost, time, quality, and sustainability concerns in recent times. But in a scenario such as scarce resources, which is often the case in developing countries like Bhutan, cost supersedes as the primary objective, either as a driver or constraint. The anecdotal evidence suggests that the current housing construction in Bhutan is expensive. In this regard, the study focuses on the cost assessment in constructing residential buildings in Thimphu, Bhutan. The cost variable is complemented by environmental sustainability assessment, which has also received lesser attention in Bhutan's building industry, despite its growing concern worldwide. Bhutan values sustainability deeply as an advocator and executant of the holistic Gross National Happiness development model (J. Y. Thinley, 2007). Thus, it is only authentic to make the shift in the overall construction sector. The prefabrication construction method through mass timber, propagated as an innovation, can be hypothesised to provide cost-competitive and sustainable housing.

In addition, this work intends to fill the knowledge gap regarding mass timber construction. While there has been a significant amount of well-documented research on the characteristics and performance of mass timber products and structural systems, there has been less on the cost implications and affordability factors of mass timber buildings above six stories (Sorathiya, 2019). Moreover, the studies on the construction cost of mass timber buildings are even more limited (Liang et al., 2019). Nevertheless, on the back of the emerging mass timber market in the USA, a series of related research compared the hypothetical 12-story mass timber building (used CLT) is compared with a functionally equivalent code-complaint concrete structure in terms of life-cycle cost analysis and environmental life-cycle assessment (Gu et al., 2020; Liang et al., 2019, 2020, 2021). These studies demonstrated the application of contrasting but essential attributes of cost and environmental concern to compare mass timber buildings with concrete buildings and thus provided an influential guide as the thesis progressed (Table 10).

Table 10: Criteria for the assessment of the construction method

Sl. No	Author	Focus	Variables/Group	Indicators
1	Pasquire et al. (2005)	Identification of the indicators for the comparison of prefabrication and traditional construction	(i) Cost, (ii) Time, (iii) Quality (iv) Health & Safety, (v) Sustainability (vi) Site issues	97 items
2	Noorzai et al. (2020)	Identification of the indicators to select the best mass housing method	(i) Cost, (ii) Time, (iii) Quality (iv) environmental concerns (v) Safety	15 items
3	Nanyam et al. (2015)	Development of multi-criteria evaluation framework which could be used to determine the most the appropriate method from a pool of emerging technologies for residential building construction	Mandatory attributes: i) strength and stability requirement ii) Performance & statutory compliance	5 items
			Preferred or Desired attributes: (i) Functional Requirement (ii) Constructability (iii) Economic Viability (iv) Maintenance (v) Sustainability and (vi) Finish Quality.	30 items
4	Chen et al. (2010)	Development of a sustainable construction method assessment criteria	Economic factors: (i) Long-term cost (ii) Constructability (iii) Quality and (iv) First cost	33 items
			Social factors: (i) Impact on health and community (ii) Architectural impact	
			Environmental factor: (i) Environmental impact	
5	Wallbaum et al (2011)	Ssustainability assessment tool (indicators) for affordable housing construction technologies.	i. Environmental ii. Social iii. Economic	10 items

Sl. No	Author	Focus	Variables/Group	Indicators
6	Atta et al (2021)	Tool to select appropriate/suitable construction technologies for sustainable affordable housing.	i. Environmental ii. Social iii. Economic	12 indicators
7	Moghayedi et al (2021)	CSFs for implementing sustainable innovative and affordable housing.	i. Environmental ii. Social iii. Economic iv. Technical	35 indicators for element cluster 18 indicators for method cluster 13 indicators for technology cluster
8	Moghayedi and Windapo (2018)	Selection of key performance criteria for the wall construction method	i. Time ii. Cost iii. Quality iv. Ease of construction v. Availability of method & skill	

2.8 Sustainable housing construction

This work employs technological construction innovation toward sustainable transformation. The sustainable transformation in this study targets sustainable housing construction comprising economic and environmental benefits. In other words, this work relies on technological aspects such as construction materials and methods to achieve sustainable housing. The following section justifies the selections mentioned, followed by various interpretations of sustainable housing.

Housing construction and delivery can include multi-disciplinary nature, even though this work focuses on innovating only the construction aspects for sustainability. For instance, housing supply side drivers include significant factors such as land acquisition, design, approval and construction, while the demand side drivers include population growth, income and availability of finance for housing (Anacker, 2019; Moghayedi et al., 2021).

The sustainability aspect of housing focuses on the economics and environment. The rapid rise in urban population has challenged governments today to provide affordable housing to their people. However, the supply side often tends to be insufficient or unaffordable, failing to match the increasing demand (Anacker, 2019), thereby leading to housing unaffordability and shortage. The capital city of Thimphu faces similar problems primarily due to construction costs. Besides the anecdotal evidence and acknowledgment, scientific studies to recognise possible causes or potential solutions to the apparent high construction cost are lacking. Therefore, this study aims to provide economical or cost-effective housing solutions.

Likewise, the environmental sustainability of construction, another pertinent concern, has received less attention in the country. The current construction practice in Bhutan depends on an on-site building process employing mostly mineral-based building materials such as bricks, cement and steel. Developing countries like Bhutan lack scientific studies relating to sustainability, although, from anecdotal evidence, they have proven to be problematic. Kumanayake et al. (2018) reiterated the significant gap in the current research on the environmental issues of buildings in developing countries. For these two significant reasons, this study proposes an innovative housing construction method that is cost-cutting and environmentally sustainable to establish a comprehensive sustainability perspective (Gundes, 2016), while the social domain is beyond the scope of this research.

It is an unconventional strategy to address the issue of affordable housing by integrating the philosophy of sustainability (Gan et al., 2017). However, the inclusion of the sustainability concept in affordable housing, particularly in developing nations, has recently gained popularity (Adabre & Chan, 2019; Atta et al., 2021). This shift in thinking, although exacerbating the housing delivery due to current societal demand for the inclusion of sustainability principles, is significant in reducing the environmental impacts (Moghayedi et al., 2021), considering that nearly 40% to 60% of total national energy today is consumed by the building sector (Green et al., 2013).

Several studies have attempted to present critical success factors (CSFs) for attaining sustainable, affordable housing (Adabre & Chan, 2019; Chan & Adabre, 2019; Mulliner & Maliene, 2011; Oyebanji et al., 2017;). These studies present many housing-related parameters conditioned to accomplish the vision of the bottom-line perspective of social, economic and environmental sustainability. For instance, Oyebanji et al. (2017) identified 21 critical factors (CSFs) in achieving sustainable social housing (SSH), some of which are adequate finance provision, efficient planning, appropriateness & environmental friendliness of the construction system, appropriate design and social parameters such as security and social cohesion. He defines SSH as the housing provided by the governments or non-profit organisations through housing programmes aligning with the social, economic, and environmental principles of sustainability.

Balancing housing affordability with sustainability can be challenging and require comprehensive, trans-disciplinary and collaborative efforts to achieve sustainable affordable housing (Salama & Alshuwaikhat, 2006). Nevertheless, the current thesis condenses its area of study to the construction system (material and method) in pursuit of sustainable and cost-effective housing in the context of Bhutan. According to Moghayedi et al. (2021), sustainable housing implies that the buildings are constructed using sustainable methods and materials and promote green practices that enhance a more sustainable lifestyle. Likewise, sustainable housing in this study would refer to using sustainable building material and approach that is environmentally friendly, has low embodied energy, and reduces construction costs.

Moghayedi et al. (2021) include an additional concept of innovative housing to the SSH, reasoning that affordable housing in the contemporary world should aspire to more than just creating habitable spaces by offering solutions that incorporate sustainable and innovative features. Although adopting innovative technologies and practices in sustainable affordable housing is nascent, its contribution to realising the same is undeniable (Moghayedi et al., 2021). In this regard, Moghayedi et al. (2021) define sustainable innovative and affordable housing (SIAH) as the incorporation of innovative methods, materials, technologies and practices in the development of sustainable and affordable housing to enhance and optimise the potential of these houses to not only provide for the economic, social and environmental needs of low- and medium-income earners, but also to satisfy the technical aspects, and minimise the negative impact on the environment without compromising the affordability of houses across their lifecycle.

2.8.1 Environmental sustainability

Braganca et al. (2010) believe building embracing every dimension of sustainability, including environmental, economic, social, and cultural, can be considered sustainable. Sustainability assessment in the form of Life cycle assessment (LCA) gained ground in the early 2000s with the remarkable growth of scientific studies and methodology standardization (Guinée et al., 2011). Today, the construction sector boosts various sustainability assessment approaches commonly adopted for environmental certification (eg: BREEAM in the U.K. and LEED in the U.S.). Life-cycle assessment (LCA) tools such as Eco-Quantum (Netherlands), EcoEffect (Sweden), ENVEST (U.K.), BEES (U.S.), ATHENA (Canada) and LCA House (Finland) are available that are specially developed to address the building as a whole (Bragança et al., 2010). Sustainability assessments aim to gather and report information for decision-making during different phases of building construction, design, and use (Bragança et al., 2010; Sala et al., 2015). The subsequent section will discuss the broad background of the life cycle assessment framework.

2.1.1.1 Life cycle assessment

According to Chau et al. (2015), Life Cycle Assessment (LCA), Life Cycle Energy Assessment (LCEA), and Life Cycle Carbon Emissions Assessment (LCCO_2A) constitute three types of assessment studies—widely employed to evaluate the environmental impacts of buildings. The LCA consists of four distinct analytical steps (Figure 21) based on the international standards of series ISO 14040: Defining the goal and scope, creating the inventory known as life cycle inventory (LCI), assessing the impact under *life-cycle impact assessment (LCIA)* and finally interpreting the results (Mateus et al., 2013; Cabeza, 2017; International Organisation for Standardisation, 2006; Ortiz et al., 2009).

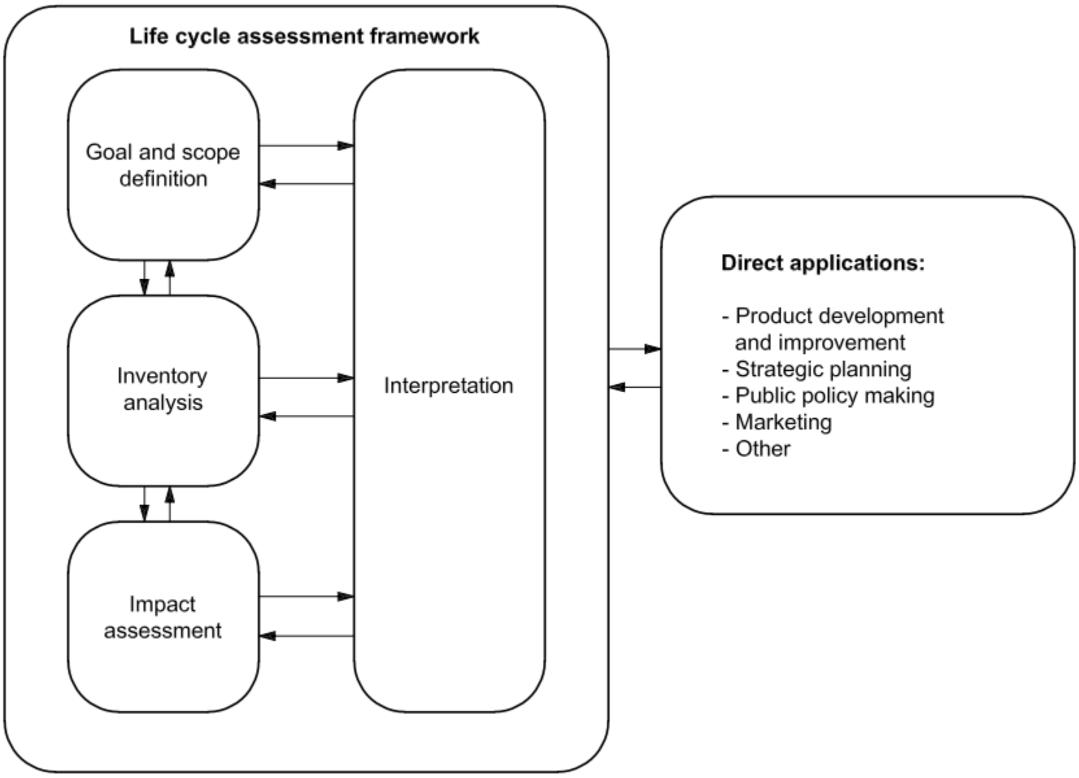


Figure 21: Stages of Life cycle analysis
Source: (International Organisation for Standardisation, 2006)

LCA methodology evaluates an environmental load of processes and products (goods and services) during their life cycle from the cradle to the grave (Figure 22), which comprise raw material extraction, manufacturing, use, and end-of-life (EOL) (Cabeza et al., 2014; Mateus et al., 2013; Nie & Zuo, 2003; Ortiz et al., 2009). LCIA integrates the LCI data of each building stage (modules A1-A5) to quantify the total life-cycle environmental impacts (Liang et al., 2020) in various impact categories of climate change, ozone depletion, ecotoxicity, human toxicity, photochemical ozone formation, acidification, eutrophication, resource depletion, and land use. (Cabeza et al., 2014). The environmental impacts are generally modeled in location-relevant software. For instance, Liang et al. (2020) & Liang et al. (2021) used SimaPro data sources to compare the life-cycle impact of mass timber buildings with the concrete structure in the USA.

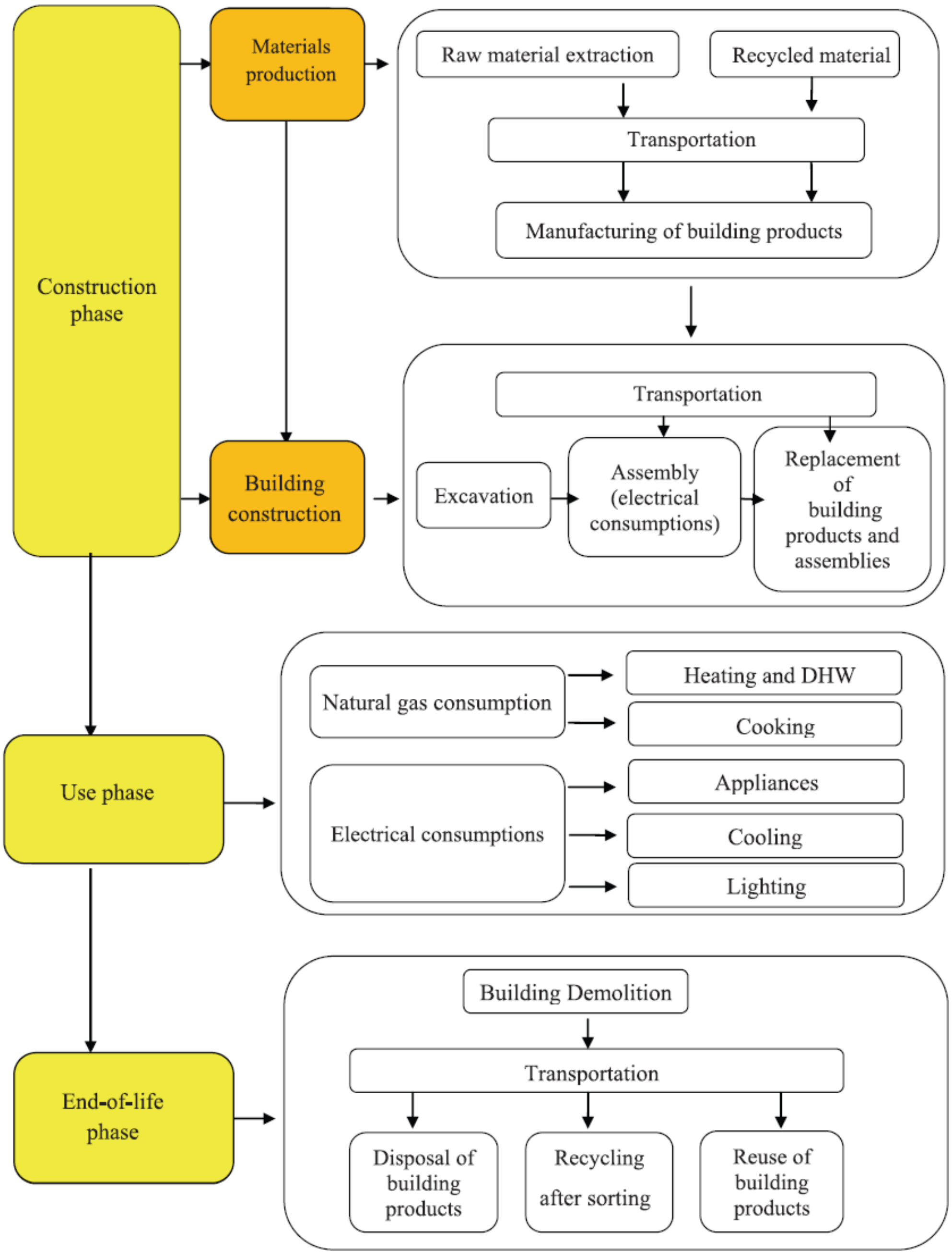


Figure 22: Life cycle system boundaries
Source: (Asdrubali et al., 2013)

Such sustainability assessment primarily intends to gather and report information for decision-making during various stages of a building—construction, design, and use (Bragança et al., 2010; Sala et al., 2015). Ortiz et al. (2009) opine that applying LCA is essential for building and construction sustainability and improvement. LCA can target various scales of analysis ranging from smaller systems like building materials, building products and construction elements to more extensive systems comprising independent zone, buildings, and neighbourhood levels (Bragança et al., 2010). For instance, Koroneos and Dompros (2007) demonstrated the application of integrated LCA in the building material category of brick production in Greece.

But implementing environmental LCA in buildings and construction is a complicated and onerous task (Bragança et al., 2010; Sala et al., 2015). Moreover, data for developing and emerging countries are still lacking (including Bhutan), leading to the use of European and American databases, which may not lead to correct decision-making (Ortiz et al., 2009). LCA's challenges include site-specific limitations, model complexity, and scenario uncertainty, such as operational energy consumption and EoL scenario (Buyle et al., 2013). Therefore, the following section explores the alternatives of embodied impacts of energy and CO_2 emissions as an environmental assessment tool.

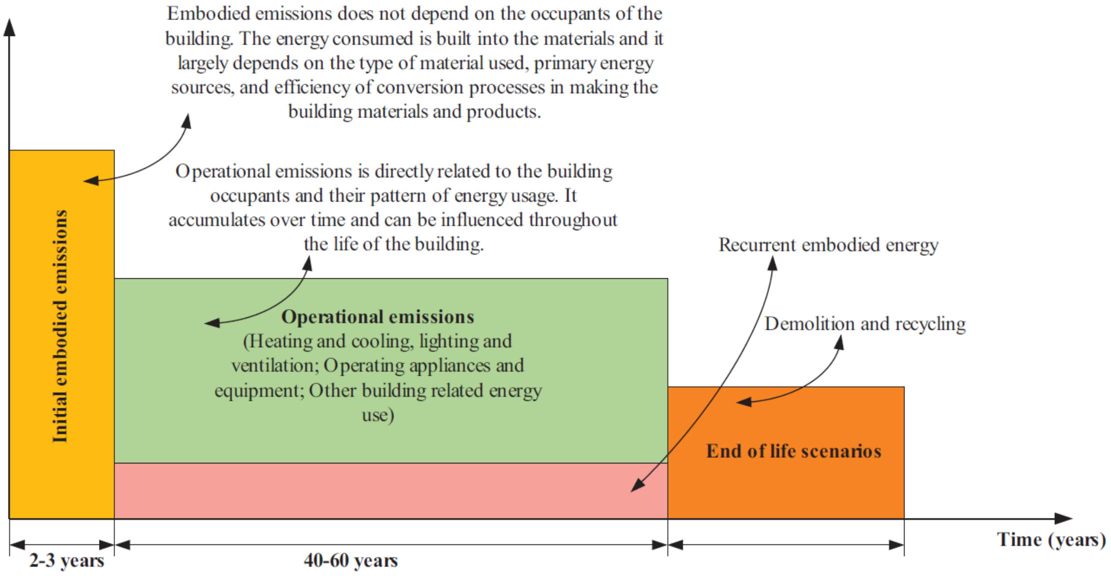
2.1.1.2 Embodied energy and embodied CO2

Within the LCA studies, this research focused on the sustainability metric of embodied energy (EE) under LCEA and embodied CO_2 (ECO_2) under $LCCO_2A$; to achieve appropriate *research scope* and due to their *significance* as discussed hereafter.

Life cycle energy analysis of buildings includes both embodied energy and operating energy (Buyle et al., 2013) (Figure 23). Operational emissions occur during the use stage, while embodied emissions range from all direct and indirect processes related to the construction of the building, its maintenance and end of life (Ibn-Mohammed et al., 2013). Buyle et al. (2013) concluded in their review that the dominance of the use phase is mainly due to energy consumption relating to heating and cooling, ranging from 60-90% of the total environmental burdens, particularly concerning GWP.

Implementing comprehensive LCA in Bhutan is currently limited mainly due to a lack of appropriate data and tools. Therefore, this investigation simplified by adopting only the attainable sustainability metric of EE under LCEA and ECO_2 emission under $LCCO_2A$ in a cradle-to-site (A1-A5) boundary, comprised of material production and construction stage (Figure 24). The literature contains several studies focusing similarly on EE and CO_2 (Reddy & Jagadish, 2003; Shams et al., 2011;

Syngros et al., 2017). ECO_2 is the sum of emissions in the production and transportation stage (Chau et al., 2015; Chen et al., 2022), while EE represents the energy used in the mining, production, assembly and transportation of a specific product (Varun et al., 2012).



Embodied emissions does not depend on the occupants of the building. The energy consumed is built into the materials and it largely depends on the type of material used, primary energy sources, and efficiency of conversion processes in making the building materials and products.

Operational emissions is directly related to the building occupants and their pattern of energy usage. It accumulates over time and can be influenced throughout the life of the building.

Figure 23: Life cycle energy components of a building
source: (Ibn-Mohammed et al., 2013)

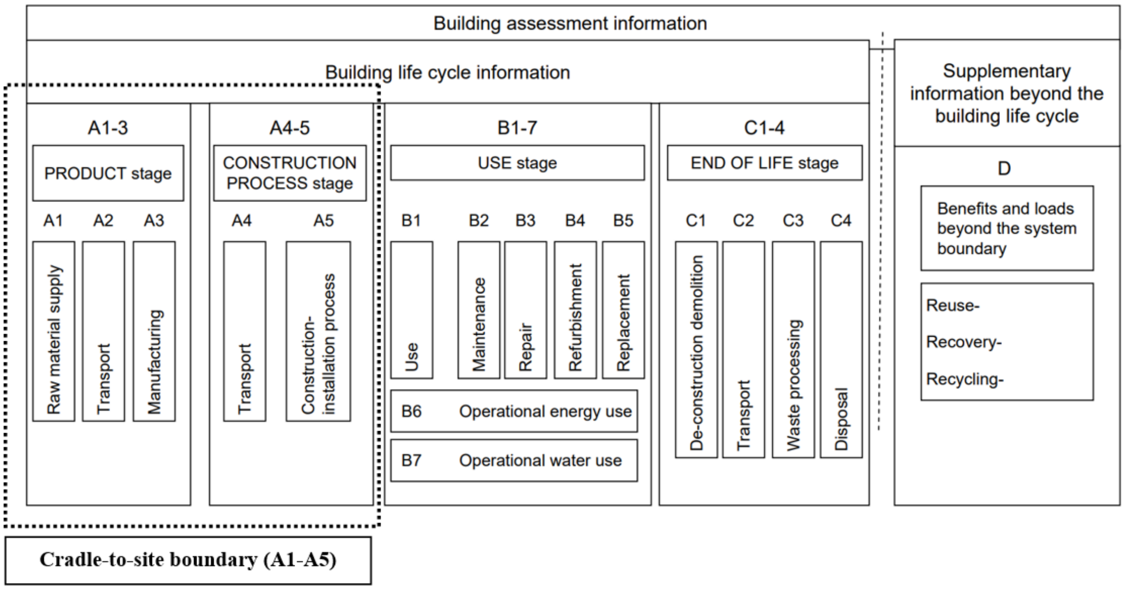


Figure 24: Building Life cycle stage.
Adapted from (Moncaster & Song, 2012)

Secondly, this study targeted EE and ECO_2 indicators due to their considerable environmental impacts; the building industry contributes to about 40% of global energy intake and about one-third of the overall carbon dioxide emission (Baek et al., 2013). CO_2 is a prominent GHG, amounting to roughly 80% of global warming (Kumanayake et al., 2018). The production of building materials requires substantial energy and is similarly associated with high CO_2 emissions. Besides, their subsequent transportation and building construction also contribute to the overall embodied estimation of energy and CO_2 emission, although to a comparatively lesser degree. Tirth et al. (2019) found that the GHG emission from transportation and construction equipment was 12% and 10%, respectively.

2.1.1.3 Related literature on embodied energy and CO_2 emissions

The extant literature suggests that common materials such as steel, bricks and cement constitute a considerable fraction of the aggregate EE and ECO_2. Every ton of cement and steel produces approximately 1 ton and 1.85 tons of CO_2, respectively (Abed et al., 2022). The EE and carbon of cement, steel and brick contribute to no less than 70% of all EE and carbon of the entire building materials (Chen et al., 2022; Kumanayake et al., 2018). In the Indian context, Debnath et al. (1995) found that around 95% of the EE is associated with the cement, steel, bricks and stone in the four-story residential building, leaving only 5% to the other materials. These materials represent the most prominent bulk application in the Indian construction industry (Reddy & Jagadish, 2003). Likewise, they accounted for about 66% of the aggregate emissions (Tirth et al., 2019) in a cradle-to-service boundary condition. Yan et al. (2010) concluded that steel and concrete contribute 94-95% of the embodied GHG emissions from production till the construction stage. These studies suggest that common building materials such as steel, cement and clay bricks constitute a significant proportion of conventional buildings and are associated with high embodied energy and CO_2 emissions.

2.8.2 Economic sustainability

The Life Cycle Cost Analysis (LCCA) is used to quantify the economic association over a product's life cycle, much like LCA focuses on the computation of environmental effects. LCCA method evaluates the cost-effectiveness of building construction from its initial cost, which incorporates permit and design cost, material and construction cost—use stage cost, which includes utility, maintenance, and replacement—and lastly, its end-of-life of building demolition costs with residual and salvage value (Gu et al., 2020 & Islam et al., 2015). Like LCA, LCCA can be tailored to the whole building or the component level; the Majority of the existing studies fall into the latter (Gundes, 2016; Petrović et al., 2021). It also encompasses discounting future expenses to the present values of analysis to account for the time value of money (Gu et al., 2020 & Islam et al., 2015). A discounted accounting approach is an effective tool for determining the cost-effectiveness of different building designs and exploring trade-offs between initial costs and long-term cost savings (Liang et al., 2021).

2.1.1.4 Life cycle cost analysis (LCCA)

The thesis also employed cradle-to-site (A1-A5) boundary conditions for the LCCA. Generally, LCCA estimates all relevant costs, including current construction costs—and future expenses arising from probable maintenance, operation and disposal scenarios— discounted and validated with a sensitivity analysis (Islam et al., 2015). But the future scenarios of operational, maintenance and disposal come with uncertainties. Without appropriate databases and tools in emerging economies like Bhutan, the scope had to be limited to include only the front-end costs of the building models. It is unsurprising in the review of Islam et al.(2015) to realise that different case studies on LCCA were from Europe, North America and Australia. The current literature lacks studies on LCCA from developing nations, possibly due to challenges faced by the lack of an appropriate database. Although the LCCA is limited to initial boundary conditions, its implications concerning future conditions are analysed in the discussion section.

In addition, the building’s construction phase accounts for the most significant fraction of the overall cost. Islam et al. (2015) found that the construction phase has the highest contribution to LCCA (58 to 88%), followed by operation (11 to 34%), maintenance (2 to 20%), then disposal (0 to 2%). Moreover, often, people are motivated by immediate project savings than the future. For these reasons, the LCCA focused on the building models' front-end cost, which will be used later in the thesis to compare alternative design strategies (Gundes, 2016).

2.1.1.5 Related literature on LCCA and mass timber construction

Compared to the significant research on the characteristics and performance of mass timber products and structural systems, the research on the cost-effectiveness of mass timber buildings is limited and is hotly debated (Gu et al., 2020). Moreover, what's available is mainly based on studies using hypothetical structures. For instance, several papers (Gu et al., 2020; Liang et al., 2019, 2021) compared the cost of a hypothetical 12-storey mass timber building (CLT and Glulam) with the functionally equivalent concrete building and are presented below.

The mass timber building design is estimated to have 26 percent higher front-end construction (A1-A5) costs than its concrete alternative (Gu et al., 2020; Liang et al., 2021), $2281 per m2 floor area (Liang et al., 2021). However, because of its much higher end-of-life salvage value than the concrete building, the TLCC calculated for a 60-year study period was expensive by about 9.6% (Liang et al., 2021). As a result, construction cost was the most significant contributor to the TLCC, accounting for 57% and 50% of mass timber and concrete buildings, respectively (Liang et al., 2021).

Elsewhere, the comprehensive construction cost comparison of a mass timber building with cross-laminated timber (CLT) with concrete structure suggested that the latter is higher than 6.43% than the former (Ahmed & Arocho, 2021). This study was based on a residential mass timber building in Canada with the modeled concrete version. Moreover, from previous studies, the authors found that timber construction costs are generally 2-6% higher than traditional concrete and steel construction. A similar trend ranging from -6% to +6% was observed in the literature review of cost-related mass timber construction, where '+' indicated cost savings of mass timber compared to concrete construction and '-' indicated cost escalation (Sorathiya, 2019). Ahmed & Arocho (2021) and Liang et al. (2021) concluded that the cost of engineered wood (CLT and Glulam in their case) as the main factor for cost escalation—along with the extensive use of cranes in the installation process and due to operational cost of human resources specialists required in mass timber construction (Ahmed & Arocho, 2021).

However, these LCCA estimates come with certain limitations. To offer a conclusive analysis, it is necessary to handle uncertainties, inadequate data, and risk factors inherent in system inputs (Gu et al., 2020). Usually, sensitivity analysis is widely adopted (Gu et al., 2020; Liang et al., 2021; Liang et al., 2019) to comprehend the effects of modifying independent variables on the outcomes under a specific set of assumptions. For instance, Gu et al. (2020) evaluated the results by altering the testing period from 20 to 75 years and the discount rate from 0 to 10%. In addition, uncertainty analysis is further carried out to account for all the possible outcomes. For instance, Figure 25 illustrates the life cycle cost difference between mass timber and concrete equivalent considering different EoL scenarios: EoL reuse percentage ranging from 25% to 100% against resale price also ranging from 25% to 100%. Liang et al. (2021) demonstrated that the building's service life span and a design that allowed for the recycling of the mass timber could significantly lower the TLCC of mass timber buildings.

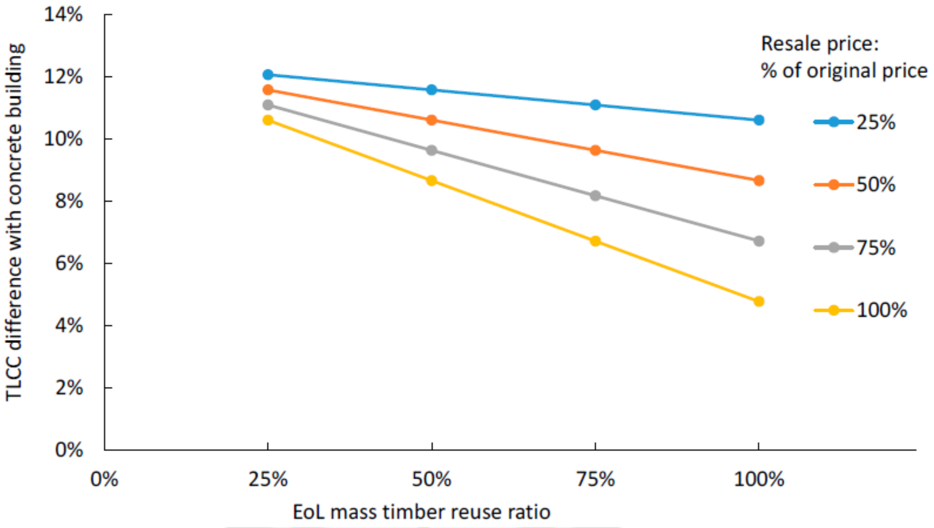


Figure 25: Total life cycle cost difference between mass timber and concrete equivalent at different mass timber End-of-life (EoL) scenarios.
source: (Liang et al., 2021)

Part C: Innovation context

This section analyses the innovation context of Bhutan's current housing construction based on three selected typical residential buildings from the capital, Thimphu. This review first narrates the historical background of the housing development in the country, followed by insights on the current scenarios and characteristics of the housing construction, comprising of planning, material inventory, material and built-up cost analysis, and import issues of construction materials (Figure 26).

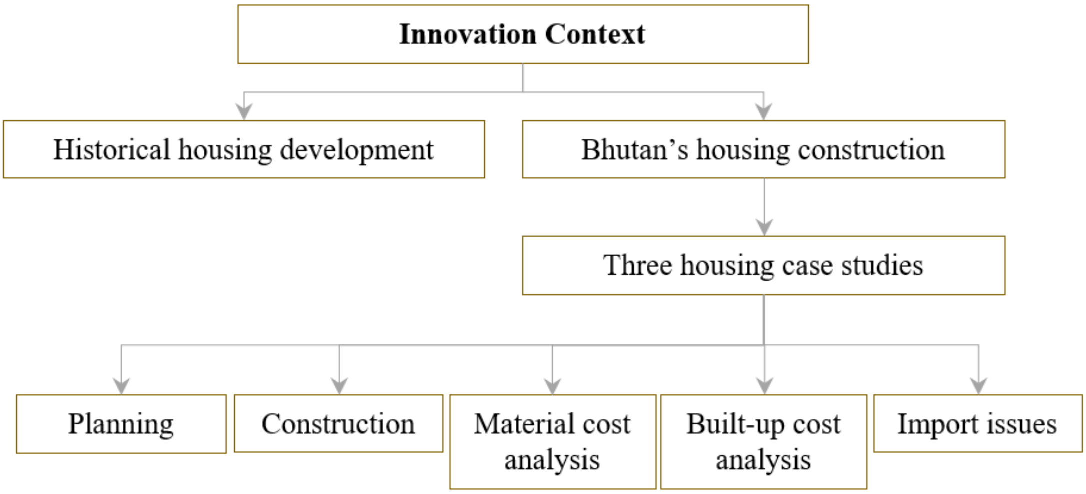


Figure 26: Summary of innovation context section.

2.9 Historical housing development in Bhutan

Bhutan remained a self-sustaining rural society in isolation from the rest of the world until the 1960s. The planned development and modernisation commenced in 1961 with the launching of the 1st Five-Year Plan (1961-1966). The 1st Five-Year Plan (FYP) witnessed the first-ever road construction which connected the Phuentsholing in the south to the capital, Thimphu (Royal Government of Bhutan [RGoB], 1961). Likewise, the initial development plans of the 1st FYP and the subsequent FYP of 2nd (1966-1971), 3rd (1971-1976), and 4th (1976-1981) targeted the creation of basic infrastructural facilities such as roads, power, communication system, transport, and suitable administrative set-up (RGoB, 1966; RGoB, 1972; RGoB, 1977). During this period, their respective departments or ministries constructed housing for government employees. In the 5th FYP (1981-1986), owing to the disparities and wasteful use of land resources, the trend was replaced by the pool housing system to reduce the cost of construction and maximise the utilisation of urban land. It was during this time that the Central Town Planning Committee (CTPC) was reconstituted and renamed as National Urban Development Corporation (NUDC) in 1984 to foresee the planning and execution of all urban development-related activities (RGoB, 1981; RGoB, 1987). NUDC became responsible for ensuring housing for civil servants and maintaining all government housing in the country (MoWHS, 2015).

With modernisation came an enormous increase in housing construction in rural and urban areas. The 6th FYP (1987-1992) reported that between 1980 and 1986, the government constructed approximately 5000 houses. However, most of these houses were not cost-effective and were built without design, quality, or structure improvement. For example, the housing lacked vital aspects such as sanitation and insulation for comfort and an improved standard of living (RGoB, 1987). To improve housing, mainly rural housing, the NUDC constructed 18 prototype houses (RGoB, 1987), demonstrating new construction methods, including planning, insulating envelopes, using local materials and embracing traditional architecture (MoWHS, 2015). The government introduced incentives and a subsidy system for those who adopted the prototype specifications. These houses were built adopting traditional Bhutanese architecture and using local construction techniques like rammed mud walls, adobe, and improved materials like mud blocks with cement (MoWHS, 2015).

As of 1997, there were 566 and 649 Royal Government housing units in Thimphu and Phuentsholing, respectively. Private supply accounted for 3,371 and 1,174 housing units in Thimphu and Phuentsholing, respectively (RGoB, 2002). By the late 1990s, the urban population was reportedly 15%. For the first time, the 8th FYP (1997-2002) recognised the impacts of rapid urbanisation. As a result, housing received attention like never before, as evidenced by one of the objectives of the 8th FYP (RGoB, 1997); "provision of affordable and climatically suitable housing for all." With the quickening pace of development in the last 15-20 years, Bhutan was already experiencing signs of urban growth pressures (ADB, 2002). To establish new modalities for the promotion of affordable housing, the government undertook a comprehensive review of the shelter sector, including supply, demand, affordability, and financing facilities available at that time, with technical support from the Asian Development Bank (ADB) (ADB, 2002; RGoB, 1997). In this regard, in 2001, the government sanctioned the construction of about 600 new apartments to mitigate the housing shortage in two of Bhutan's most significant towns, Thimphu and Phuentsholing (MoWHS, 2015). These housing structures represent G+2+attic space constructed in RCC framing with infill brick walls and corrugated sheet-sloping roofing. In 2002, the government formulated the national housing policy to address the increasing lack of shelter, especially for lower and middle-income groups.

Emphasis on the urban infrastructure, especially housing, continued in the 9th FYP (2002-2007). National Housing Development Corporation Limited (NHDCL) was established in 2003 with the mandate to formulate and implement housing programs in the country. The easy accessibility of conventional building materials (steel, cement, bricks) and labour across the border led to the construction of multi-storied buildings (Department of Urban Development and Housing [DUDH], 2002), which altered and modified the traditional architecture of Bhutan (RGoB, 2002). In response, in 2002, "Traditional Architecture Guidelines" was published to streamline the construction of various buildings with appropriate architectural styles. The guideline emphasised the organisation of traditional features, their modes of construction, thopthang (entitlements), and minimum requirement of traditional features depending on the type of building (DUDH, 2002)

With the rising urban population, ensuring affordable housing became one of the critical issues of urban Bhutan. However, it became increasingly difficult for the government to replenish the growing housing stock due to competing needs and considerable resource constraints. In this regard, the 10th FYP (2008-2013) recognised private entities as a dominant housing supplier and the government as an enabler of this approach. As a result, the government proposed plans to facilitate housing development by providing land on lease, promoting public-private partnerships, and introducing various innovative financial schemes (RGoB, 2008). The subsequent projects of the 11th FYP (2013-2018) and 12th FYP (2018-2023) further acknowledged the importance and challenges of providing affordable housing. In 2016, following His Majesty, the King's Royal Command, NHDCL implemented a Special Housing Project in Phuntsholing by constructing 62 buildings (RCC framing with brick infills), with 506 units, for the displaced across the border due to housing shortages. The project, which started in the mid of 2016, was completed in early 2019, and its subsidised rents range from Nu 4,500 to Nu 6,000 (Thinley & Chimi, 2020). Lastly, the revision of the National Housing Policy of 2002 in 2019, which identifies affordability and homeownership as key goals (RGoB, 2013; RGoB, 2018), has been the latest intervention toward solving the bigger picture of housing issues.

2.10 Current housing construction practices

In Bhutan, the government (Figure 27), to a lesser extent, and individual private entities predominantly (Figure 28) provide housing. In the capital, around 60% of the household pay rent; of this, 85% of them live in housing provided by private individuals and leaving only around 15% for government and public corporations (NSB, 2017). While the government prioritises affordable housing, especially for the lower section of the population, profit maximisation attracts private investments in housing construction.

NHDCL and National Pension and Provident Fund (NPPF) are notable institutions working towards affordable housing (Thinley & Chimi, 2020). The NHDCL is concerned with its mandate to manage residential housing for civil servants, whereas NPPF approaches housing development as its investment avenue (RAA, 2019). As of 2018, NPPF housing accommodated only 3.47% of its 20,890 (Thinley & Chimi, 2020).

The conventional on-site method predominates housing construction in Bhutan. As a result, every house builder experiences a fragmented approach to procuring construction materials, hiring/buying equipment and equipment, constructing temporary scaffolding and securing various personnel/contractors/consultants for their project. More often than not, such a sporadic and unconsolidated process leads to inefficient project management, resulting in higher construction costs.

Figure 27: Housing provided by NHDCL and NPPF (public entities)

Figure 28: Housing provided by private landlords (private entities)

The 11th FYP acknowledged that the predominantly conventional construction sector was incurring high construction costs, delivering poor quality work, and requiring high maintenance costs. Additionally, in its annual report (2017-2018), Construction Development Board [CDB] (2018) reported that one of the significant issues faced by the construction industry is time overrun; on average, from 2014 to 2018, the construction delay stood at 35.5% and cost overrun by 53.3%.

Several entities reverberated the inadequacies of the current construction model. Firstly, RAA (2019) revealed that the current construction practice impedes housing development. The current construction practice is a result of its long association with India since Bhutan opened its border to the outside world. Most of these conventional construction materials, including labour, are imported, resulting in a high construction cost. Since housing development is a derivative of the construction industry, the RAA (2019) recommended the mechanisation of construction methods and domestic production of construction materials as two important schemes to catalyse the construction industry in general. Secondly, the Economic Development Policy 2016 broadly outlined that the Royal Government shall adopt Industrialised Building Systems and encourage the manufacture of prefabricated and standardised components. Lastly, the Draft National Construction Industry Policy 2018 recognised the need to improve the quality of the construction industry: Promote local manufacturing of construction materials by providing incentives. The abovementioned concerns and suggestions reflect the shortcomings of the current construction model. The subsequent section investigates the housing construction method employing multiple case studies of typical housing structures.

2.10.1 Multiple case studies: Housing construction in Bhutan

These case studies (Figure 29, Figure 30 & Figure 31) represent the archetype housing construction currently flourishing in Thimphu. The assessments on planning approach, construction material and method, and material and built-up rate analysis establish the apparent model of housing construction. Although contemporary architectural typologies include all sorts of building uses, most of these structures conform to 4 to 6-storied repetitive box-like buildings of RCC framed structures with infill walls adorned with corrugated sloping roofs. Such residential structures, in particular, are becoming increasingly omnipresent in Thimphu and are currently shaping the urban landscape of Bhutan, much like the traditional rammed earth dwellings that once populated the historical rural landscape of Bhutan. A survey revealed a significant proportion of nearly 60% of the urban structures have walls made of cement/RCC wall, bricks or cement blocks (National Statistics Bureau [NSB], 2018). Therefore, the selected case studies share many similarities between themselves and other residential buildings and, arguably, with additional building typologies. For this reason, the findings from this study can be generalised (Groat & Wang, 2013; Yin, 2009) to the building industry in general.

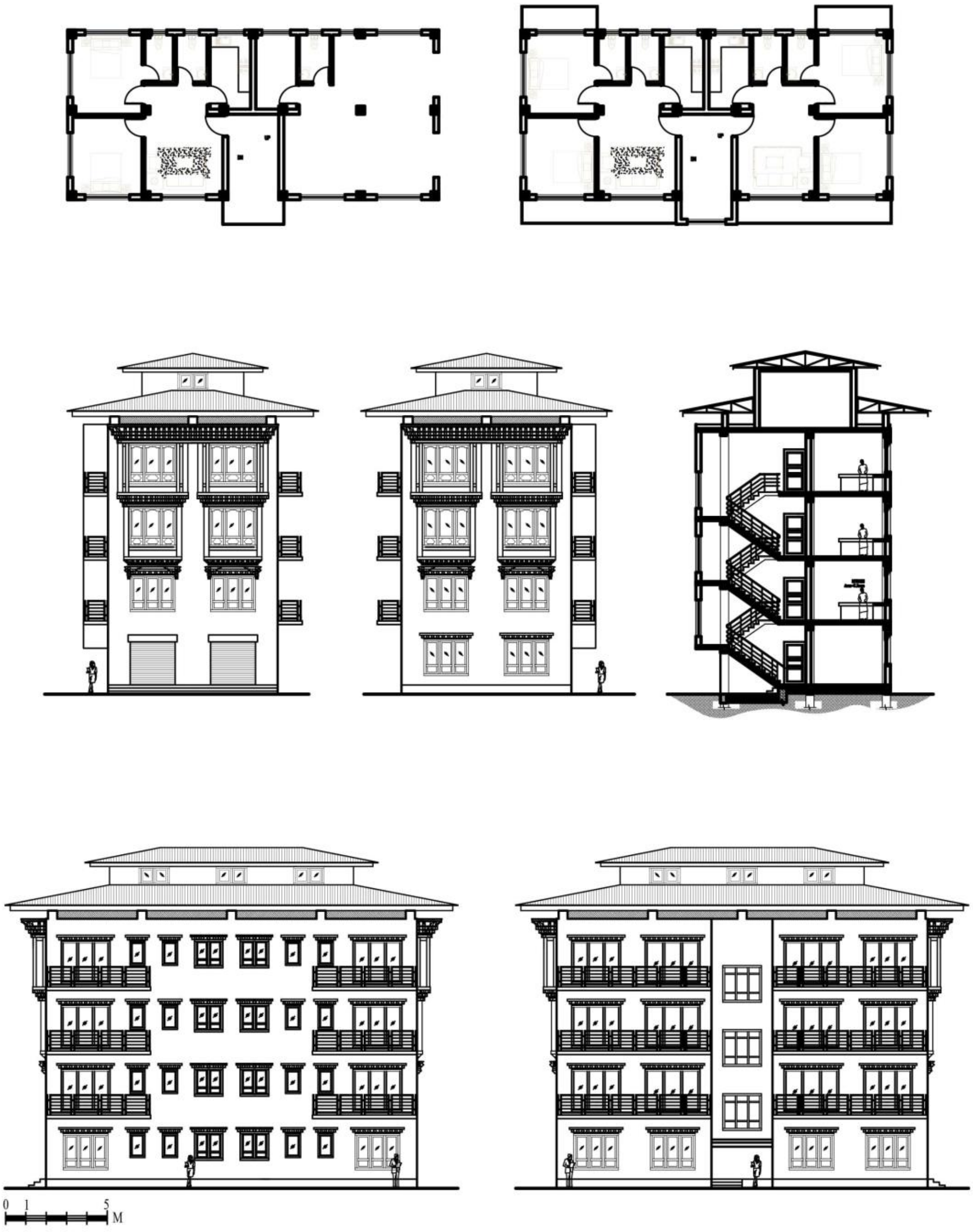


Figure 29: Building A.
TOP LEFT: Ground floor plan, TOP RIGHT: Typical floor plan (first floor & above), MIDDLE LEFT & CENTER: Side elevations, MIDDLE RIGHT: Section, BOTTOM LEFT & RIGHT: Longitudinal elevations

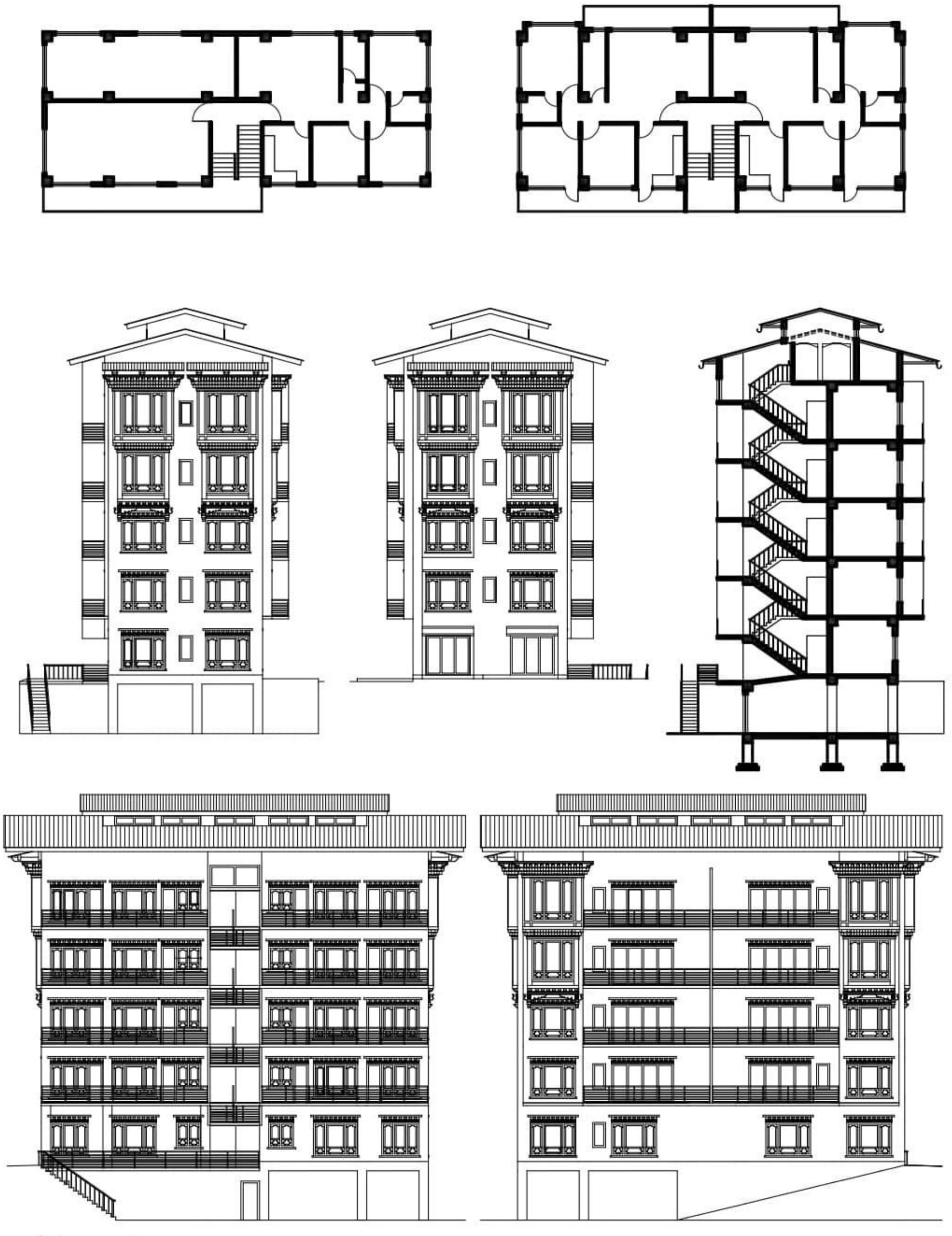


Figure 30: Building B.
TOP CENTER: Typical floor plan (Ground floor & above), MIDDLE LEFT & CENTER: Side elevations, MIDDLE RIGHT: Section, BOTTOM LEFT & RIGHT: Longitudinal elevations

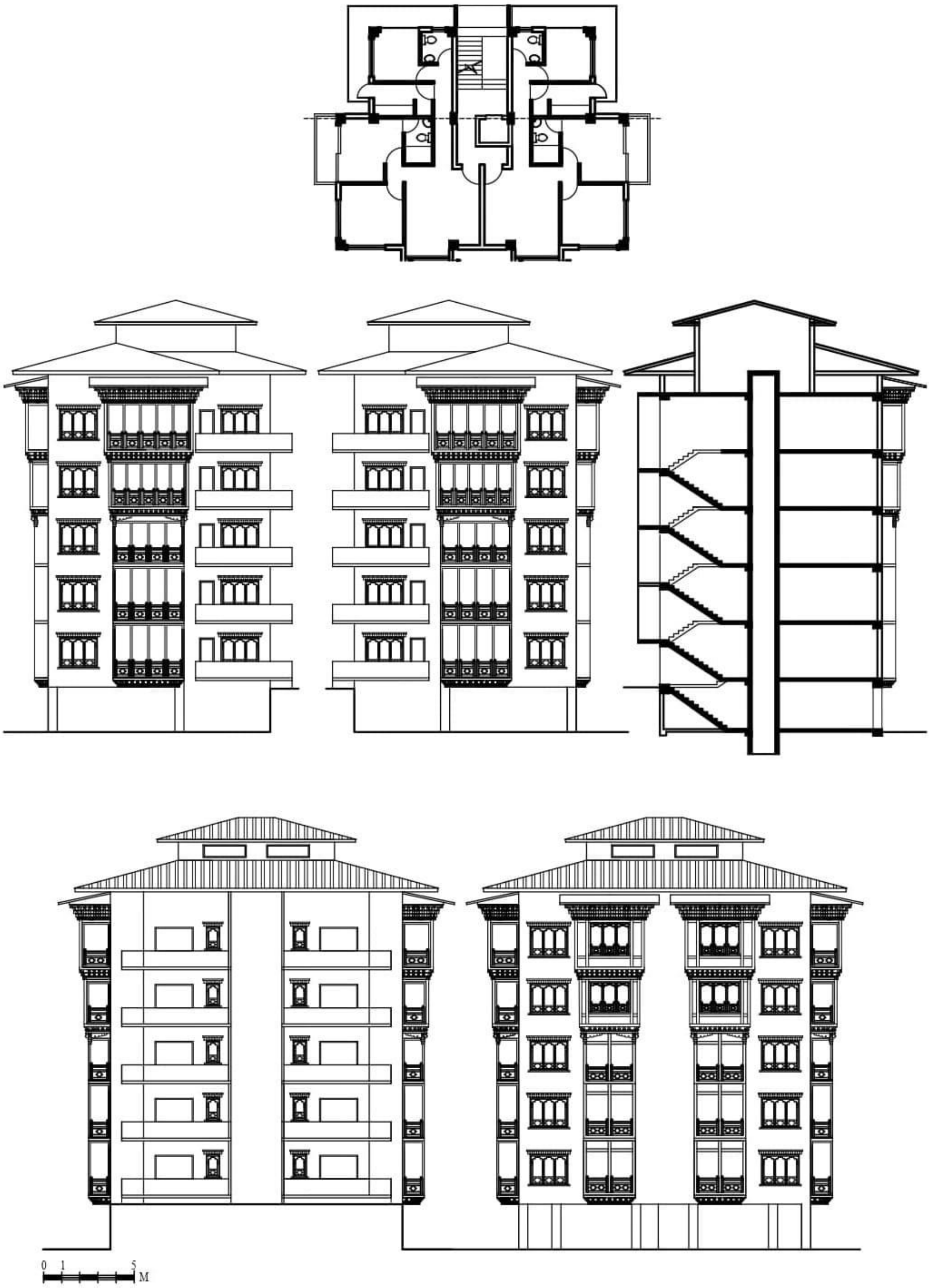


Figure 31: Building C.
TOP LEFT: Ground floor plan, TOP RIGHT: Typical floor plan (first floor & above), MIDDLE LEFT & CENTER: Side elevations, MIDDLE RIGHT: Section, BOTTOM LEFT & RIGHT: Longitudinal elevations

2.10.1.1 Planning

The planning of these buildings follows a rectilinear scheme which attempts to generate maximum usable built space by negotiating the site constraints with the relevant regulations, such as the Bhutan Buildings Rules, 2018 (BBR) and Development Control Regulation, 2016 (DCR) of Thimphu. For instance, the height of the building, ground coverage, buildings setbacks and type of allowable building type construction is prescribed by the DCR 2016 and BBR 2018. Similarly, the building façade has to align with the traditional architectural entitlements and proportions as laid out in the Bhutanese Architecture Guidelines, 2014 (BAG). The BAG is an advisory and introductory guideline that prescribes the components and proportions of the beautiful expression of Bhutanese architecture as per the building type. Table 11 compares the characteristics of case studies, while Figure 32 compares the typical planning layout.

Most landowners choose to venture into mixed-use buildings, predominantly rental units. Typically, some portion of the ground floor contains commercial spaces such as shops and go-downs (Figure 32), while the upper floors are dedicated to rental units of preferably 2BHK and 3BHK units. The monthly rents of these units range. 8000–10000 Nu (Ngultrum) for 2BHK and 11000-13000 Nu for 3BHK. The Tenancy act of 2002 regulates the modest rise once every two years, but the reality is that the rents have been roaring over recent years.

Table 11: Characteristics of the residential buildings in Bhutan

Characteristics	Building A	Building C	Building B
Client	Private landlord		
Designer	Architect		
Plinth Area	153sq.m	180sq.m	172sq.m
No. of floors	G+3	B+G+4	B+G+4
Building structure	RCC framing with Brick wall infill		
Type & Use	7/8 units: Residential (Rental) 1/8 unit: Commercial	B: Parking 10/10 units: Residential (Rental)	B: Parking, storage 9/10 units: Residential (Rental) 1/10 unit: Commercial
Dwelling unit	2BHK	3BHK	3BHK
Material	RCC, burnt bricks, Autoclave aerated blocks (AAC), Tiles, timber, Corrugated roofing sheets		
Wall (brick)	External: 250mm; Internal: 125mm		

Characteristics	Building A	Building C	Building B
thickness			
RCC column size	400mmX400mm	500mmX500mm 350mmX 600mm	500mmX500mm
Column spacing (c/c)	2.9m-5.3m	1.8m-6.9m	3.15m-5.2m
RCC beam size	Main: 300mmX450mm	Main:350mmX500mm Main:350mmX350mm	Main:500mmX500mm
Construction time	Approx.: 2 years	-	-
Architectural features	Sloping roofs, Box design, Façade design as per the regulation (Bhutan Building Rules, 2018), Projecting balconies.		

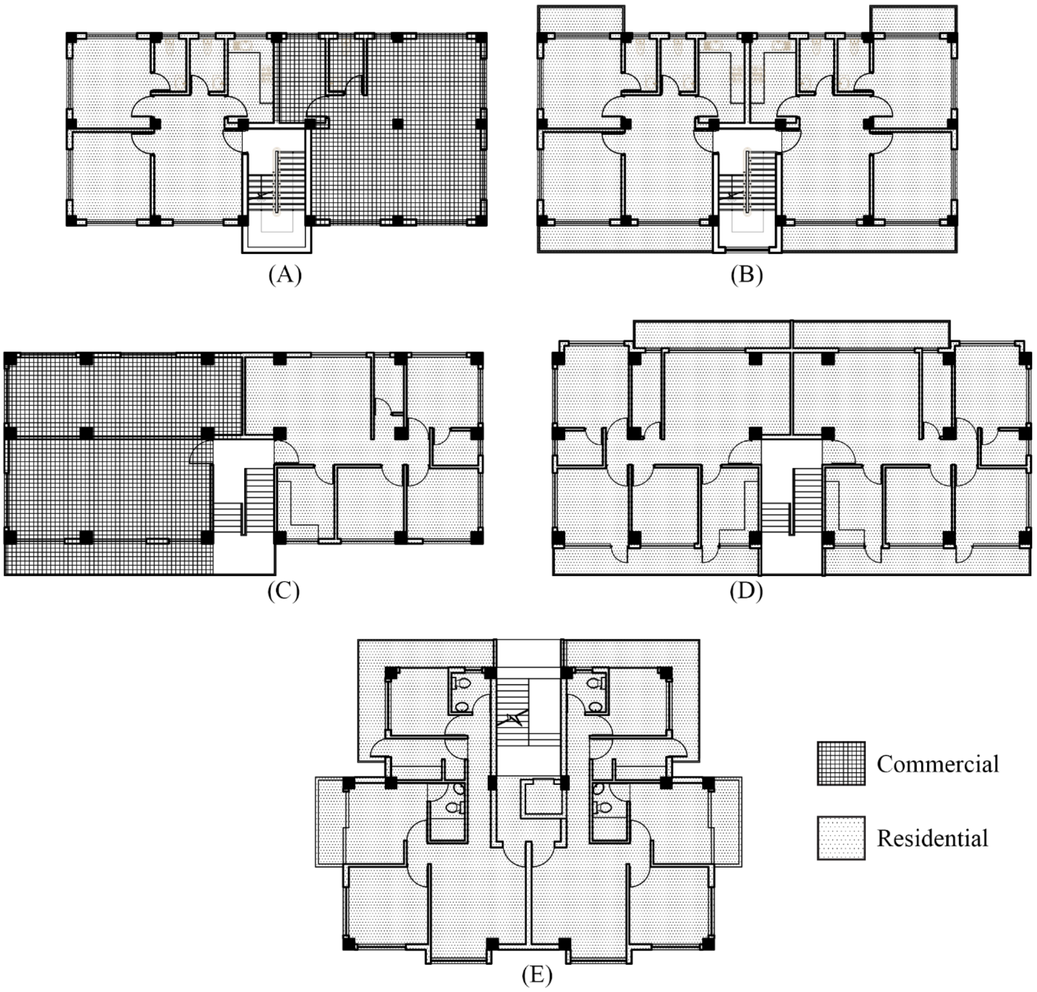


Figure 32: Comparison of planning of residential buildings.
TOP ROW; Building A; (A)-Ground floor (GF) plan, (B)-Typical plan above GF. MIDDLE ROW; Building B; (C)-GF plan, (D)-Typical plan above GF. BOTTOM ROW; Building C; (E)- Typical floor plan.

2.10.1.2 Construction.

The case study buildings comprise the conventional construction method of RCC framing with brick infill walls. The typical building materials range from wood, sand and cement, which are sourced locally; however, many other materials, such as corrugated roofing sheets, burnt bricks, tiles and reinforcement bars, are imported from India. In addition, the construction industry depends on foreign labourers, primarily Indian, as was reported in these case study projects. It is a familiar scene to spot Indian labourers in every construction project, from roads to buildings. In 2017, the Population and Housing Census of Bhutan (PHCB) reported nearly 42,425 legal foreign labourers, which converts to almost 6% of Bhutan's total population (735,553). The construction time of the case study projects typically ranges from 1-2 years, and the estimated cost of construction, excluding the price of land, falls in the approx. bracket of $150,000-$300,000. As for finance, the landowners depend on bank loans for construction. The bank in Bhutan provides a housing loan (60% of the estimated project cost) at an interest rate of 9-10% for 20 years, which was revised to 30 years in early 2021.

2.10.1.3 Material cost analysis

The construction of housing structures in Bhutan employs the conventional method of the RCC framing system with infill walls. Table 12 compares the unit price of common building materials with the border town Phuentsholing (155km south) to demonstrate the cost escalation of building materials in the capital. Most of the building materials originate from Phuentsholing, including imported materials and those manufactured nationally. The city is known as the country's economic gateway. According to Bhutan Trade Statistics 2020, nearly 70% of the imports entered through the city, and construction-related materials accounted for one-third of the total imports (RAA, 2019).

The locally available materials such as sand, stone aggregates and timber are realistically transported from the nearest sources and not necessarily from Phuentsholing. For example, Bhutan has a vast deposit of materials to produce stone aggregates and sand in quarries and riverbanks (Ministry of Economics Affairs[MoEA], 2019). Nevertheless, compared with Phuentsholiong, these materials are associated with higher costs in the capital. For instance, crushed stone constitutes nearly one-fourth of the additional expense and sand by staggeringly 137%.

However, sand in the capital predominantly comes from the Wangdue district, and nearly 60-65% of the sand supply to 11 central and western Bhutan districts comes from this region (Dorji, 2018). Like other natural resources, since early 2018, the sand supply has been streamlined by the government corporation Natural Resource Development Corporation (NRDCL). As of 2021, NRDCL maintained the commercial rate of sand from the dredging site of Wangdue at Nu. 287.80 per cubic meter (cu.m.), whereas in Thimphu, the same quantity charges Nu. 1124.15/cu.m, a significant escalation of roughly 290%.

Most building materials, imported and manufactured nationally (Table 12), are routed from Phuentsholing. Significant materials by volume, like infill wall materials of AAC and red bricks, contribute about 62.5% and 46.5% additional charges in Thimphu, respectively. Likewise, other materials (Table 12) also have varying cost escalations. Consequently, the inflated material rates in Thimphu, contributing substantially in some cases, can be, amongst others, associated with transportation.

Table 12: Comparative rates of the common building materials in Bhutan

Code	Description	Units	Phuentsholing	Thimphu	% Difference
Predominantly available construction materials locally					
MT0070	Crushed rock (20mm)	Cu.m	967.2	1199.85	24%
MT0043	Sand	Cu.m	473.33	1124.15	137%
MT0145	Cement (OPC/PSC)	tonne	6627.5	8147.5	23%
MT0331	Rough-sawn timber (Class A conifer)	Cu.m	13361.95	13498.8	1%
Construction materials are manufactured nationally and imported as well					
MT0130	Concrete blocks bricks (hollow)	1000#	41053	47446.5	16%
MT0131	Concrete blocks bricks (solid)	1000#	7823.63	12265.4	57%
MT0140	Autoclaved aerated cement (AAC block)	Cu.m	4000	6500	63%
MT0208	Thermo-Mechanically Treated (TMT) bars, yield strength-500MPa	Kg	51.29	61.09	19%
Construction materials predominantly imported					
MT0125	Bricks 2nd class	1000#	9666.67	14166.7	47%
MT0275	Corrugated galvanised iron sheets 24G (0.63mm)	tonne	71667.43	77445.5	8%
MT0656	Plain glass (4mm thick)	Sq.m	390.95	524.39	34%
MT0741	Wall putty	Kg	35.25	43	22%
MT0710	Cement primer	litre	103	126.07	22%
MT0720	Finishing coat (Aluminium paint)	litre	297.5	327.86	10%

MT0724	Finishing coat (Acrylic emulsion)	litre	201.04	311.43	55%
MT0725	Vinyl plastic emulsion paint (for cement plaster)	litre	288.53	406.67	41%

Source: (BSR 2021)

2.10.1.4 Built-up rate analysis

This section compares the built-up rates of prominent building assemblages with voluminous contribution, wall and structural systems—for Thimphu with Phuentsholing. For example, Table 13 shows that Thimphu's built-up rate of typical brickwork (250mm) without the finishings accounts for more than one-third additional cost of Phuentsholing. Similarly, concrete works in structural systems (beam, column and slab) account for more than one-fifth (Table 14).

Table 13: Breakdown of work and its associated rates in the construction of a brick wall

Code	Descriptions	Units	Phuentsholing	Thimphu	% Diff
BW0001+ BW0012 (Extra 331.47)	2nd class brickwork (250mm) in 1:4 mortar in the superstructure above the plinth level and up to floor two level	Cu.m	7156.69	9642.38	35%
BW0001+ BW0013 (Extra 124.65)	2nd class brickwork (250mm) in 1:4 mortar in the superstructure above the floor, two levels per floor	Cu.m	6949.87	9436.56	36%
PL0091 (Cement plaster)	18mm cement plaster in two coats; under layer 12mm (1 cement: 5 sand) and top layer 6mm thick (1 cement: 6 sand) finished even and smooth and curing etc. complete	Sq.m	203.27	203.47	0%
PL0125 (putty)	Providing & applying putty of thickness 2mm or more over the plastered surface to make the surface even and complete.	Sq.m	192.89	213.69	11%
PT0052 (Finishing coat)	Vinyl plastic emulsion paint for cement, masonry, plaster, two coats on new work	Sq.m	100.88	117.56	17%
PT0055 (finishing coat)	Aluminium paint, two coats on new work	Sq.m	88.36	91.2	3%

Source: (BSR 2021)

Table 14: Breakdown of work and its associated rates in the construction of RCC structures

Code	Descriptions	Units	Phuentsholing	Thimphu	% Diff
RC0083	Providing & fixing TMT bars for RCC work, including cutting, bending, binding, and placing in position complete	Kg	77.38	89.38	16%

Code	Descriptions	Units	Phuentsholing	Thimphu	% Diff
RC0010 (RCC column)	1:1.5:3 of concrete work for a column, excluding the cost of shuttering, centering and reinforcement	Cu.m	5551.19	6795.46	22%
RC0018 (RCC beam)	1:1.5:3 of concrete work for beam, lintels, bands & staircase, excluding the cost of shuttering, centering and reinforcement	Cu.m	5546.3	6790.57	22%
RC0014 (RCC slab)	1:1.5:3 of concrete work for floors, landing & balconies, excluding the cost of shuttering, centering and reinforcement	Cu.m	5717.43	6961.7	22%
RC0093	Formwork from start to removal for column	Sq.m	654.36	669.51	2%
RC0095	Formwork from start to removal for slabs, landing and balconies	Sq.m	855.78	873.9	2%
PL0091 (Cement plaster)	18mm cement plaster in two coats; under layer 12mm (1 cement: 5 sand) and top layer 6mm thick (1 cement: 6 sand) finished even and smooth and curing etc. complete	Sq.m	203.27	203.47	0%
PL0125 (putty)	Providing & applying putty of thickness 2mm or more over the plastered surface to make the surface even and complete.	Sq.m	192.89	213.69	11%
PT0052 (Finishing coat)	Vinyl plastic emulsion paint for cement, masonry, plaster, two coats on new work	Sq.m	100.88	117.56	17%
PT0055 (finishing coat)	Aluminum paint, two coats on new work	Sq.m	88.36	91.2	3%

Source: (BSR 2021)

2.10.1.5 Import issues of building materials

The building industry of Bhutan depends mainly on imported materials and foreign labour, raising sustainability concerns. Firstly, the dependency will only aggravate the trade deficit of Bhutan owing to the outflowing economic trend from the construction sector. In addition, the COVID-19 pandemic demonstrated the severe implications of this trend when the border had to be sealed, adversely affecting the labour and material shortage and leading to burdensome cost escalation of construction commodities.

Although Bhutan has steel plants, they import about 23,000 MT (Figure 33) of scrap iron annually, valued at about 495 million Nu, compared to negligible scrap generation in the country of 10 million, as reported in 2018. Similarly, the infill wall materials like red bricks and cement-based bricks are consistently imported. Importing red bricks hinges around 32 million numbers per annum, valued close to 208 million Nu, as shown in Figure 34. The gradual decline observed since 2016 is potentially due to the government's order passed in December 2015 that mandated the government and public corporations to use locally produced bricks to achieve the goal of self-reliance by curbing imports and creating employment. In this regard, the establishment of many private brick-manufacturing enterprises was encouraged. But at the same time, with the introduction of Autoclaved Aerated Concrete (AAC) blocks as an innovative construction building material, the import and use of concrete blocks increased. Import statistics show an exponential rise in the import of cement/concrete building blocks and bricks since 2017 (Figure 35). The value of imports increased significantly by 373% in 2018.

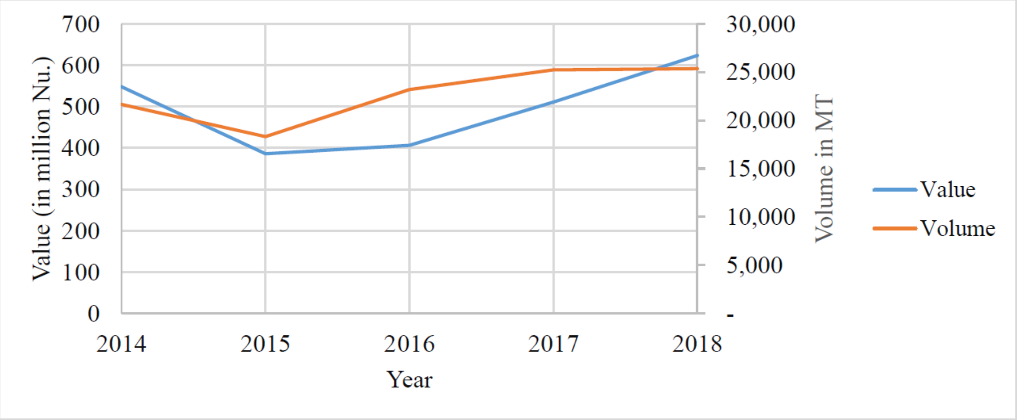


Figure 33: Import trend of scrap iron (raw material for steel products).
Source: (MoEA, 2019)

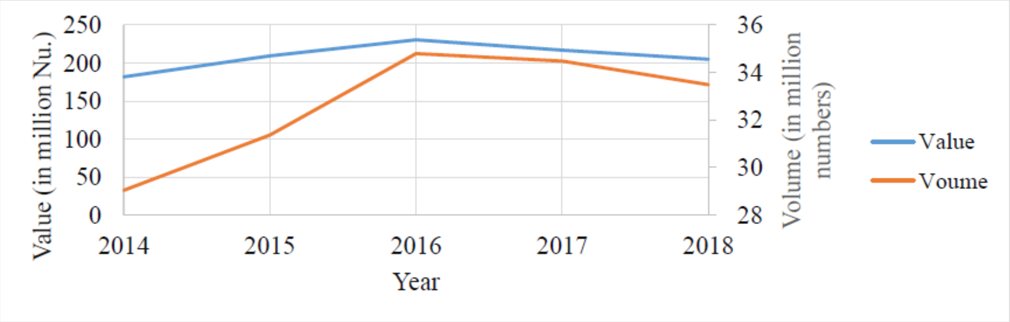


Figure 34: Import trend of fire clay bricks (2014-2018).
Source: (MoEA, 2019)

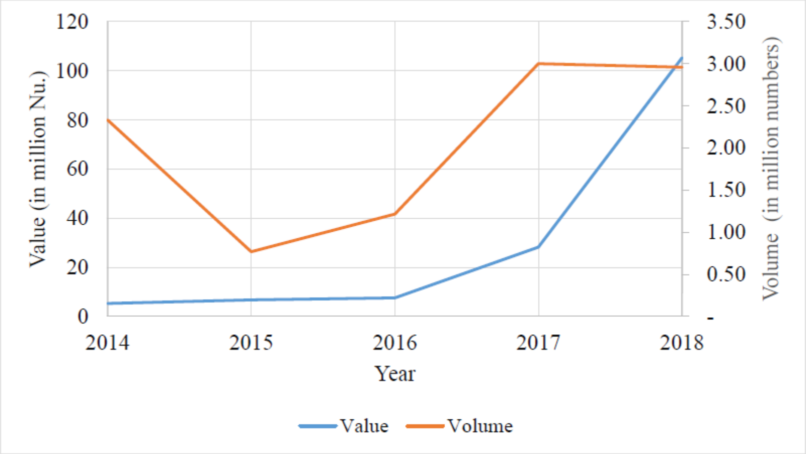


Figure 35: The import trend of building blocks and bricks (cement-based) (2014-2018).

Source: (MoEA, 2019)

Despite the availability of local cement-based bricks, certified by the National Statistics Bureau (NSB) of Bhutan, the import of similar bricks and bricks and even red bricks seem to have continued. The Green Public Procurement in Bhutan (GPPB) study in 2015 found that this is primarily due to the general assumption that local products are comparatively more expensive and of inferior quality than imported products. These assumptions arise from the higher labour charges in the country and the historically low capacity of local enterprises to produce and supply products with consistent quantity and quality (GPPB, 2015). The study also concluded that despite the availability of locally produced materials, the procurers (builders and contractors) tend to prefer imported materials due to limited communication, coordination and more misperceptions. To this, Ofori (1985) recommended adequate attention to socio-cultural and historical factors for the effective development, propagation and utilisation of construction materials after witnessing similar frustration in Ghana. The current fragmentation in the supply chain could be integrated with appropriate supply chain management for the greener construction industry (SCM) (Dainty et al., 2001; Ofori, 2000); however, this is beyond the scope of this thesis.

PART D: CONCEPTUAL FRAMEWORK

This section summarises and constructs linkages of thesis-relevant concepts and variables of the study from Part A, Part B and Part C, which highlighted the state-of-the-art background on these concepts. In summary, Part A, innovation input, recognised prefabrication technology using mass timber construction; Part B, innovation outcome, reasoned the focus on the economic and environmental sustainability of sustainable housing construction; and Part C, innovation context, established the characteristics of Bhutan's housing construction. The theoretical foundation of the study combines the construction innovation framework (technological) of Xue et al (2014) with Uusitalo & Lavikka's (2020) technology transfer model for the delivery of economical and environmentally sustainable housing in Bhutan.

Figure 36 illustrates the conceptual framework of the thesis. The technology transfer happens in the residential building construction, from the world's successful experiences to the context of Bhutan. In simple terms, technology transfer could be understood as the transfer of technology from one unit to another (Uusitalo & Lavikka, 2020). Likewise, the construction innovation involve the application of new technology, be it new material or method to produce sustainable residential building (Koebel, 1999). Table 15 interprets various concepts of the thesis for utmost clarity. The technology transfer will focus on innovating materials/methods in voluminous and essential building assemblages of the wall system and structural system of a typical residential building. This theoretical technology transfer of innovative housing construction method will be a case study project-oriented and governed by an analytical approach.

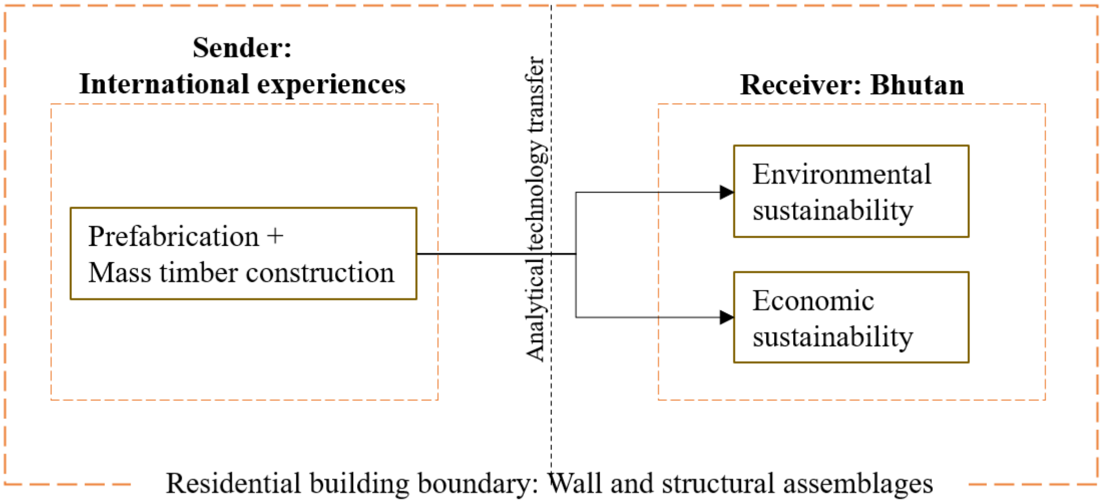


Figure 36: Relationship (conceptual framework) of independent and dependent variables

Table 15: Concepts/variables of the thesis

Concept/variables	Definition/Interpretation
Housing/Residential	These terms are used interchangeably and represents the typical 4-6 storey residential structure in Thimphu.
Technology transfer	Technology transfer from one unit to another (Uusitalo & Lavikka, 2020).
Construction innovation	Construction innovation involves applying new technology, be it new material or method to produce economical and environmentally sustainable residential building (Koebel, 1999).
Prefabrication	Pre-assembly or assemble before (Gibb, 2001)
Mass timber construction	Preassembly wood products laminated from smaller boards or lamella into larger structural components (Churkina et al., 2020) using either glue or non-glued methods like nails and dowels.
Life cycle cost analysis (LCCA)	LCCA estimates comprehensive costs across whole life cycle of material/product/project (Islam et al., 2015) but LCCA in this study includes front-end cost comprising of cradle-to-ste (A1-A5) boundary condition
Embodied energy (EE)	Embodied energy represents the energy used in the mining, production, assembly and transportation of a specific product (Varun et al., 2012) but excludes the transportation phase in this study.
Embodied CO$_2$ (ECO$_2$)	Embodied CO$_2$ is the sum of emissions in the production and transportation stage (Chau et al., 2015; Chen et al., 2022) but excludes the transportation phase in this study.

The widely adopted taxonomy of prefabrication constitutes a five-level qualitative model given by Gibb (2001) as presented in the literature section. However, due to limited road infrastructure, the appropriate level of prefabrication in Bhutan will include levels 1 and 2: Sub-components like lintels and non-volumetric elements like wall and floor panels. Therefore, this study aims to develop an innovative and sustainable prefabricated mass timber 2D house component (wall and structural), hypothesised to reduce the current inefficiencies resulting from the conventional model of housing construction in Bhutan.

2.11 Dependent and independent variable

The independent variables comprise prefabrication using mass timber construction, acknowledged in this study as an innovative solution. A growing body of literature recognises prefabrication technology and mass timber construction as innovative housing construction, reaping several benefits of cost reduction, time-saving, quality products and sustainable construction. In contrast, the dependent variables include two contrasting but significant construction-related subcomponents of sustainability: economic and environmental. The economic goal often supersedes any project's primary purpose, while environmental aspects remain mostly unattended but pose severe long-term implications. The economic variables are measured in terms of LCCA (A1-A5), whereas environmental concern is measured using embodied energy (A1-A3) and embodied CO_2 emissions (A1-A3).

The above-stated indicators are quantified first for the benchmark, an existing residential building built in Thimphu—also measured for the innovative construction model (hypothetical) of mass timber alternative—and then compared explicitly between them. Since the analysis and comparison focus on voluminous building assemblages of wall and structural systems excluding respective finishings, all other building assemblages are assumed to be equivalent in both the benchmark and the proposed MTC alternative.

2.12 Extraneous and intervening variable

Since the study assumes a theoretical setting, several other factors operating in a real-life situation, known as extraneous variables (Kumar, 2019), may affect the dependent variables. Therefore, practical validation is beyond the scope of the thesis and thus opens action-research avenues for the future researcher. Secondly, the study comprises two intervening variables that establish a link/effect between the independent and dependent variables: Wood type in the case of LCCA estimation and wood density in the case of embodied energy and CO_2 emission quantification. In this regard, the study presents an analysis of the wood type most commonly available (class 'B') in Bhutan, and its rates are referred from the BSR 2021—while a wood density constant of 500kg/m^3 was assumed in the environmental category in the absence of available resources.

2.13 Conclusion

The literature chapter was structured into four distinct sections: Part A, innovation input; Part B, innovation outcome; Part C, innovation context; and finally concluded with Part D, conceptual framework. Under the construction innovation framework, the first part of the innovation input aimed to innovate Bhutan's existing construction model. The extant literature suggested prefabrication technology as an innovative method to move away from conventional construction systems and to harvest the benefits such as sustainability, cost reduction, reduced time and labour, and improved quality. As a result, the prefabrication review covered various aspects such as definitions, benefits and hindrances, classifications systems, factors influencing its adoption and prefabrication of house components as appropriate levels for adoption. After that, building material in Bhutan was inventoried to identify the potential category to adopt the prefabrication method. Ultimately, prefabrication using wood, known as mass timber construction, was posited as an innovative construction method appropriate for Bhutan. Moreover, prefabrication of non-volumetric building elements which has significant mass-volume, cost and complicacy contribution in a building, wall, and structural system, was determined as appropriate levels of adoption and investigation for this study.

In section B, innovation outcome reviewed several studies to develop an understanding and application of various project-related outcomes before focusing on sustainable housing construction, which represents the core focus of the thesis and is measured in terms of economic and environmental sustainability. The LCA methodology underpins this thesis to generate/target quantifiable variables for each of the above two domains of sustainability. As a result, the economic parameter focused on the essential project performance criterion of cost in terms of LCCA, and environmental sustainability focused on context-relevant indicators of embodied energy and CO_2 emissions.

Thirdly, Part C analysed the innovation context of Bhutan’s current housing construction based on three selected typical residential buildings from the capital, Thimphu. This review first provided the historical background of the housing development in the country, followed by insights on the current scenarios and characteristics of the housing construction, comprising of planning, material inventory, and material cost analysis.

The last section on conceptual framework constructed linkages of the concepts identified in the previous sections. In summary, Part A, innovation input, recognised prefabrication technology using mass timber construction; Part B, innovation outcome, reasoned the focus on the economic and environmental sustainability of sustainable housing construction; and Part C, innovation context, established the characteristics of Bhutan’s housing construction.

CHAPTER III

RESEARCH METHODOLOGY

3.1 Introduction

This thesis aims to innovate the housing construction model for sustainable transformation and this chapter elucidates the overall structure employed to realise the aim. The sequence of this chapter follows both Groat & Wang (2013) and Creswell & Creswell (2018)s' systematic top-down hierarchical framework to explain research approaches. Firstly, the broad paradigm/system of inquiry/worldviews and school of thought are stated, followed by specific research strategy/research design and research tactics/research methods adopted in this investigation.

3.2 Broad philosophical assumptions

The author's broad philosophical assumption, usually hidden in the research, dictates the research approaches (plans and procedures) (Creswell & Creswell, 2018). These philosophical worldviews have different interpretations based on their proponent, such as "a basic set of beliefs that guide action," "paradigms," "broadly conceived research methodologies," and "epistemologies and ontologies." The author presents four worldviews: post-positivism, constructivism, transformative, and pragmatism. In this regard, this study asserted a pragmatist stand as the study emphasised the research problem instead of focusing only on the research methods. The epistemology of the research assumes knowledge creation by understanding practical but analytical engagement, while ontology assumes the possibility of diverse outcomes. The study undertook pluralistic approaches relevant to the research problem and question, resonating with the pragmatic paradigm characteristics. The research design section below covers these research approaches adopted.

3.3 Research design and methods

Figure 37 illustrates the research design of the thesis. The prominent research design adopted in this study constitutes a case study design, both *multiple case studies* and a *single case study* approach. The former is a review of Bhutan’s current housing construction, which entails three multi-storied residential buildings (4-6 stories) randomly selected from the capital, Thimphu, Bhutan. The review was presented in Part C of the literature review chapter under the theme of innovation context and is qualitative, explanatory, and theory-building. Due to a lack of information, the case study method presented as an appropriate data collection method. Wherever possible, the case study is enriched with relevant literature, primarily government documents.

On the other hand, the single case study prepares one of the case studies for further in-depth investigation and comparison with its hypothetical equivalent of mass timber construction, proposed as an innovative construction method. Therefore, the detailed preparation and assessment methods for a selected single case study and its alternative design exploration of mass timber construction represent the essential component of the thesis and are presented hereafter.

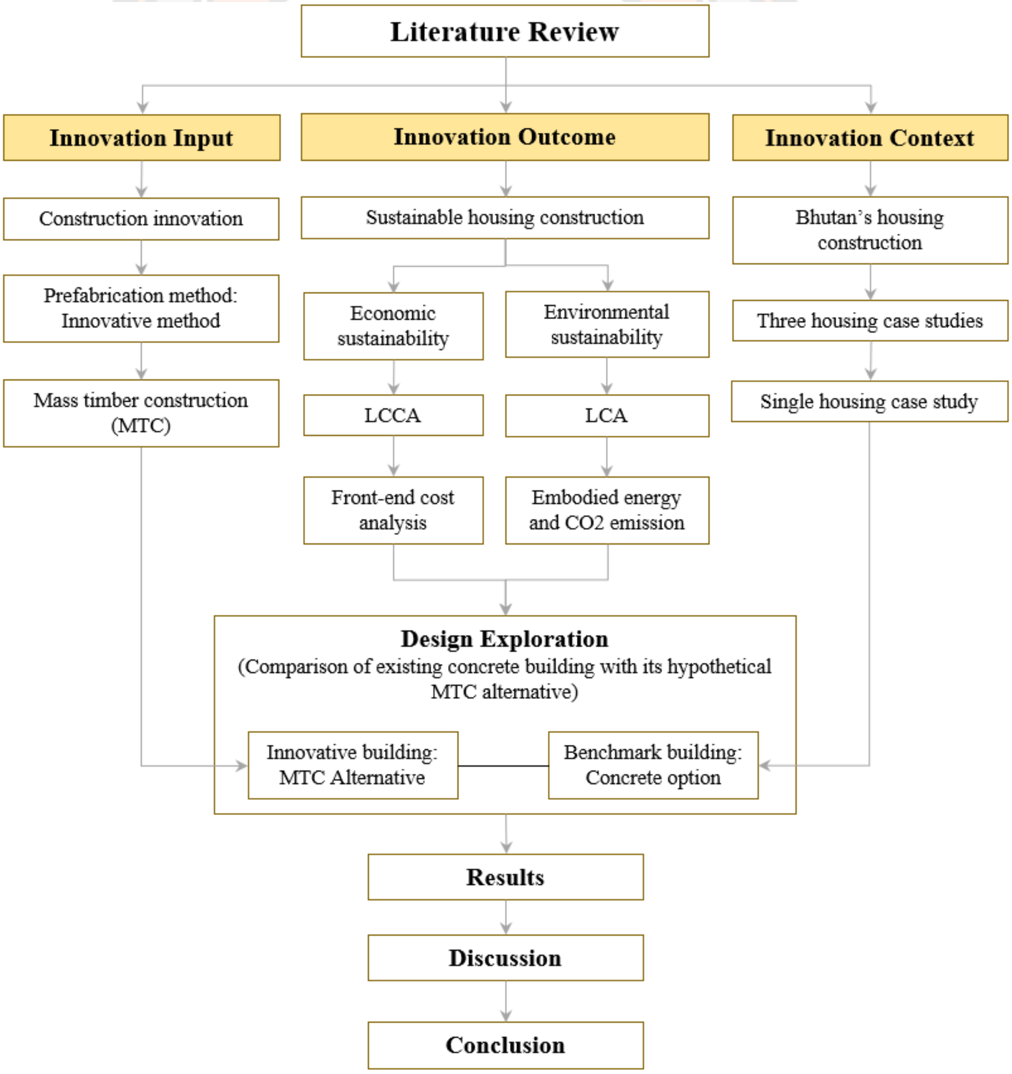


Figure 37: Flow chart of research design

3.3.1 Existing building: Concrete option

The existing building A, detailed in the literature, was identified as the benchmark for further analysis and the MTC design exploration exercise. Table 16 adopts a bill of quantities (BOQ) methodology to quantify constituent materials of the wall and structural system (Figure 38) in terms of kilograms and cubic meters for the estimation of selected indicators of LCCA, embodied energy and embodied CO2 emissions. This material quantification of the existing concrete building is detailed in the appendix. The subsequent section outlines methods adopted to estimate the economic and environmental sustainability of the benchmark concrete building.

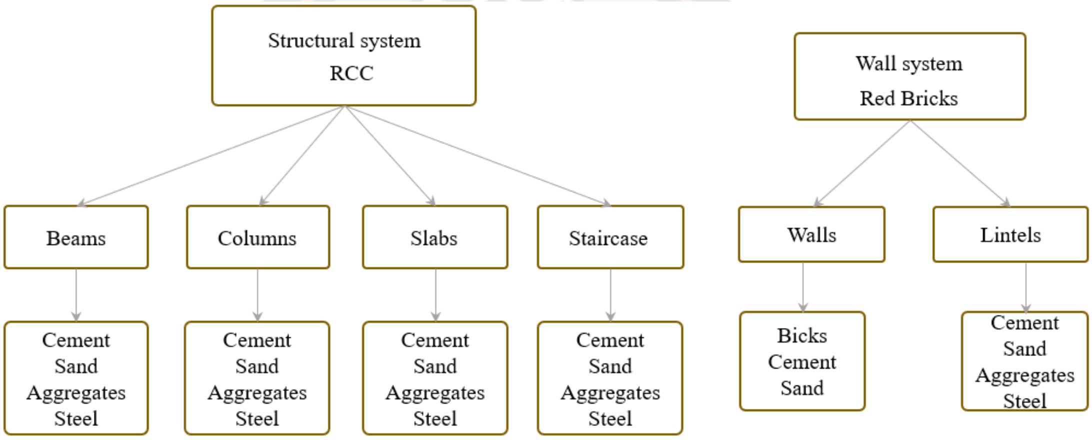


Figure 38: Breakdown of structural and wall systems into their constituent materials

Table 16: Summary of material quantification of building A

Building assemblage	**Material**	**Quantity in m^3**	**Quantity in KG**
RCC	Cement (tons)	*71.85	71846.77
	Sand (m^3)	74.84	119744.62
	Aggregates (m^3)	149.68	224521.17
	Steel (tons)	*19.82	19824.08
Wall	Clay bricks (m^3)	181.65	**90824.06
	Cement (tons)	*18.40	18403.51
	Sand (m^3)	51.12	81793.39
	Lintels		
	Cement (tons)	*3.23	3234.35
	Sand (m^3)	3.37	5390.59
	Aggregates (m^3)	6.74	10107.35
	Steel (tons)	*1.27	1270.13

*Quantity of cement and steel in tons, **Quantity of clay bricks in numbers
Assumptions: Steel density= 7850Kg/m3, Cement density= 1440Kg/m3, Sand density= 1600Kg/m3, Aggregate density= 1500Kg/m3, Weight of one brick= 2.25kg

3.3.1.1 Economic assessment: Life cycle cost analysis (LCCA)

The life cycle cost of the concrete option was calculated based on its bill of quantities and as per the material and built-up rates specified in the Bhutan Schedule of Rates 2021 (BSR 2021). The constituent material volumes were multiplied with their respective rates from the BSR 2021 to get material and built-up costs (Details in the Appendix section). We adopted this approach for cost analysis due to the absence of recorded construction costs. Even during the availability of the cost data, it would be redundant and inappropriate for the current research.

Built-up rate specifications in BSR 2021 are inclusive of the following: A fixed 5% cost for sundries is equated into the budget for the building, and a fixed 1% for water charges (sanitation, mixing of mortar, drinking, curing, etc.), while 10% is allocated for the contractor's profit and overhead expenses. Therefore, built-up rates in this work mean the overall construction costs and all the above considerations. In this regard, subtracting the material cost from its respective built-up rates will give us the actual construction cost, including miscellaneous charges. In other words, if X= built-up cost, Y= material cost, then Z=construction cost= X-Y.

X-Y= Z = construction cost.

(Construction cost includes 5% cost for sundries, 1% for water charges, and 10% for contractor's profit and overhead expenses).

3.3.1.2 Environmental assessment: Embodied energy and Embodied CO2

The main methods for estimating EE and ECO_2 emissions are input-output, process-based, and hybrid analysis (Hoxha, 2020; Syngros et al., 2017). This study employed a widely adopted process-based analysis comprising a three-step (bottom-up) process; material analysis, quantitative analysis of the material, and followed EE and ECO2 calculations (Syngros et al., 2017). First, the material and quantity analysis involved breaking building components (wall and structural system) into their constituent materials through the building drawings (Kumanayake et al., 2018; S. Shams et al., 2011; Syngros et al., 2017; Varun et al., 2012). After that, we determined EE and ECO_2 emissions by multiplying material quantities with their respective coefficients, MJ/Kg and KgCO2/Kg, respectively (Chau et al., 2015; Chen et al., 2022; Hoxha, 2020; Kumanayake et al., 2018; Luo et al., 2019; Shams et al., 2011; Syngros et al., 2017; Varun et al., 2012; Yan et al., 2010). However, various truncation errors plague the process-based analysis (Dixit et al., 2010; Hoxha, 2020; Syngros et al., 2017).

In the absence of local coefficients, this study, like previous studies, referenced foreign values. Nevertheless, we attempted to adopt the most relevant, recognised, and applicable database (Table 17). For instance, EE estimation is based on the database of India by Reddy & Jagadish (2003) due to commonalities in the construction sector. Likewise, the ECO2 emission coefficient referenced the widely recognised Inventory of Carbon and Energy (ICE) assembled by the University of Bath (Hammond & Jones, 2008). Although the energy and CO_2 emissions quantification adopted foreign databases, they provided valuable indicative estimates.

Table 17: Embodied energy and CO_2 emission coefficients.

Material	[1]EE (MJ/unit)	[2]Transportation EE (MJ/KM/Cu.m)	[3]ECO_2 ($KGCO_2$/KG)	[5]Transportation ECO_2 ($KGCO_2$/T*KM)
Cement	5850/ton	1	0.83	0.057
Sand	0	1.75	0.005	0.057
Aggregates	20.5/m^3	1.75	0.005	0.057
Steel	42000/ton	1	1.71	0.057
Clay bricks	2550/m^3	2	[4]427.99	0.179

[1]Production EE (embodied energy) & [2]Transportation EE coefficients adopted from Reddy and Jagadish (2003).
[3]ECO_2 (embodied CO_2) from Hammond and Jones (2008). [5]Transportation ECO_2 from Chen et al. (2022).
[4]ECO_2 coefficient in $KGCO_2$/1000 bricks from Maheshwari and Jain (2017).
Assumptions: Cement, clay bricks, and steel transported from Phuentsholing (155KM): Sand from Wangdue (70KM): Aggregates within the vicinity (25KM) of Thimphu.

Due to the complexity and diversity of the analysis process, including comprehensive building materials in a building would be difficult (Zhang & Wang, 2015). As a result, the study focused on components with a voluminous contribution, walls, and structural systems. Moreover, this approach interlaces with the findings established from the literature section: The prefabrication using mass timber construction of non-volumetric building elements that have the highest mass-volume, cost and complicacy contribution in a building, wall and structural system was determined as appropriate levels of adoption and investigation. Excluding the foundation, these two components account for a significant fraction of the materials in a conventional building. Previous studies have demonstrated the value of narrowing focus to include essential materials or products (Chen et al., 2022; Hoxha, 2020; Varun et al., 2012).

3.3.2 Innovative building: MTC alternative

This study establishes the MTC as a suitable and superior alternative to the current construction of residential buildings: RCC framing and infill wall system. For this reason, a hypothetical MTC equivalent of building A is proposed as an innovative model. The following outlines the theoretical design exploration of MTC, followed by the methods adopted to estimate the economic and environmental sustainability of the proposed MTC alternative.

The theoretical design exploration of the MTC alternative is limited to only structural framing and wall system, excluding respective finishing, assuming that all other design assemblages are the same as that of the concrete option. For the design exploration, a detailed redesign of MTC with structural analysis is beyond the scope of the thesis. But it is not based only on the material replacement concept in which the wood replaces equivalent materials from the concrete option in the MTC alternative. In this regard, the design exploration instead took a balanced approach—Timber Bay Design tool from Fast + Epp firm (details in the appendix) provided preliminary estimates of structural member sizes and the appropriate grid layout (Figure 39). Table 18 summarises these design estimates alongside the concrete option. The MTC alternative comprises glulam columns, beams, and DLT/NLT floor slab for its structural system. For wall assemblage, the GPLT (Gun-nailed parallel laminated timber) wall explored by Bylund (2014) (Figure 40) is adopted in this exercise, but without the insulation. In addition to being cheaper than the CLT and Glulam, the preference for NLT or DLT is primarily due to the former not requiring a dedicated manufacturing unit and its convenience of being assembled with basic carpentry tools.

The plinth area of the MTC alternative is 153.6 sq.m, slightly more than the concrete option of 152.4 sq.m(Table 18), although they are being claimed of equivalency in this case study. This additional plinth area in the MTC alternative resulted because the design exploration attempted to generate an appropriate design comprising grid layout and structural members for the MTC alternative rather than simply using the material replacement concept.

Table 18: Summary of MTC alternative with the concrete option

Assemblage		Concrete Option (Plinth=152.4 sq.m)		MTC alternative (Plinth= 153.6 sq.m)	
		Quantity (cu.m)	**Description**	**Quantity (cu.m)**	**Description**
Structural frame	**Floor slab**	103.77	RCC (150mm thick)	100.53	NLT (150mm thick)
	Column	32.64	RCC (400mmx400mm)	8.82	Glulam (190mmx215mm)
	Beam	33.58	RCC (structural depth of 300m excluding slab depth)	24.51	Glulam (structural depth of 266mm excluding slab depth)
Wall	**Wall**	181.65	125mm: interior (red bricks) 250mm: exterior (red bricks)	140.02	GPLT* (190mm thick with 23% hollow)
	Lintel	8.09	RCC (Depth: 100mm-150mm)	-	-

*GPLT- Gun-nailed parallel laminated timber wall design is adopted from Bylund (2014).

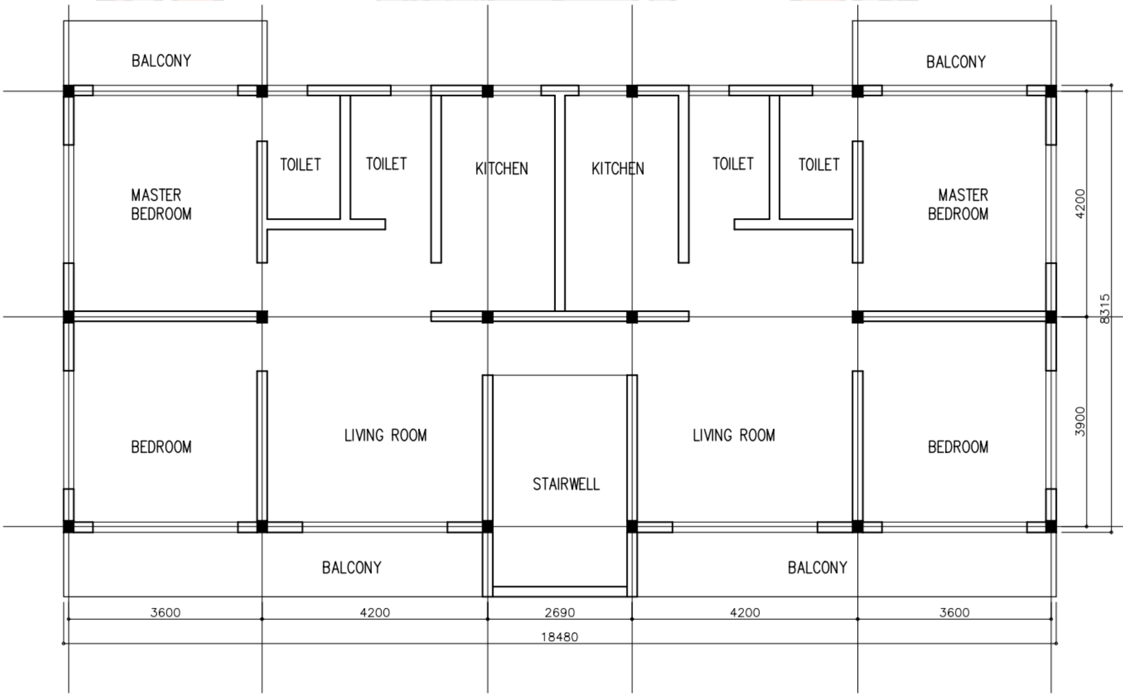


Figure 39: Typical layout of MTC alternative

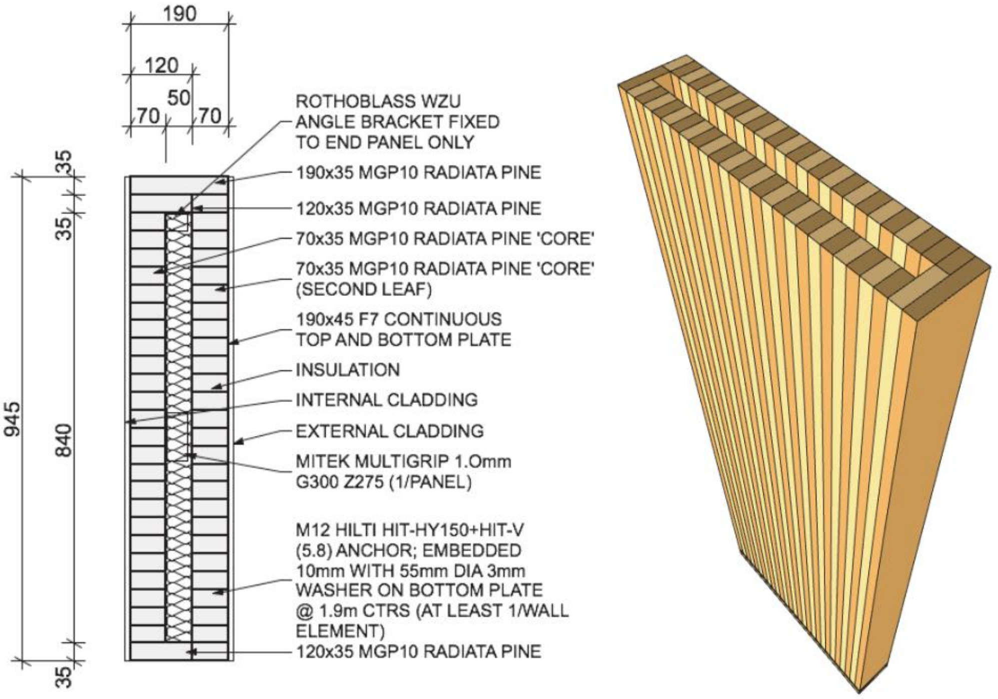


Figure 40: Plan and perspective view of GPLT (Gun-nailed Parallel Laminated Timber) wall panel for the MTC alternative

Source: Adapted from (Bylund, 2014)

3.3.2.1 Economic assessment: Life cycle cost analysis (LCCA)

Without precedent of mass timber building in Bhutan, it posed challenges to calculate the related construction costs. Liang et al. (2019) showed that both economic data and research were limited, which reduced the accuracy of estimating the initial expenses of mass timber buildings. Nonetheless, the quantification of the life cycle cost (A1-A5) of the MTC alternative has been attempted in this study. The material production (A1- A3) cost of glulam products is based on the unit price of 1080 Nu per cubic feet obtained from the glulam production unit already set up at Pangbisa, Paro, Bhutan (50km away from the capital). The subsequent construction cost (A4-A5), including labour, equipment, and overhead costs, equates to 25% of the total built-up cost (A1-A5). This cost ratio was referenced from similar mass timber studies from an American context (Gu et al., 2020; Liang et al., 2019). The material and built-up cost computation are provided in the appendix section.

Table 19 represents four types of timber classes and the rates for sawn timber and timber dressing work. The NLT floor slabs and GPLT walls resemble the dressed timber framing since all can be assembled or constructed with similar fabrication and low-tech woodworking techniques. For this reason, the material cost (A1-A3) and built-up cost (A1-A5) adopted conifer class B's woodworking rates since it's the most commonly used timber in Bhutan.

Table 19: Different timber types in Bhutan and their rates

Timber class	Rough-sawn timber (Rate/cu.m)	Dressed timber work (Rate/cu.m) *
Class B (conifer)	**Nu.13498.83**	**Nu.26522.54**
Class A (conifer)	Nu.13886.92	Nu.26997.91
Class A (Broadleaf)	Nu.12063.29	Nu.24764.18
Class B (Broadleaf)	Nu.11610.30	Nu.24209.33

*Dressed timber woodwork cost includes all costs involved in providing & fixing in-position dressed woodwork in frames of doors, windows, clerestory windows, and other frames, wrought and framed (Adapted from BSR, 2021)

3.3.2.2 Environmental assessment: Embodied energy and Embodied CO2

This study used cradle-to-gate embodied energy and carbon coefficients from the ICE database owing to the lack of a local database. These values in ICE infer worldwide studies, although targeted at the United Kingdom. We adopted it as they would provide valuable indicative probable estimates. Due to the lack of collected data for NLT products, the study assumes that the general wood category's presented values are comparable for representing a less rigorous production process compared to glulam products. The estimates of embodied energy (Table 20) and carbon (Table 21) are calculated in best and worst-case scenarios. The best case for embodied energy excludes the bioenergy contribution. Likewise, in embodied CO_2 estimation, the best case is without the biocarbon. Biocarbon is not included as part of the best-case calculations as this accounts for the carbon naturally sequestered through the growing process. The best-case estimate aligns with the Intergovernmental Panel on Climate Change (IPCC) determination that biomass-based material emissions are effectively carbon neutral. Since this determination is not entirely accepted, (bio) carbon is included in worst-case calculations for mass timber. Worst-case assumes the material is derived from a wholly raw or virgin state (Zeits, 2019).

Table 20: Embodied energy coefficients (MJ/KG).

Material	**Worst case**	**Best practice**
Glulam	4.91 (bio)+ 7.11 (fossil)= 12	7.11 (fossil)
General wood	4.3 (bio)+ 5.7 (fossil)=10	5.7 (fossil)

Source: (Hammond & Jones, 2011)

Table 21: Embodied carbon coefficients (KGCO2/KG).

Material	Worst case	Best practice
Glulam	0.45 (bio)+ 0.39 (fossil)	0.39 (fossil)
General wood	0.41 (bio)+ 0.30 (fossil)	0.3

Source: (Hammond & Jones, 2011)

The quantification of materials in terms of kilograms required the density of the wood. But no studies were available that quantified the density of wood species in Bhutan. Therefore, the analysis presented here assumes that the density of softwood (spruce and pine) is 500kg/m3 at 12% moisture content.

3.4 Conclusion

This chapter reasoned the research design and methods adopted in the thesis. From a broader perspective, this study assumes pluralistic approaches relevant to the research problem—epistemological assumption relied on knowledge creation by practical but analytical engagement—and research ontology assumes the possibility of diverse outcomes. The overall research design constituted a case study design, both *multiple case studies* and a *single case study* approach. The former comprised three multi-storey residential buildings to develop a theory on the current housing construction model in Thimphu, Bhutan. The latter, a single case study, identified one of these case studies and prepared for further in-depth investigation and comparison with its hypothetical equivalent of mass timber construction, proposed as an innovative construction method. The methods adopted to estimate economic and environmental sustainability assessment for concrete benchmark buildings and the proposed MTC alternative were also covered. The following chapter will present these results.

CHAPTER IV

RESULTS

4.1 Introduction

This study intended to innovate and demonstrate the performance improvements attainable in housing construction. Therefore, this chapter first presents economic sustainability in terms of LCCA and environmental sustainability in terms of embodied energy and CO_2 emissions—separately for the existing benchmark concrete building and the proposed hypothetical equivalent of the MTC alternative. Lastly, this chapter compares the performance of the concrete structure with the MTC alternative.

4.2 Existing building: Concrete option

4.2.1 Economic assessment: Life cycle cost analysis (LCCA)

Table 22 illustrates the quantification of wall and structural assemblage in terms of material cost (A1-A3), Nu. 3,483,931 (3.5 million) and built-up cost (A1-A5), Nu. 5,849,777 (5.85 million). The individual cost estimation of the components and subsequent materials are provided in the appendix. The material cost is nearly 60% of the total built-up cost, while the construction cost (A4-A5) represents the remaining 40%. Lastly, although the material cost of structural and wall systems is nearly comparable, the built-up cost of the former is double that of the latter.

Table 22: Quantification of LCCA (cradle-to-site) of concrete option

Items/Assemblage	**Material cost (A1-A3)**	**Built-up cost (A1-A5)**
A. RCC structural frame		
Floor slab		722447
RCC columns		221804
RCC beams		228033
RCC staircase		64850
Cement	406508	
Sand	84132	
Aggregates	179594	
Steel	1257633	
Cost of centering, shuttering, and reinforcement.		
Providing & fixing Thermo-Mechanically Treated reinforcement bar (Yield Strength 500 MPa) for RCC work, including cutting, bending, binding, and		1840027

Items/Assemblage	Material cost (A1-A3)	Built-up cost (A1-A5)
placing in position complete		
Providing & fixing centering and shuttering (formwork), including strutting, propping, etc., and removal of formwork		851401
TOTAL (RCC work)	**1927868**	**3928562**
B. Brickwork		
Brick wall (exterior wall + interior wall)		1690002
Bricks	1286704	
Cement	122427	
Sand	61255	
Aggregates (lintels)	8085	
Steel (lintels)	77592	
Lintels and bands in Brickwork		56633
i) Cost of centering, shuttering, and reinforcement.		113524
ii) Formwork		61056
TOTAL (Brickwork)	**1556063**	**1921215**
GRAND TOTAL (RCC+Brickwork)	**3483931**	**5849777**
Total material cost (RCC+ Brickwork)- %	**60%**	
Construction cost excluding material cost (A4-A5)	**2365847**	
Construction cost excluding material cost (A4-A5)-%	**40%**	

4.2.2 Environmental assessment: Embodied energy and embodied CO_2

Table 23 demonstrates the breakdown of structural and wall assemblages into their subsequent material quantities, which are then multiplied with their corresponding coefficients to obtain estimates of embodied energy for production (1899GJ). At the same time, Figure 41 presents a graphical summary excluding the production EE of sand and aggregates due to negligible values.

Table 23: Quantification of Embodied energy (EE) in the production stage

Building assemblage	Material	Quantity	Production Coefficient (MJ/unit)	Production EE (MJ)
RCC	Cement (tonnes)	71.85	5850	420304
	Sand (Cu.m)	74.84	0	0
	Aggregates (Cu.m)	149.68	20.5	3068
	Steel (tonnes)	19.82	42000	832612
	RCC Total			**1255984**
Wall	Clay bricks (Cu.m)	181.65	2550	463203
	Cement (tonnes)	18.40	5850	107661
	Sand (Cu.m)	51.12	0	0

Building assemblage	Material	Quantity	Production Coefficient (MJ/unit)	Production EE (MJ)
	Lintels			
	Cement (tonnes)	3.23	5850	18921
	Sand (Cu.m)	3.37	0	0
	Aggregates (Cu.m)	6.74	20.5	138
	Steel (tonnes)	1.27	42000	53345
			Wall Total	**643268**
			RCC Total + Wall Total	**1899251**

Production EE coefficient and Transportation EE coefficient from Reddy and Jagadish (2003)

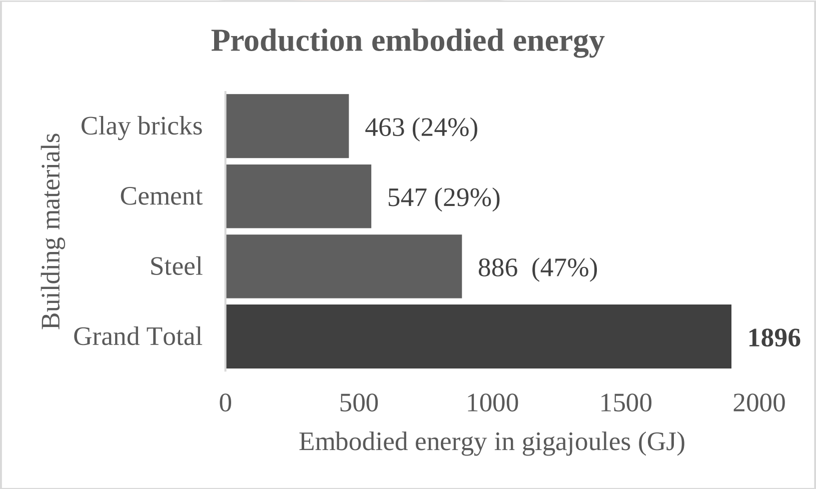


Figure 41: Breakdown of production energy contribution

Steel, cement, and clay bricks account for a significant proportion of EE in the case study building. Steel has the highest contribution at 47%, followed by cement and clay bricks, with a roughly equal contribution at nearly half that of steel (Figure 41).

Table 24 quantifies embodied CO_2 by multiplying material quantities of structural and wall systems with the corresponding CO_2 coefficients, while Figure 42 graphically represents the breakdown of total embodied CO_2 (154,743kg).

Table 24: Quantification of Embodied CO2 emission (ECO2) in the production stage

Building assemblage	Material	Quantity	CO2 Coefficient KGCO2/KG	Embodied CO2 emission (KGCO2)
RCC	Cement (KG)	71846.77	0.83	59633
	Sand (KG)	119744.6	0.005	599
	Aggregates (KG)	224521.2	0.005	1123
	Steel (KG)	19824.08	1.71	33899
			RCC Total	**95253**
Wall	Cement (KG)	18403.51	0.83	15275
	Sand (KG)	81793.39	0.005	409

Building assemblage	Material	Quantity	CO2 Coefficient KGCO2/KG	Embodied CO2 emission (KGCO2)
	Clay bricks (Nos.)	90824.06	427.99*	38872
	Lintels			
	Cement (KG)	3234.353	0.83	2685
	Sand (KG)	5390.588	0.005	27
	Aggregates (KG)	10107.35	0.005	51
	Steel (KG)	1270.13	1.71	2172
			Wall Total	**59490**
			RCC Total + Wall Total	**154743**

CO2 coefficient (KGCO2/KG) from Hammond and Jones (2008)
**CO2 coefficient (KGCO2/1000 bricks) from Maheshwari and Jain (2017)*
Density of steel= 7850Kg/m3, Density of cement= 1440Kg/m3, Density of sand= 1600Kg/m3, Density of aggregates= 1500Kg/m3, Weight of one brick= 2.25kg

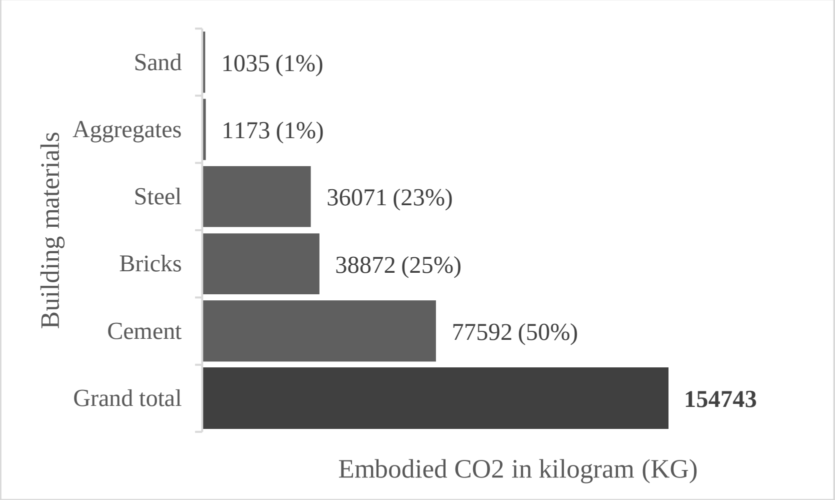


Figure 42: Breakdown of production CO2 emission.

Like embodied energy, steel, cement, and clay bricks are substantially responsible for embodied CO$_2$ emissions. Cement has the highest CO$_2$ emission of about 50% of the aggregate ECO$_2$ emission, followed by clay bricks and steel, with a nearly similar proportion of almost a quarter (Figure 42).

4.3 Innovative building: Mass Timber Alternative

4.3.1 Economic assessment: Life cycle cost analysis (LCCA)

Table 25 quantifies wall and structural assemblage in terms of material cost (A1-A3), Nu. 4,518,472 (4.5 million) and built-up cost (A1-A5), Nu. 8,075,087 (8 million). The material amounts to 58% of the total built-up cost, while construction cost (A4-A5) represents 42%.

Table 25: Quantification of LCCA (cradle-to-site) of Mass timber alternative

Items/Assemblage	Quantity (Cu.m)	Material cost (A1-A3)	Construction cost (A4-A5)	Total built-up cost (A1-A5)
Glulam columns & beams	33	1271350	423783	1695134
NLT floor slab	101	1357058	1309293	2666351
GPLT wall	140	1890064	1823539	3713603
Total	**274**	**4518472**	**3556615**	**8075087**

4.3.2 Environmental assessment: Embodied energy and embodied carbon

Table 26 and Table 27 estimate the embodied energy and CO_2, respectively, for the structural and wall system of the MTC alternative under two scenarios of best case and worst case. The best-case scenario for embodied energy excludes the bioenergy contribution, and best case scenario for embodied CO_2 excludes biocarbon. In the best case, embodied energy consumption amounts to 804GJ and embodied CO_2 emission to 43 tons (T). In contrast, under worst-case scenarios, embodied energy roughly doubles to 1403GJ while embodied CO_2 is about double (99 T).

Table 26: Quantification of Embodied energy of Mass timber alternative

Sl.No.	Assemblage	Quantity	Worst case Coefficient	Best case Coefficient	Worst case Quantity	Best case Quantity
	Units	KG	MJ/KG	MJ/KG	GJ	GJ
1	Floor slabs (NLT)	50266	10	5.7	503	287
2	Columns and beams (Glulam)	16667	12	7.11	200	119
3	Walls (NLT)	70008	10	5.7	700	399
				Total	**1403**	**804**

Table 27: Quantification of embodied CO_2 of Mass timber alternative

Sl.No.	Assemblage	Quantity	Worst case Coefficient	Best case Coefficient	Worst case Quantity	Best case Quantity
	Units	KG	KGCO2/KG	KGCO2/KG	TCO2	TCO2
1	Floor slabs (NLT)	50266	0.71	0.3	36	15
2	Columns and beams (Glulam)	16667	0.84	0.39	14	7
3	Walls (NLT)	70008	0.71	0.3	50	21
				Total	**99**	**43**

4.4 Comparison: Concrete option vs. MTC alternative

4.4.1 Economic assessment: Life cycle cost analysis (LCCA)

Table 28 summarises the LCCA (A1-A5) of concrete case study building (Nu.5.85 million) with its hypothetical equivalent in MTC (Nu.8 million). The material cost of the MTC alternative is more than 30% more than the concrete option, and it is expensive by about 38% in terms of built-up cost. Regarding individual assemblages, MTC structural system causes 36% additional material cost than the concrete option—but the wall system of MTC causes 93% additional built-up cost. Figure 43 compares the concrete option with the MTC alternative regarding the material cost of the wall and structural systems, while Figure 44 compares the total built-up cost.

Table 28: LCCA (A1-A5) comparison of concrete option and MTC alternative

Assemblage	**Concrete option (A)**		**MTC alternative (B)**		**% Difference (B-A/A)**	
	Material (A1-A3)	Built-up (A1-A5)	Material (A1-A3)	Built-up (A1-A5)	Material (A1-A3)	Built-up (A1-A5)
Structural system	1927868	3928562	2628408	4361484	36%	11%
Wall system	1556063	1921215	1890064	3713603	21%	93%
Total	**3483931**	**5849777**	**4518472**	**8075087**	**30%**	**38%**

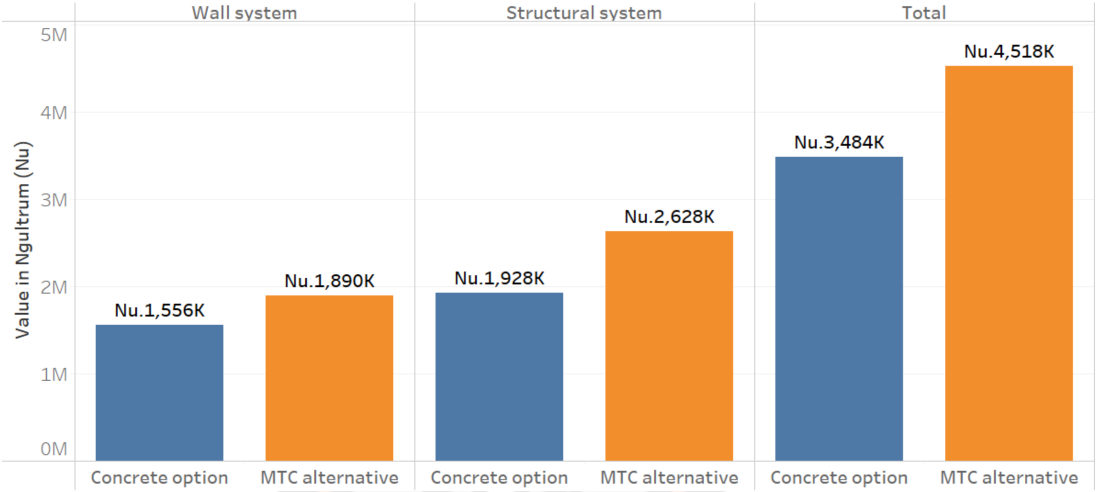


Figure 43: Comparison of material cost (A1-A3) between concrete option and MTC alternative

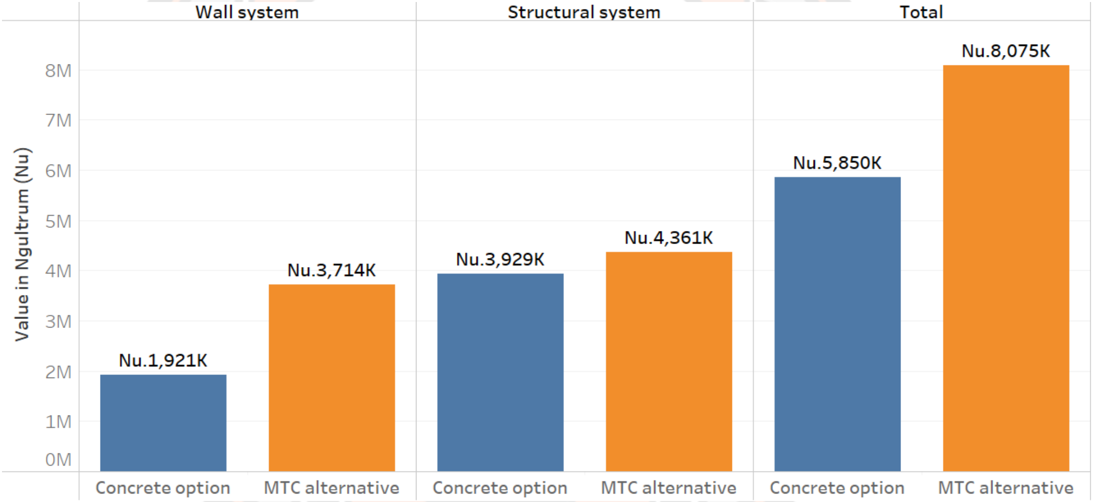


Figure 44: Comparison of built-up cos (A1-A5) between concrete option and MTC alternative

4.4.2 Environmental assessment: Embodied energy and embodied CO_2

Table 29 compares the estimates of cradle-to-gate embodied energy of concrete option and MTC alternative under two scenarios, best-case and worst-case—while Table 30 does it for the embodied CO_2. In terms of embodied energy, the savings can be around 71% under the worst-case scenario, which can go as high as 271% under the best-case scenario. Similarly, embodied CO2 emission reduction under worst-case and best-case scenarios are 111% and 525%, respectively.

Table 29: Embodied energy (cradle-to-gate) quantification

Assemblage	Concrete option	MTC alternative		Comparison	
	EE (GJ)	EE (GJ)		EE savings (%)	
		Worst case	*Best case*	*Worst case*	*Best case*
Structural frame	1256	703	405	-79%	-210%
Wall	643	700	399	8%	-61%
			Total EE savings	**-71%**	**-271%**

Table 30: Embodied CO_2 (cradle-to-gate) quantification

Assemblage	Concrete option	MTC alternative		Comparison	
	ECO2 (T)	ECO2 (T)		ECO2 saving (%)	
		Worst case	*Best case*	*Worst case*	*Best case*
Structural frame	95	50	22	-92%	-341%
Wall	59	50	21	-20%	-183%
			Total ECO2 savings	**-111%**	**-525%**

4.5 Conclusion

This chapter compared the existing concrete building with the hypothetical equivalent of the MTC alternative, which is propagated as the innovative construction model. The economic assessment comprising LCCA showed that the material cost (A1-A3) and built-up cost (A1-A5) of MTC alternatives are expensive by nearly 30% and 38%, respectively. In contrast, the environmental assessment of embodied energy and embodied CO_2 estimated for worst-case and best-case scenarios showed significant savings for both the categories. These results are interpreted and compared with the extant literature in the next chapter.

CHAPTER V

DISCUSSION

5.1 Introduction

The discussion chapter interprets the results for relevancy and significance. First and foremost, the economic assessment of LCCA considered only the front-end construction cost (A1-A5) and is subject to inherent assumptions and limitations. For this reason, this section discusses the possibilities of the results by considering various uncertain scenarios involving timber price, end-of-life, prefabrication cost savings and operational performance. This is followed by the environmental assessment of embodied energy and CO_2, which are interpreted and compared with similar studies from the literature to affirm the results.

5.2 Economic assessment: LCCA

The life cycle cost computed in this study represents cradle-to-site (A1-A5). Under these assumptions, the MTC alternative resulted in a higher cost than the concrete option in terms of material cost (30%) and overall built-up cost (38%). Under the similar boundary condition of cradle-to-site, the hypothetical 12-storey mass timber building (CLT and Glulam) showed 26% higher front-end costs than the functionally equivalent concrete building (Gu et al., 2020; Liang et al., 2021). However, because of its much higher end-of-life salvage value than the concrete building, the LCCA calculated for a 60-year study period was expensive just by about 9.6% (Liang et al., 2021).

Elsewhere, the comprehensive construction cost comparison of a mass timber building with cross-laminated timber (CLT) with concrete structure suggested that the latter is higher than 6.43% than the former (Ahmed & Arocho, 2021). This study was based on a residential mass timber building in Canada with the modeled concrete version. Moreover, from previous studies, the authors found that timber construction costs are generally 2-6% higher than traditional concrete and steel construction. A similar trend ranging from -6% to +6% was observed in the literature review of cost-related mass timber construction, where ‘+’ indicated cost savings of mass timber compared to concrete construction and ‘-’ indicated cost escalation (Sorathiya, 2019). Ahmed & Arocho (2021) and Liang et al. (2021) concluded that the cost of engineered wood (CLT and Glulam in their case) as the main factor for cost escalation—along with the extensive use of cranes in the installation process and due to operational cost of human resources specialists required in mass timber construction (Ahmed & Arocho, 2021). However, this study compared the NLT, a cheaper alternative to CLT, and usual Glulam structural system with their concrete equivalent. Therefore, although the limited previous studies presented cost information, direct comparison with the results of this study is not viable due to varying assumptions.

The findings from this investigation concluded that the price of timber primarily impacted the overall built-up cost of the MTC alternative, followed by the construction cost (A4-A5) of the wall assemblage. The following section discusses these matters, followed by an end-of-life scenario analysis and the broad implication of MTC in terms of energy consumption and prefabrication characteristics.

5.2.1 Material (timber) price

The primary reason for the high cost of MTC is the apparent high cost of timber in Bhutan—mainly because of operating expenses in the extraction process, including transportation and the low-level technologies in the processing stage. Firstly, timber extraction requires construction and maintenance of service roads that ultimately inflate the log costs—and their subsequent transportation to the sawmills, mainly in the city centres, incur additional charges. Secondly, the sawmill is a primary processing plant for converting logs into sawn timber in Bhutan. The Department of Forests and Park Services (DoFPS) has advocated upgrading outdated sawmilling technologies since 2008. However, there is still some resistance from existing sawmill owners (Forest Resources Management Division, 2017). As a result, the performance rating of sawmills ranges from 56% to 78% (Forest Resources Management Division, 2017). Table 31 summarises some of the commonly utilised sawmill types with their performance.

Table 31: Bhutan's sawmill types and their performance

Sawmill Type	Performance
Indian Sawmill	56%
LucasMill	56%
Timberking 2000	73.69%
Woodmizer LT70	78.44%
Norwood HD36	64.62%

Adapted from (Forest Resources Management Division, 2017)

Wood Resources International (2019) reported the Global sawlog price index (GSPI) and European sawlog price index (ESPI) respectively as \$71.9/m3 (Nu. 5,895) and €76.4/m3 (Nu. 6417). Log costs account for 65-70% of the production costs when manufacturing softwood lumber (Wood Resources International, 2019)—considering log costs entail 70% of the cost, the global lumber, and European lumber cost estimate to Nu. 8421/m^3 and Nu. 9167/m^3 respectively. In 2022, Bhutan's NRDCL maintained the conifer (class B) timber log price at Nu. 5714/m^3 (161.79/ft^3) and sawn timber at Nu. 13512/m^3 (382.62/ft^3), normalised to 2021 rates—log cost, Nu. 5708 and sawn timber, Nu. 13499: *Regarded as current-case*—to match with the rest of the analysis framework. The lumber or sawn timber price in Bhutan is high by 60% compared with the global price and 47% to the European price.

For sawn timber/lumber production in Bhutan, the log price accounts for 42% (Nu. 5708), and its conversion to sawn timber/lumber represents the remaining 58%. The subsequent hike of the sawn timber can be, amongst others, possibly associated with the low-level saw milling technologies in the country. Hypothetically, considering the 70% log price and 30% to convert to lumber, the actual cost of sawn timber should be Nu.8163/m^3 in Bhutan: *Regarded as best-case*—which is roughly 40% lesser than the current case. Figure 45 presents a scenario analysis of the current case with four possible scenarios of best-case; best-case-I, 10%; best-case-II, 20%; best-case-III, 30% and best-case-IV, 40%, which is the maximum reduction attainable. The scenario analysis suggests the possibility of attaining a cost advantage over the conventional concrete option by the best-case-II, a 30% reduction of the timber price.

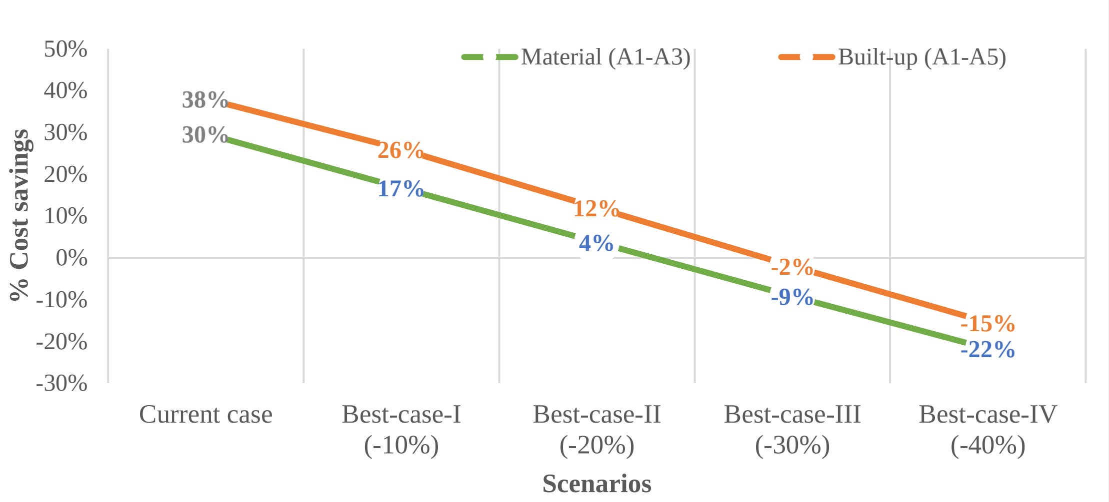


Figure 45: Scenario analysis of possible cost savings

5.2.2 End-of-life scenario

One of the most significant advantages is the higher reusability of mass timber construction than concrete structures. But end-of-life has substantial uncertainties. Therefore, scenario analysis (Figure 46) evaluated varying degrees of resale prices (25%-100%) and quantities (25% -100%) to suggest possible outcomes—as demonstrated in a similar previous study by Liang (2021).

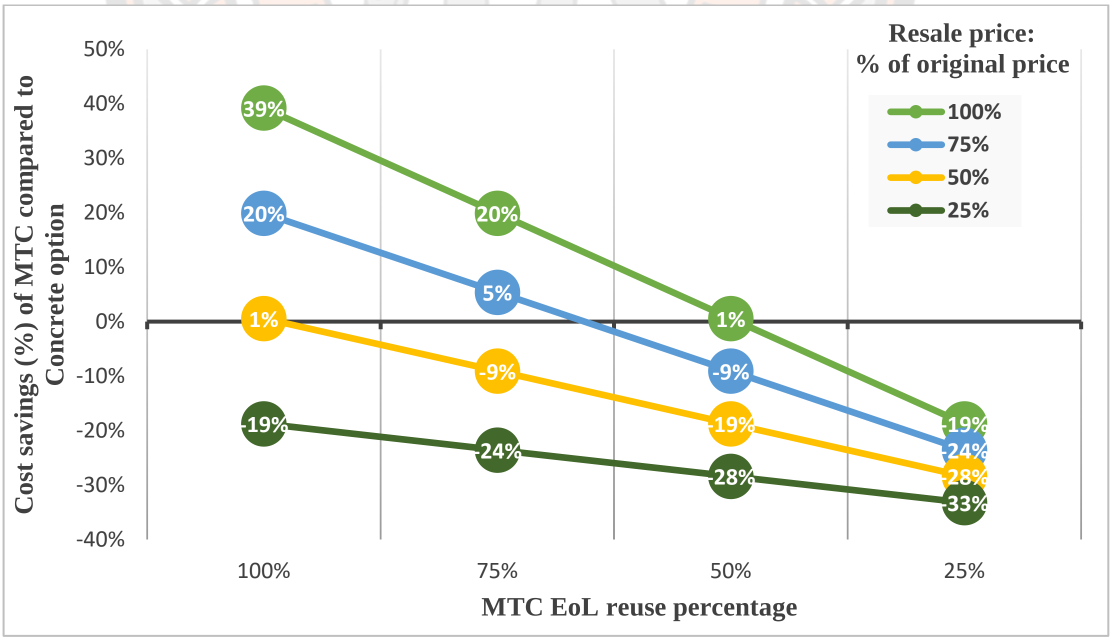


Figure 46: End-of-life scenario analysis

Although the front-end cost of MTC is more than the concrete option, considering the EoL salvage value of MTC, the total LCCA is comparable with the concrete option. For instance, one possible scenario—75% quantity reclaimed for 75% of its original price—indicates MTC alternative is cheaper by 5% than the concrete option. Likewise, considering the resale price at 75% and 50% reuse value, MTC is expensive by only 9%.

5.2.3 Reaping prefabrication cost savings

NLT floor and GPLT wall assumed fabrication equivalent to the current dressed timber woodworking rates due to the similar nature of labour-intensive and low-tech woodworking techniques. However, mechanisation and prefabrication could reduce costs by about 20% (project schedule reduction).

5.2.4 Considering operational energy consumption

This study was based on cradle-to-site (A1-A5) boundary conditions. Future studies that include the operational stage can reap further cost advantage of mass timber products over conventional steel and concrete due to better thermal performance (eg; lower thermal conductivity) to save a building's heating/cooling energy (Asadi et al., 2018; Liang et al., 2021).

5.3 Environmental assessment: Embodied energy and CO_2 emissions

Sustainability is probably the most significant advantage of the MTC alternative. In terms of embodied energy, the savings can be around 71% under the worst-case scenario, which can go as high as 271% under the best-case scenario. Similarly, embodied CO2 emission reduction under worst-case and best-case scenarios are 111% and 525%, respectively. Although the sustainability analysis focuses only on the wall and structural systems, it represents the bulk material consumption and most energy-intensive materials (cement, steel & clay bricks) in a conventional residential building, if not the entirety. For instance, Chen et al. (2022) found that conventional materials account for more than 70% of most common building materials' total embodied energy.

Moreover, Debnath et al. (1995) concluded that these materials represent nearly 85% of the overall embodied energy in a four-story RCC structure with clay brick infills. Similarly, these materials constitute more than 70% of all carbon emissions of an entire building (Kumanayake et al., 2018). The findings indicate that the voluminous assemblages of the wall and the structural system would represent the significant characteristics of a building.

5.3.1 Embodied energy

The production EE of the concrete option (1896 GJ) translates to 2.5GJ/m^2 after dividing by the gross floor area of 763 m^2. Reddy and Jagadish (2003) found that the EE of RCC framed structure in India with infilled burnt clary brick masonry walls of an 8-storied building to be 4.2GJ/m^2. Similarly, Shams et al. (2011) found 4.24GJ/m^2 production EE from the study of a five-storied residential building in Bangladesh. Elsewhere, Dixit et al. (2010), after reviewing several similar studies with significant variations in EE figures, suggested a mean of 5.506GJ/m2 with a standard deviation of 1.56GJ/m^2. Considering the common variations and exclusions such as foundation and other building assemblages, the finding from this study seem to portray close agreement with the EE described above from the literature. The MTC alternative reduces the EE consumption to 1.8GJ/m^2 under the worst-case scenario and 1GJ/m^2 considering the best-case scenario.

5.3.2 Embodied CO_2

The production ECO_2 of 154.7T (154,743KG) interprets to about 203KG/m^2 after accounting for its gross floor area. This estimate is comparatively lower than the related studies in the literature. For instance, Shams et al. (2011) reported 340 kg/m^2 of embodied CO_2 emission, and Kumanayake et al. (2018) found 629.6KG/m^2 from a three-story office building in Sri Lanka. These differences can be associated with higher CO_2 coefficients. Also, the former study considered more comprehensive materials and possibly since the latter was a commercial building. Therefore, under the worst-case and best case-scenarios, the MTC alternative reduces to 131kg/m^2 and 56 kg/m^2 respectively.

5.4 Overall implication

The previous sections of this chapter discussed the possibilities and interpretations of the results comprising economic and environmental assessments. In contrast, this section will suggest actions toward achieving sustainable transformation by adopting the MTC construction model, which was the focus of this investigation.

This study posits timber as a sustainable material harvested using sustainable forest management practices. Bhutan has a great forest cover of 71% (Department of

Forests and Park Services, 2021), and its constitution mandates a minimum coverage of 60% for all times to come. Therefore, although the country can sustainably triple its current timber extraction, increased demand for timber in construction would have to be supported by a solid legal and political commitment to sustainable forest management.

With strong, sustainable forest management principles, the next aim would be to reduce the current high timber extraction and production cost. The Department of Forests and Park Services (DoFPS) has advocated upgrading outdated sawmilling technologies since 2008 but has faced resistance from existing sawmill owners (Forest Resources Management Division, 2017). Reducing timber cost is crucial as it will make the MTC products competitive and a viable option to the current on-site conventional method.

Despite the primary cost advantage, MTC, as a new construction method to Bhutan, has inherent disadvantages and barriers, including knowledge and labour, research, logistics, planning, acoustics & vibration, job displacement, code permits, wind, and component flexibility (Smith et al., 2015). These issues provide a future guide for the researcher to delve deeper and thereby substantiate with more relevant information. Furthermore, apart from a Glulam manufacturing unit, Bhutan does not have other mass timber products such as commonly adopted CLT (cross-laminated timber). Although other mass timber products like DLT and NLT provide cheaper promises without the dedicated manufacturing units, a practical precedent must first be proven in Bhutan since this study provided only analytical precedent. MTC Demonstration projects, which are currently planned, could provide valuable insights into these uncertainties and, as a result, influence the construction practitioners to accept and adopt the MTC model.

5.5 Limitations and recommendations for future research

Like any other research, this study has limitations summarised hereafter. This research advocated the technological construction solution comprising of material and method as an innovative and appropriate solution to solve the current inadequacies of economic and environmental sustainability in Bhutan’s residential buildings. This study is bounded by an analytical approach and thus excludes any unaccounted practical-related parameters which could affect the study results. However, the research validity cannot be dismissed because it provided valuable indicative estimates, setting a precedent for future investigations.

The environmental assessment in this work had to be limited to the embodied impacts of energy and CO_2 emissions. Moreover, it is based on data from international databases and literature due to the unavailability of country-specific data for Bhutan. Therefore, a more realistic estimation of embodied carbon values for the country would have been achieved if national data were available. Similarly, a more comprehensive LCA would have been possible if the data had been available. In the future, with the development of national databases of embodied energy and carbon of building materials for Bhutan, it is expected that researchers will be able to overcome this barrier.

Only the voluminous building assemblages of walls and structural systems were considered for the study, assuming all other components and building processes, such as formwork, external works, materials, and components for building services, were considered constant. Future research work can be extended to incorporate these areas, thus providing more representative value for buildings' overall embodied energy and CO2 emissions.

This study focused on a single residential building in Bhutan. As this kind of building typified the buildings sector in the country, a residential building was considered appropriate for the study. In the future, embodied carbon emission studies can be extended to Bhutan's commercial and other building categories, providing more opportunities to compare results.

Lastly, this study provided scientific evidence for cost and sustainability construction issues from specific lenses. However, further comprehensive studies are needed to provoke innovative restructuring of current inadequacies into a more productive, cost-effective, and sustainable building industry.

CHAPTER VI

CONCLUSION

6.1 Introduction

The primary rationale of current construction inadequacies that impede Bhutan's housing construction and delivery in terms of economic and environmental concerns gave impetus for this study to explore innovative construction methods. This chapter concludes by responding to the research questions.

6.2 Answers to research questions

1. What are the current practices and characteristics of Bhutan's housing construction in the country?

To answer this question, this study employed a review of the current housing construction using a multiple case study approach, randomly selecting three 4-6 multi-storied residential buildings to formulate a theory. Part C: The innovation context from the literature chapter correlates to this research question. Further, one of the case studies was investigated from the environmental standpoint of embodied energy and CO_2 emissions. Thus, the current housing construction practices included insights into planning and construction, rate analysis including material and built-up costs, and environmental assessment.

The planning and construction approach suggested that the housing construction relies on the on-site conventional construction system of the RCC structural system with infill walls. Most of these structures conform to a 4 to 6-storied repetitive box-like design. The material rate analysis revealed that the imported and local construction materials cause a high-cost escalation in Thimphu, thereby impacting the built-up costs. Compared with the predominant construction material sources, material cost analysis revealed almost 300% cost escalation of sand in Thimphu, followed by infill wall material of autoclave aerated concrete blocks and red bricks at about 62.5% and 46.5%, respectively, which incurs high construction costs.

In addition, these buildings conform to the bulk consumption of energy and CO_2 emission-intensive building materials such as steel, concrete and bricks, mostly imported. The environmental assessment estimated production embodied energy and CO_2 emissions of $2.5GJ/m^2$ and $203KG/m^2$, respectively: this implies the energy-intensive and carbon-intensive nature of the urban building stock, a trend likely to aggravate in the future with increasing construction activities unless alternatives become available. In summary, the existing conventional practice leads to sporadic, fragmented, and inefficient processes, raising economic and environmental concerns.

2. How can Bhutan innovate housing construction methods?

Part A: Innovation input answers this question and will be summarised in this section. The extant literature advocated prefabrication as an innovative alternative to the conventional on-site construction method and its inadequacies, not necessarily as the invention but in the acceptance and adoption of the technology. As a result, a comprehensive review touched on various aspects of prefabrication, such as definitions, benefits and hindrances, classifications systems, factors influencing prefabrication adoption and prefabrication of house components as appropriate levels of adoption.

Volumetric mass production of houses is probably the fastest and cheapest way. Still, it cannot be adopted owing to its failure to respond to customers' unique requirements (mass customisation) and other issues of production and transportation limitations. This led to the non-volumetric prefabrication of house components as a more appropriate and balanced solution towards mass production and mass customisation to reap the benefits of off-site construction. Then came the question of which building components, as the exploration of prefabrication to every building component, would be beyond the scope of this thesis and might not even lead to significant outcomes. To this, Bildsten (2011) recommends most complex areas of the house to be the most favorable to adopt the prefabrication technique. In this regard, the scope of the investigation contextualised to building components with significant mass-volume, complexity, and cost contribution in a typical residential building of Bhutan: Wall systems and structural systems. These building assemblages constitute the largest and most complex due to the many sub-processes associated with their assembly.

Following this, Bhutan’s waste, mineral and bio-based building materials were inventoried to identify the potential category to realise prefabrication. These materials were assessed for their prefabrication potency in terms of expected environmental sustainability and scalability for widespread adoption. Based on these selection criteria and the general acceptance of mass timber construction as an innovative construction method in the literature—timber was posited as more relevant and appropriate than the other two categories. For instance, although reusing waste resolves sustainability concerns, it does not provide any potential for mass-scale adoption. Likewise, mineral resources are abundant but not sustainable as they are extracted, requiring high energy and carbon-intensive approaches. Moreover, MTC products like DLT or NLT do not require a dedicated manufacturing unit and can be assembled with basic carpentry tools. Thus, prefabrication using mass timber was postulated as an innovative construction method for Bhutan.

3. How does the selected innovation perform in terms of economic and environmental sustainability compared with the conventional counterpart?

Part A: Innovation input of the literature chapter identified prefabrication using timber as an innovative construction method. Likewise, Part B: Innovation outcome reasoned the focus on sustainable housing construction, assessed for economic and environmental sustainability. The result and discussion chapters presented the main findings regarding the abovementioned sustainability performances of innovative mass timber buildings with their concrete counterpart.

The study aimed to innovate Bhutan’s housing construction method for sustainable transformation comprising economic gain in terms of LCCA and environmental assessments in embodied energy and CO_2 emissions of the building materials. In this regard, prefabrication using mass timber was posited as an innovative construction model. The scope of the above assessment was demonstrated for significant building assemblages of wall and structural systems. Unsurprisingly, the findings revealed that mass timber construction could achieve substantial environmental savings, which is probably their most significant advantage. For instance, in terms of embodied energy, the savings can be around 71% in the worst-case scenario, which can go as high as 271% in the best case. Moreover, the production embodied energy of the concrete option (1899 GJ) translated to 2.5GJ/m^2

after dividing by the gross floor area, while MTC's worst and best case categories reduced to 1.8GJ/m^2 and 1.0GJ/$m^{2,}$ respectively.

Similarly, the MTC alternative demonstrated the reduction of CO_2 emissions in the worst-case scenario at 111% and a remarkable 525% in the best-case scenario. The production embodied CO_2 emissions of the concrete option (154 T) are about 202KG/m^2 concerning its gross floor area. In contrast, in the worst and best scenarios, the MTC alternative signified savings at 131 KG/m2 and 56 KG/m2, respectively.

In contrast, Life-cycle cost analysis revealed higher construction costs than the typical concrete building. The MTC alternative resulted in 30% higher expenses than the concrete option in terms of material and a 38% overall built-up cost. This was primarily due the surprisingly higher cost of timber in Bhutan, although forest resource is plenty. But the scenario analyses under the life-cycle cost analysis presented concrete evidence that will make the overall construction of MTC cheaper or competitive with the concrete option: For instance, the scenario analysis that accounted for the predicted salvage value of MTC drastically reversed the overall construction costs. Likewise, the scenario analysis demonstrating the potential timber cost reduction also resulted in the MTC alternative being cheaper than the concrete option. For these reasons, this investigation advocated mass timber construction as appropriate innovation to restructure the current construction adequacies to a sustainable future.

6.3 Conclusion

In conclusion, this thesis advocated prefabrication technology using mass timber as an innovative alternative to Bhutan's existing housing construction inadequacies to achieve sustainable transformation. Furthermore, the design exploration of mass timber demonstrated its substantial environmental benefits and cost-saving potency compared to the existing concrete structures.

This study supplements the criticism of on-site conventional construction practices with a scientific quantification of essential economic and environmental sustainability parameters. By doing so, it also augments the consensus regarding the conservative tendency of the construction industry and prioritises the need and potentialities of emerging innovative ideas. The possibilities of prefabrication using mass timber construction as an innovative and sustainable model will provide additional information to the construction practitioners and policymakers towards a much-required sustainable built environment transformation.

REFERENCES

Abed, J., Rayburg, S., Rodwell, J., & Neave, M. (2022). A Review of the Performance and Benefits of Mass Timber as an Alternative to Concrete and Steel for Improving the Sustainability of Structures. *Sustainability*, *14*(9). https://doi.org/10.3390/su14095570

Abergel, T., Dean, B., & Dulac, J. (2017). *UN Environment and International Energy Agency (2017): Towards a zero-emission, efficient, and resilient buildings and construction sector. Global Status Report 2017*. https://www.worldgbc.org/news-media/global-status-report-2017

Abouhamad, M., & Abu-Hamd, M. (2021). Life cycle assessment framework for embodied environmental impacts of building construction systems. *Sustainability*, *13*(2), 1–21. https://doi.org/10.3390/su13020461

Adabre, M. A., & Chan, A. P. C. (2019). Critical success factors (CSFs) for sustainable affordable housing. *Building and Environment*, *156*(March), 203–214. https://doi.org/10.1016/j.buildenv.2019.04.030

ADB. (2002). *Technical assistance to the Kingdom of Bhutan for housing sector reform*. https://doi.org/10.1057/9780230271333_46

Ahmed, S., & Arocho, I. (2021). Analysis of cost comparison and effects of change orders during construction: Study of a mass timber and a concrete building project. *Journal of Building Engineering*, *33*(August 2020). https://doi.org/10.1016/j.jobe.2020.101856

Ajayi, S. O., Oyedele, L. O., & Ilori, O. M. (2019). Changing significance of embodied energy: A comparative study of material specifications and building energy sources. *Journal of Building Engineering*, *23*(May 2018), 324–333. https://doi.org/10.1016/j.jobe.2019.02.008

Akmam Syed Zakaria, S., Gajendran, T., Rose, T., & Brewer, G. (2018). Contextual, structural and behavioural factors influencing the adoption of industrialised building systems: a review. *Architectural Engineering and Design Management*, *14*(1–2), 3–26. https://doi.org/10.1080/17452007.2017.1291410

Al Kashif, M., Abdel Mooty, M., Fahmy, E., Abou Zeid, M., & Haroun, M. (2012). Nonlinear Modeling and Analysis of AAC in- filled Sandwich Panels for out of Plane Loads. *International Journal of Civil, Environmental, Structural, Construction and Architectural Engineering*, *6*(4), 272–276.

Alaloul, W. S., Musarat, M. A., Rabbani, M. B. A., Iqbal, Q., Maqsoom, A., & Farooq, W. (2021). Construction sector contribution to economic stability: Malaysian gdp distribution. *Sustainability*, *13*(9), 1–26. https://doi.org/10.3390/su13095012

Anacker, K. B. (2019). Introduction: housing affordability and affordable housing. *International Journal of Housing Policy*, *19*(1), 1–16. https://doi.org/10.1080/19491247.2018.1560544

Asadi, I., Shafigh, P., Abu Hassan, Z. F. Bin, & Mahyuddin, N. B. (2018). Thermal conductivity of concrete – A review. *Journal of Building Engineering*, *20*, 81–93. https://doi.org/https://doi.org/10.1016/j.jobe.2018.07.002

Asdrubali, F., Baldassarri, C., & Fthenakis, V. (2013). Life cycle analysis in the construction sector: Guiding the optimization of conventional Italian buildings. *Energy and Buildings*, *64*, 73–89.

https://doi.org/10.1016/j.enbuild.2013.04.018

Asdrubali, F., Bianchi, F., Cotana, F., D’Alessandro, F., Pertosa, M., Pisello, A. L., & Schiavoni, S. (2016). Experimental thermo-acoustic characterization of innovative common reed bio-based panels for building envelope. *Building and Environment*, *102*, 217–229. https://doi.org/10.1016/j.buildenv.2016.03.022

Asdrubali, F., Pisello, A. L., D’Alessandro, F., Bianchi, F., Fabiani, C., Cornicchia, M., & Rotili, A. (2015). Experimental and numerical characterization of innovative cardboard based panels: Thermal and acoustic performance analysis and life cycle assessment. *Building and Environment*, *95*, 145–159. https://doi.org/10.1016/j.buildenv.2015.09.003

Asian Development Bank. (2010). *Managing Hazardous Wastes (Technical Assistance Consultant ’ s Report)* (Issue October).

Atta, N., Dalla Valle, A., Campioli, A., Chiaroni, D., & Talamo, C. (2021). Construction technologies for sustainable affordable housing within fragile contexts: Proposal of a decision support tool. *Sustainability (Switzerland)*, *13*(11), 1–14. https://doi.org/10.3390/su13115928

Badir, Y. F., Kadir, M. R. A., & Hashim, A. H. (2002). Industrialized Building Systems Construction in Malaysia. *Journal of Architectural Engineering*, *8*(1), 19–23. https://doi.org/10.1061/(asce)1076-0431(2002)8:1(19)

Baek, C., Park, S. H., Suzuki, M., & Lee, S. H. (2013). Life cycle carbon dioxide assessment tool for buildings in the schematic design phase. *Energy and Buildings*, *61*, 275–287. https://doi.org/10.1016/j.enbuild.2013.01.025

Bamigboye, G. O., Davies, I., Nwanko, C., Michaels, T., Adeyemi, G., & Ozuor, O. (2019). Innovation in Construction Materials- A Review. *IOP Conference Series: Materials Science and Engineering*, *640*(1). https://doi.org/10.1088/1757-899X/640/1/012070

Barreca, F., Martinez Gabarron, A., Flores Yepes, J. A., & Pastor Pérez, J. J. (2019). Innovative use of giant reed and cork residues for panels of buildings in Mediterranean area. *Resources, Conservation and Recycling*, *140*(October 2018), 259–266. https://doi.org/10.1016/j.resconrec.2018.10.005

Benayoune, A., Abdul Samad, A. A., Trikha, D. N., Abang Abdullah, A. A., & Akhand, A. M. (2004). Precast Reinforced Concrete Sandwich Panel as an Industrialised Building System. *International Conference On Concrete Engineering and Technology University Malaya*, 6.

Bertelsen, S. (2004). Lean construction: where are we and how to proceed? *Lean Construction Journal*, *1*(October), 46–69.

Bertelsen, S. (2005). Modularization - A third approach to making construction lean? *13th International Group for Lean Construction Conference: Proceedings*, *July*, 81–88.

Betts, D., Sadeghian, P., & Fam, A. (2019). Impact behanior of sustainable sandwich panels with flax FRP faces and cardboard cores. *Integrated Building Solutions—The National Agenda*, 80–85.

Bhandari, P. (2016). Evaluating Properties of Lightweight Sandwich Wall Panels. *International Journal for Scientific Research & Development*, *4*(06), 175–178.

Bildsten, L. (2011). Exploring the opportunities and barriers of using prefabricated house components. *19th Annual Conference of the International Group for Lean Construction 2011, IGLC 2011*, 320–329.

Bragança, L., Mateus, R., & Koukkari, H. (2010). Building sustainability assessment. *Sustainability*, *2*(7), 2010–2023. https://doi.org/10.3390/su2072010

Brandner, R., Flatscher, G., Ringhofer, A., Schickhofer, G., & Thiel, A. (2016). Cross laminated timber (CLT): overview and development. *European Journal of Wood and Wood Products*, *74*(3), 331–351. https://doi.org/10.1007/s00107-015-0999-5

Bras, A., Ravijanya, C., de Sande, V. T., Riley, M., & Ralegaonkar, R. V. (2020). Sustainable and affordable prefab housing systems with minimal whole life energy use. *Energy and Buildings*, *220*(2020), 110030. https://doi.org/10.1016/j.enbuild.2020.110030

Buratti, C., Belloni, E., Lascaro, E., Merli, F., & Ricciardi, P. (2018). Rice husk panels for building applications: Thermal, acoustic and environmental characterization and comparison with other innovative recycled waste materials. *Construction and Building Materials*, *171*, 338–349. https://doi.org/10.1016/j.conbuildmat.2018.03.089

Buyle, M., Braet, J., & Audenaert, A. (2013). Life cycle assessment in the construction sector: A review. *Renewable and Sustainable Energy Reviews*, *26*, 379–388. https://doi.org/10.1016/j.rser.2013.05.001

Bylund, D. M. (2014). *A COMPARATIVE STUDY OF THE SWEDISH AND AUSTRALIAN TIMBER CONSTRUCTION SECTORS LEADING TO THE DEVELOPMENT OF A This dissertation is presented for the degree of Doctor of Philosophy at The University of Western Australia .* University of Western Australia.

Cabeza, L. F., Rincón, L., Vilariño, V., Pérez, G., & Castell, A. (2014). Life cycle assessment (LCA) and life cycle energy analysis (LCEA) of buildings and the building sector: A review. *Renewable and Sustainable Energy Reviews*, *29*, 394–416. https://doi.org/10.1016/j.rser.2013.08.037

CDB. (2018). *Construction Development Board (Annual report 2017-2018)*.

Chan, A. P. C., & Adabre, M. A. (2019). Bridging the gap between sustainable housing and affordable housing: The required critical success criteria (CSC). *Building and Environment*, *151*(November 2018), 112–125. https://doi.org/10.1016/j.buildenv.2019.01.029

Chan, D. W. M., & Chan, A. P. C. (2002). Public housing construction in hong kong: A review of its design and construction innovations. *Architectural Science Review*, *45*(4), 349–359. https://doi.org/10.1080/00038628.2002.9696950

Chau, C. K., Leung, T. M., & Ng, W. Y. (2015). A review on life cycle assessment, life cycle energy assessment and life cycle carbon emissions assessment on buildings. *Applied Energy*, *143*(1), 395–413. https://doi.org/10.1016/j.apenergy.2015.01.023

Chen, W., Yang, S., Zhang, X., Jordan, N. D., & Huang, J. (2022). Embodied energy and carbon emissions of building materials in China. *Building and Environment*, *207*(PA), 108434. https://doi.org/10.1016/j.buildenv.2021.108434

Cherian, P., Paul, S., Krishna, S. R. G., Menon, D., & Meher Prasad, A. (2017). Mass Housing Using GFRG Panels: A Sustainable, Rapid and Affordable Solution. *Journal of The Institution of Engineers (India): Series A*, *98*(1–2), 95–100. https://doi.org/10.1007/s40030-017-0200-8

Churkina, G., Organschi, A., Reyer, C. P. O., Ruff, A., Vinke, K., Liu, Z., Reck, B. K., Graedel, T. E., & Schellnhuber, H. J. (2020). Buildings as a global carbon sink. *Nature Sustainability*, *3*(4), 269–276. https://doi.org/10.1038/s41893-019-0462-4

Cornaro, C., Zanella, V., Robazza, P., Belloni, E., & Buratti, C. (2020). An innovative straw bale wall package for sustainable buildings: experimental characterization, energy and environmental performance assessment. *Energy and Buildings*, *208*, 109636. https://doi.org/10.1016/j.enbuild.2019.109636

Correia Lopes, G., Vicente, R., Azenha, M., & Ferreira, T. M. (2018). A systematic review of Prefabricated Enclosure Wall Panel Systems: Focus on technology driven for performance requirements. *Sustainable Cities and Society*, *40*(December 2017), 688–703. https://doi.org/10.1016/j.scs.2017.12.027

Crawford, R. H., & Cadorel, X. (2017). A Framework for Assessing the Environmental Benefits of Mass Timber Construction. *Procedia Engineering*, *196*(June), 838–846. https://doi.org/10.1016/j.proeng.2017.08.015

Creswell, J. W., & Creswell, J. D. (2018). *Research design: Qualitative, quantitative and mixed methods approaches* (5th ed.). Thousand Oaks, CA: Sage Publications. http://library1.nida.ac.th/termpaper6/sd/2554/19755.pdf

Cripps, A. (2004). Cardboard as a construction material: A case study. *Building Research and Information*, *32*(3), 207–219. https://doi.org/10.1080/09613210410001686273

Dainty, A. R. J., Briscoe, G. H., & Millett, S. J. (2001). New perspectives on construction supply chain integration. *Supply Chain Management*, *6*(4), 163–173. https://doi.org/10.1108/13598540110402700

Debnath, A., Singh, S. V., & Singh, Y. P. (1995). Comparative assessment of energy requirements for different types of residential buildings in India. *Energy and Buildings*, *23*(2), 141–146. https://doi.org/10.1016/0378-7788(95)00939-6

Department of Forests and Park Services. (2013). *Forest Resources Potential Assessment of Bhutan 2013*.

Department of Forests and Park Services. (2016). *National Forest Inventory Report: Stocking Nation's Forest Resources (Vol I)*.

Department of Forests and Park Services. (2021). *Annual Forestry Statistics 2021*.

Department of Urban Development and Housing. (2002). *Traditional Architecture Guidelines*. Department of Urban Development and Housing.

Dey, D., Gyeltshen, T., Aich, A., Naskar, M., & Roy, A. (2020). Climate adaptive crop-residue management for soil-function improvement; recommendations from field interventions at two agro-ecological zones in South Asia. *Environmental Research*, *183*(November 2019), 109164.

https://doi.org/10.1016/j.envres.2020.109164

Dixit, M. K., Fernández-Solís, J. L., Lavy, S., & Culp, C. H. (2010). Identification of parameters for embodied energy measurement: A literature review. *Energy and Buildings*, *42*(8), 1238–1247. https://doi.org/10.1016/j.enbuild.2010.02.016

Dorji, T. (2018). *Revised sand supply system goes nationwide*. Kuenselonline. https://kuenselonline.com/revised-sand-supply-system-goes-nationwide/

Durlinger, B., Crossin, E., & Wong, J. (2013). *Life cycle assessment of a cross laminated timber building*. https://researchrepository.rmit.edu.au/esploro/outputs/report/Life-cycle-assessment-of-a-cross-laminated-timber-building/9921861834901341#file-0

El-Didamony, H., Amer, A. A., Mohammed, M. S., & El-Hakim, M. A. (2019). Fabrication and properties of autoclaved aerated concrete containing agriculture and industrial solid wastes. *Journal of Building Engineering*, *22*(June 2018), 528–538. https://doi.org/10.1016/j.jobe.2019.01.023

Evison, D. C., Kremer, P. D., & Guiver, J. (2018). Mass timber construction in Australia and New Zealand-status, and economic and environmental influences on adoption. *Wood and Fiber Science*, *50*, 128–138. https://doi.org/10.22382/wfs-2018-046

Falk, B. (2009). Wood as a sustainable building material. *Forest Products Journal*, *59*(9), 6–12.

Forest Resources Management Division. (2017). *Report of Evaluation of Different Sawmill Technologies Using Multi-Criteria Analysis (MCA)*. https://www.dofps.gov.bt/reports/

Gan, X., Zuo, J., Wu, P., Wang, J., Chang, R., & Wen, T. (2017). How affordable housing becomes more sustainable? A stakeholder study. *Journal of Cleaner Production*, *162*, 427–437. https://doi.org/10.1016/j.jclepro.2017.06.048

Ganiron Jr, T. U. (2016). Development and efficiency of prefabricated building components. *International Journal of Smart Home*, *10*(6), 85–94. https://doi.org/10.14257/ijsh.2016.10.6.10

Gibb, A. G. . (1999). *Offsite Fabrication: prefabrication, pre-assembly and modularisation*. John Wiley & Sons.

Gibb, A. G. F. (2001). *Pre-assembly in Construction (CRISP)* (Issue May). https://hdl.handle.net/2134/25702

Gibb, A. G. F., & Isack, F. (2003). Re-engineering through pre-assembly: Client expectations and drivers. *Building Research and Information*, *31*(2), 146–160. https://doi.org/10.1080/09613210302000

González, O. M., García, A., Guachambala, M., & Navas, J. F. (2021). Innovative sandwich-like composite biopanels–towards a new building biomaterials concept for structural applications in nonconventional building systems. *Wood Material Science and Engineering*, *16*(2), 132–148. https://doi.org/10.1080/17480272.2020.1819871

Green, E., Hope, T., & Yates, A. (2013). *Sustainable Buildings*. Institution of Civil Engineers.

Green Public Procurement in Bhutan. (2015). *Market Assessment of Green Goods , Services and Works in Bhutan Contextualising and validating target sectors and creating the Green Public*

Procurement in Bhutan (Issue September).

Groat, L., & Wang, D. (2013). *Architectural research methods*. John Wiley & Sons. https://www.researchgate.net/publication/269107473_What_is_governance/link/548173090cf22525dcb61443/download%0Ahttp://www.econ.upf.edu/~reynal/Civil wars_12December2010.pdf%0Ahttps://think-asia.org/handle/11540/8282%0Ahttps://www.jstor.org/stable/41857625

Gu, H., Liang, S., & Bergman, R. (2020). Comparison of building construction and life-cycle cost for a high-rise mass timber building with its concrete alternative. *Forest Products Journal*, *70*(4), 482–492. https://doi.org/10.13073/FPJ-D-20-00052

Guinée, J. B., Heijungs, R., Huppes, G., Zamagni, A., Masoni, P., Buonamici, R., Ekvall, T., & Rydberg, T. (2011). Life cycle assessment: past, present, and future. *Environmental Science & Technology*, *45*(1), 90–96. https://doi.org/10.1021/es101316v

Gundes, S. (2016). The Use of Life Cycle Techniques in the Assessment of Sustainability. *Procedia - Social and Behavioral Sciences*, *216*, 916–922. https://doi.org/https://doi.org/10.1016/j.sbspro.2015.12.088

Haas, C. T., & Fagerlund, W. R. (2002). *Preliminary research on prefabrication, pre-assembly, modularization and off-site fabrication in construction* (Issue July).

Hammond, G., & Jones, C. (2008). *Inventory of Carbon & Energy (Ice)*.

Harte, A. M. (2017). Mass timber – the emergence of a modern construction material. *Journal of Structural Integrity and Maintenance*, *2*(3), 121–132. https://doi.org/10.1080/24705314.2017.1354156

Hoxha, V. (2020). Measuring embodied CO2 emission in construction materials in Kosovo apartments. *International Journal of Building Pathology and Adaptation*, *38*(3), 405–421. https://doi.org/10.1108/IJBPA-02-2019-0013

Ibn-Mohammed, T., Greenough, R., Taylor, S., Ozawa-Meida, L., & Acquaye, A. (2013). Operational vs. embodied emissions in buildings - A review of current trends. *Energy and Buildings*, *66*, 232–245. https://doi.org/10.1016/j.enbuild.2013.07.026

International Organization for Standardization. (2006). Environmental Management - Life Cycle Assessment - Principles and Framework (ISO 14040:2006). In *ISO*. https://www.iso.org/standard/23151.html

Islam, H., Jollands, M., & Setunge, S. (2015). Life cycle assessment and life cycle cost implication of residential buildings—A review. *Renewable and Sustainable Energy Reviews*, *42*, 129–140. https://doi.org/https://doi.org/10.1016/j.rser.2014.10.006

Joseph, J. D. R. (2021). Precast Concrete Sandwich Panels for Mass Housing Systems: Plan and Design Strength Requirements. *Journal of The Institution of Engineers (India): Series A*, *102*(1), 359–368. https://doi.org/10.1007/s40030-020-00486-w

Kadir, M. R. A., Lee, W. P., Jaafar, M. S., Sapuan, S. M., & Ali, A. A. A. (2006). Construction performance comparison between conventional and industrialised building systems in Malaysia.

Structural Survey, *24*(5), 412–424. https://doi.org/10.1108/02630800610712004

Kalpana, M., & Mohith, S. (2020). Study on autoclaved aerated concrete: Review. *Materials Today: Proceedings*, *22*(xxxx), 894–896. https://doi.org/10.1016/j.matpr.2019.11.099

Kamar, A. M., Abd Hamid, Z., Mna, A., Anuar Mohd Kamar, K., Nor Azhari Azman, M., & Sanusi Ahamad, M. S. (2011). Industrialized Building System (IBS): Revisiting Issues of Definition and Classification STEM Education Modules View project Affordable Housing Project View project Industrialized Building System (IBS): Revisiting Issues of Definition and Classification. *International Journal of Emerging Sciences*, *1*(2), 120–132. https://www.researchgate.net/publication/251422513

Katwal, T. (2013). Multiple Cropping in Bhutanese Agriculture – Present Status and Opportunities. *Regional Consultative Meeting on Popularizing Multiple Cropping Innovations as a Means to Raise Productivity and Farm Income in SAARC Countries"*, 1–36.

Khan, R. A., Liew, M. S., & Ghazali, Z. Bin. (2014). Malaysian Construction Sector and Malaysia Vision 2020: Developed Nation Status. *Procedia - Social and Behavioral Sciences*, *109*, 507–513. https://doi.org/10.1016/j.sbspro.2013.12.498

Koebel, C. (1999). Sustaining Sustainability: Innovation in Housing and the Built Environment. *Journal of Urban Technology*, *6*, 75–94. https://doi.org/10.1080/10630739983597

Koebel, C. (2008). Innovation in Homebuilding and the Future of Housing. *Journal of the American Planning Association*, *74*, 45–58. https://doi.org/10.1080/01944360701768991

Koroneos, C., & Dompros, A. (2007). Environmental assessment of brick production in Greece. *Building and Environment*, *42*(5), 2114–2123. https://doi.org/10.1016/j.buildenv.2006.03.006

Kulatunga, U., Amaratunga, D., & Haigh, R. (2006, January 1). Construction innovation: a literature review on current research. *Sixth International Postgraduate Research Conference in the Built and Human Environment, Delft*.

Kumanayake, R., Luo, H., & Paulusz, N. (2018). Assessment of material related embodied carbon of an office building in Sri Lanka. *Energy and Buildings*, *166*, 250–257. https://doi.org/10.1016/j.enbuild.2018.01.065

Kumar, R. (2019). *Research methodology: A step-by-step guide for befinners.* Sage Publications Limited.

Liang, S., Gu, H., & Bergman, R. (2021). Environmental life-cycle assessment and life-cycle cost analysis of a high-rise mass timber building: A case study in pacific Northwestern United States. *Sustainability*, *13*(14). https://doi.org/10.3390/su13147831

Liang, S., Gu, H., Bergman, R., & Kelley, S. S. (2020). Comparative life-cycle assessment of a mass timber building and concrete alternative. *Wood and Fiber Science*, *52*(2), 217–229. https://doi.org/10.22382/wfs-2020-019

Liang, S., Gu, H., Bilek, T., & Bergman, R. (2019). Life-Cycle Cost Analysis of a Mass Timber Building: Methodology and hypothetical case study. In *Research Paper FPL-RP-702* (Issue October).

Lippke, B. B., Wilson, J., Perez-garcia, J., Bowyer, J., & Meil, J. (2004). CORRIM : Life-Cycle Environmental Performance of Renewable Building Materials. *Forest Products Journal*, *54*(6), 8–19.

Lu, W., Chen, K., Xue, F., & Pan, W. (2018). Searching for an optimal level of prefabrication in construction: An analytical framework. *Journal of Cleaner Production*, *201*, 236–245. https://doi.org/10.1016/j.jclepro.2018.07.319

Luo, Z., Cang, Y., Zhang, N., Yang, L., & Liu, J. (2019). A Quantitative Process-Based Inventory Study on Material Embodied Carbon Emissions of Residential, Office, and Commercial Buildings in China. *Journal of Thermal Science*, *28*(6), 1236–1251. https://doi.org/10.1007/s11630-019-1165-x

MacDicken, K. G., Sola, P., Hall, J. E., Sabogal, C., Tadoum, M., & de Wasseige, C. (2015). Global progress toward sustainable forest management. *Forest Ecology and Management*, *352*, 47–56. https://doi.org/10.1016/j.foreco.2015.02.005

Mateus, R., Neiva, S., Bragança, L., Mendonça, P., & Macieira, M. (2013). Sustainability assessment of an innovative lightweight building technology for partition walls - Comparison with conventional technologies. *Building and Environment*, *67,* 147–159. https://doi.org/10.1016/j.buildenv.2013.05.012

Ministry of Agriculture and Forests. (2011). *National Forest Policy of Bhutan 2011*. Royal Government of Bhutan.

Ministry of Economic Affairs. (2018). Detailed Feasibility Study on Industrial Linkages and Cluster (Mineral Based Industry). In *Detailed Feasibility Study on Industrial Linkages and Cluster (Mineral Based Industry)* (Issue June). https://www.moea.gov.bt/wp-content/uploads/2017/10/Final-Report-Complete.pdf

Ministry of Economics Affairs. (2019). *Report on import substitution opportunities*.

Ministry of Works & Human Settlement. (2019). *National housing policy (Revised), 2019* (Issue March). Ministry of Works & Human Settlement.

Moghayedi, A., Awuzie, B., Omotayo, T., Le Jeune, K., Massyn, M., Ekpo, C. O., Braune, M., & Byron, P. (2021). A critical success factor framework for implementing sustainable innovative and affordable housing: A systematic review and bibliometric analysis. *Buildings*, *11*(8), 1–31. https://doi.org/10.3390/buildings11080317

Moncaster, A. M., & Song, J.-Y. (2012). A comparative review of existing data and methodologies for calculating embodied energy and carbon of buildings. *International Journal of Sustainable Building Technology and Urban Development*, *3*(1), 26–36. https://doi.org/10.1080/2093761X.2012.673915

Mousa, M. A., & Uddin, N. (2009). Experimental and analytical study of carbon fiber-reinforced polymer (FRP)/autoclaved aerated concrete (AAC) sandwich panels. *Engineering Structures*, *31*(10), 2337–2344. https://doi.org/10.1016/j.engstruct.2009.05.009

MoWHS. (2015). *Infrastructure Development in Bhutan: A journey through time*. MoWHS.

https://www.mowhs.gov.bt/wp-content/uploads/2014/03/Final_MoWHS_Magazine_2015-1.pdf

Mulliner, E., & Maliene, V. (2011). Environmental Engineering Criteria for Sustainable Housing Affordability. *Environmental Engineering The 8th International Conference*, 1–8. http://enviro.vgtu.lt

Nanyam, V., Basu, R., Sawhney, A., & Prasad, J. K. (2015). Selection Framework for Evaluating Housing Technologies. *Procedia Engineering*, *123*, 333–341. https://doi.org/10.1016/j.proeng.2015.10.044

National Environment Commission. (2019). *National Waste Management Strategy 2019*.

National Statistics Bureau. (2018). *Population and housing census of Bhutan 2017 (National Report)*. https://www.nsb.gov.bt/download/5006/

Natural Resources Canada. (2021). *The State of Mass Timber in Canada 2021*. https://scf.rncan.gc.ca/publications?id=40364

Navaratnam, S., Ngo, T., Gunawardena, T., & Henderson, D. (2019). Performance Review of Prefabricated Building Systems and Future Research in Australia. *Buildings*, 1–14. https://doi.org/10.3390/buildings9020038

Nie, Z., & Zuo, T. (2003). Ecomaterials research and development activities in China. *Current Opinion in Solid State and Materials Science*, *7*(3), 217–223. https://doi.org/10.1016/j.cossms.2003.09.009

Noorzai, E., Gharouni Jafari, K., & Naeni, L. (2020). Lessons Learned on Selecting the Best Mass Housing Method Based on Performance Evaluation Criteria in Iran. *International Journal of Construction Education and Research*. https://doi.org/10.1080/15578771.2020.1867258

NSB. (2017). *Bhutan living standards survey*.

O'Hegarty, R., & Kinnane, O. (2020). Review of precast concrete sandwich panels and their innovations. *Construction and Building Materials*, *233*, 117145. https://doi.org/10.1016/j.conbuildmat.2019.117145

O'Hegarty, R., Kinnane, O., Grimes, M., Newell, J., Clifford, M., & West, R. (2021). Development of thin precast concrete sandwich panels: Challenges and outcomes. *Construction and Building Materials*, *267*, 120981. https://doi.org/10.1016/j.conbuildmat.2020.120981

Ofori, G. (1985). Indigenous construction materials programmes. *Habitat International*, *9*(1), 71–79. https://doi.org/10.1016/0197-3975(85)90034-7

Ofori, G. (2000). Greening the construction supply chain in Singapore. *European Journal of Purchasing and Supply Management*, *6*(3–4), 195–206. https://doi.org/10.1016/S0969-7012(00)00015-0

Ofori, G. (2015). Nature of the construction industry, its needs and its development: A review of four decades of research. *Journal of Construction in Developing Countries*, *20*(2), 115–135.

Oladinrin, T., Ogunsemi, D., & Aje, I. (2012). Role of Construction Sector in Economic Growth: Empirical Evidence from Nigeria. *FUTY Journal of the Environment*, *7*(1), 50–60. https://doi.org/10.4314/fje.v7i1.4

Oliver, C. D., Nassar, N. T., Lippke, B. R., & McCarter, J. B. (2014). Carbon, Fossil Fuel, and Biodiversity Mitigation With Wood and Forests. *Journal of Sustainable Forestry*, *33*(3), 248–275. https://doi.org/10.1080/10549811.2013.839386

Ortiz, O., Castells, F., & Sonnemann, G. (2009). Sustainability in the construction industry: A review of recent developments based on LCA. *Construction and Building Materials*, *23*(1), 28–39. https://doi.org/10.1016/j.conbuildmat.2007.11.012

Oyebanji, A. O., Liyanage, C., & Akintoye, A. (2017). Critical Success Factors (CSFs) for achieving sustainable social housing (SSH). *International Journal of Sustainable Built Environment*, *6*(1), 216–227. https://doi.org/10.1016/j.ijsbe.2017.03.006

Petrović, B., Zhang, X., Eriksson, O., & Wallhagen, M. (2021). Life cycle cost analysis of a single-family house in Sweden. *Buildings*, *11*(5). https://doi.org/10.3390/buildings11050215

Puri, V., Chakrabortty, P., Anand, S., & Majumdar, S. (2017). Bamboo reinforced prefabricated wall panels for low cost housing. *Journal of Building Engineering*, *9*(April 2016), 52–59. https://doi.org/10.1016/j.jobe.2016.11.010

RAA. (2019). *Performance audit report on housing development- adequacy and affordability*. http://www.bhutanaudit.gov.bt/wp-content/uploads/2020/08/PA-Report-on-Housing-Development-Adequacy-and-Affordability.pdf

Raj, A., Borsaikia, A. C., & Dixit, U. S. (2020). Manufacturing of autoclaved aerated concrete (AAC): present status and future trends. *Advances in Simulation, Product Design and Development*, 825–833.

Reddy, B. V. V., & Jagadish, K. S. (2003). Embodied energy of common and alternative building materials and technologies. *Energy and Buildings*, *35*(2), 129–137. https://doi.org/10.1016/S0378-7788(01)00141-4

RGoB. (1961). *First Five Year Plan (1961-1966)*. Royal Government of Bhutan. https://web.archive.org/web/20150924022742/http://www.gnhc.gov.bt/wp-content/uploads/2011/04/1stFYP.pdf

RGoB. (1966). *Second Five Year Plan (1966-1971)*. Royal Government of Bhutan. https://web.archive.org/web/20120320061913/http://www.gnhc.gov.bt/wp-content/uploads/2011/04/02fyp.pdf

RGoB. (1972). *Third Five Year Plan (1972-1976)*. Royal Government of Bhutan. https://doi.org/10.7312/flor94524-002

RGoB. (1977). *Fourth Five Year Plan (1977-1981)*. Royal Government of Bhutan. https://web.archive.org/web/20150714121631/http://www.gnhc.gov.bt/wp-content/uploads/2011/04/sailent-feature-of-4th-Plan.pdf

RGoB. (1981). *Fifth Five Year Plan (1981-1986)*. Royal Government of Bhutan. https://doi.org/10.7312/boyd90212-002

RGoB. (1987). *Sixth Five Year Plan (1987-1992)*. Royal Government of Bhutan. https://web.archive.org/web/20130618151812/http://www.gnhc.gov.bt/wp-content/uploads/2011/04/06fyp.pdf

RGoB. (1997). *Eight Five Year Plan (1997-2002)*. Royal Government of Bhutan. https://web.archive.org/web/20160304190503/http://www.gnhc.gov.bt/wp-content/uploads/2011/04/08fyp.pdf

RGoB. (2002). *Ninth Five Year Plan (2002-2007)*. Royal Government of Bhutan. https://web.archive.org/web/20120320060614/http://www.gnhc.gov.bt/wp-content/uploads/2011/04/5yp09_main.pdf

RGoB. (2008). *Tenth Five Year Plan (2008-2013)- Vol I*. Royal Government of Bhutan. https://web.archive.org/web/20140308050118/http://www.gnhc.gov.bt/wp-content/uploads/2011/10thplan/TenthPlan_Vol1_Web.pdf

RGoB. (2013). *Eleventh Five Year Plan (2013-2017)*. Royal Government of Bhutan. https://web.archive.org/web/20170120142639/http://www.gnhc.gov.bt/wp-content/uploads/2011/

RGoB. (2018). *Twelfth Five Year Plan (2018-2023)-Vol I*. Royal Government of Bhutan. https://www.gnhc.gov.bt/en/wp-content/uploads/2019/05/12FYP_VOL1_12JUN19.pdf

Ritter, M., Skog, K., & Bergman, R. (2011). *Science supporting the economic and environmental benefits of using wood and wood products in green building construction. General Technical Report FPL-GTR-206.* http://www2.fpl.fs.fed.us/products/publications/display_publications_for_specific_author.php?employee_id=10

Rosenfeld, Y. (1994). Innovative construction methods. *Construction Management and Economics*, *12*(6), 521–541. https://doi.org/10.1080/01446199400000063

Royal Audit Authority. (2019). *Performance audit report on housing development- adequacy and affordability*.

Sala, S., Ciuffo, B., & Nijkamp, P. (2015). A systemic framework for sustainability assessment. *Ecological Economics*, *119*, 314–325. https://doi.org/10.1016/j.ecolecon.2015.09.015

Salama, A. M., & Alshuwaikhat, H. (2006). A Trans-Disciplinary Approach for a Comprehensive Understanding of Sustainable Affordable Housing. *Global Built Environment Review*, *5*(3), 35–50. http://www.globalbuiltenvironmentreview.co.uk/Pages/default.aspx

Sathre, R., & O'Connor, J. (2010). Meta-analysis of greenhouse gas displacement factors of wood product substitution. *Environmental Science and Policy*, *13*(2), 104–114. https://doi.org/10.1016/j.envsci.2009.12.005

Secchi, S., Asdrubali, F., Cellai, G., Nannipieri, E., Rotili, A., & Vannucchi, I. (2016). Experimental and environmental analysis of new sound-absorbing and insulating elements in recycled cardboard. *Journal of Building Engineering*, *5*, 1–12. https://doi.org/10.1016/j.jobe.2015.10.005

Shams, A., Stark, A., Hoogen, F., Hegger, J., & Schneider, H. (2015). Innovative sandwich structures made of high performance concrete and foamed polyurethane. *COMPOSITE STRUCTURE*, *121*, 271–279. https://doi.org/10.1016/j.compstruct.2014.11.026

Shams, S., Mahmud, K., & Al-Amin, M. (2011). A comparative analysis of building materials for sustainable construction with emphasis on CO2 reduction. *International Journal of Environment and Sustainable Development*, *10*(4), 364–374. https://doi.org/10.1504/IJESD.2011.047767

Siry, J. P., Cubbage, F. W., & Ahmed, M. R. (2005). Sustainable forest management: Global trends and opportunities. *Forest Policy and Economics*, *7*(4), 551–561. https://doi.org/10.1016/j.forpol.2003.09.003

Slaughter, S. E. (1998). Models of construction innovation. *Journal of Construction Engineering and Management*, *124*, 226–231.

Smith, R. E., Griffin, G., & Rice, T. (2015). *Solid Timber Construction: Process, Practice, Performance*. https://www.nibs.org/reports/site-studies-solid-timber-construction

Sneha, K., & Tezeswi, T. P. (2016). A comparative study of construction using Schnell Concrewall® pre-cast sandwich composite panel and RC moment frame with brick infill. *International Journal of Civil Engineering and Technology*, *7*(4), 100–110.

Sorathiya, R. (2019). *Literature Review of Cost Information on Mid-Rise Mass-Timber Building Projects* (Issue August).

Steinhardt, D. A., & Manley, K. (2016). Adoption of prefabricated housing – the role of country context. *Sustainable Cities and Society*, *22*, 126–135.

Syngros, G., Balaras, C. A., & Koubogiannis, D. G. (2017). Embodied CO 2 Emissions in Building Construction Materials of Hellenic Dwellings. *Procedia Environmental Sciences*, *38*, 500–508. https://doi.org/10.1016/j.proenv.2017.03.113

Taghipour, A., Canbay, E., Binici, B., Aldemir, A., Uzgan, U., & Eryurtlu, Z. (2018). Seismic behavior of reinforced autoclaved aerated concrete wall panels. *Ce/Papers*, *2*(4), 259–265. https://doi.org/10.1002/cepa.818

Tam, C. M., Deng, Z. M., & Zeng, S. X. (2002). Evaluation of construction methods and performance for high rise public housing construction in Hong Kong. *Building and Environment*, *37*, 983–991. https://doi.org/10.1016/S0360-1323(01)00081-6

Tam, C. M., Tam, V. W. Y., Chan, J. K. W., & William, C. Y. (2005). Use of prefabrication to minimize construction waste - a case study approach. *International Journal of Construction Management*, *5*(1), 91–101. https://doi.org/10.1080/15623599.2005.10773069

Tam, V., Tam, C. M., Zeng, S. X., & Ng, W. C. Y. (2007). Towards adoption of prefabrication in construction. *Building and Environment*, *42*, 3642–3654. https://doi.org/10.1016/j.buildenv.2006.10.003

Tam, V. W. Y., Fung, I. W. H., Sing, M. C. P., & Ogunlana, S. O. (2015). Best practice of prefabrication implementation in the Hong Kong public and private sectors. *Journal of Cleaner Production*, *109*, 216–231. https://doi.org/10.1016/j.jclepro.2014.09.045

Tam, V. W. Y., Tam, C. M., & Ng, W. C. Y. (2007). An examination on the practice of adopting prefabrication for construction projects. *International Journal of Construction Management*, *7*(2), 53–64. https://doi.org/10.1080/15623599.2007.10773102

Tatum, C. B. (1986). Potential Mechanisms for Construction Innovation. *Journal of Construction*

Engineering and Management, *112*(2), 178–191. https://doi.org/10.1061/(asce)0733-9364(1986)112:2(178)

Thinley, J., & Chimi. (2020). Innovative Approaches to Affordable Housing. *The Druk Journal*, *6*(ii), 86–99. http://drukjournal.bt/wp-content/uploads/2020/11/Innovative-Approaches-to-Affordable-Housing.pdf

Tirth, V., Algarni, S., Agarwal, N., & Saxena, A. (2019). Greenhouse gas emissions due to the construction of residential buildings in Moradabad, India. *Applied Ecology and Environmental Research*, *17*(5), 12111–12126. https://doi.org/10.15666/aeer/1705_1211112126

Upton, B., Miner, R., Spinney, M., & Heath, L. S. (2008). The greenhouse gas and energy impacts of using wood instead of alternatives in residential construction in the United States. *Biomass and Bioenergy*, *32*(1), 1–10. https://doi.org/10.1016/j.biombioe.2007.07.001

Uusitalo, P., & Lavikka, R. (2020). Technology transfer in the construction industry. *Journal of Technology Transfer*, *0123456789*. https://doi.org/10.1007/s10961-020-09820-7

van Boggelen, W., & van Boggelen, J. (2018). Sustainable building solutions with new generation autoclaved aerated concrete panel applications. *Ce/Papers*, *2*(4), 513–525. https://doi.org/10.1002/cepa.825

Varun, Sharma, A., Shree, V., & Nautiyal, H. (2012). Life cycle environmental assessment of an educational building in Northern India: A case study. *Sustainable Cities and Society*, *4*(1), 22–28. https://doi.org/10.1016/j.scs.2012.03.002

Wahane, A. (2017). Manufacturing Process of AAC Block. *International Journal of Innovative Research in Science, Engineering and Technology*, *6*(2), 4–11. https://doi.org/10.5281/zenodo.4980716

Wallbaum, H., Ostermeyer, Y., Salzer, C., & Zea Escamilla, E. (2012). Indicator based sustainability assessment tool for affordable housing construction technologies. *Ecological Indicators*, *18*, 353–364. https://doi.org/10.1016/j.ecolind.2011.12.005

Wang, L., Wu, Z., Liu, W., & Wan, L. (2018). Structural behavior of load-bearing sandwich wall panels with GFRP skin and a foam-web core. *Science and Engineering of Composite Materials*, *25*(1), 173–188. https://doi.org/10.1515/secm-2015-0260

Warszawski, A. (2003). *Industrialized and Automated Building Systems: A Managerial Approach*. Routledge.

Windapo, A., Omopariola, E. D., Olugboyega, O., & Moghayedi, A. (2021). Use and performance of conventional and sustainable building technologies in low-income housing. *Sustainable Cities and Society*, *65*(May 2020), 102606. https://doi.org/10.1016/j.scs.2020.102606

Wood Resources International. (2019). *Sawlogs Price Indices*. https://woodprices.com/sawlogs-price-indices/

Wu, G., Yang, R., Li, L., Bi, X., Liu, B., & Li, S. (2019). Factors influencing the application of prefabricated construction in China : From perspectives of technology promotion and cleaner production. *Journal of Cleaner Production*, *219*, 753–762.

https://doi.org/10.1016/j.jclepro.2019.02.110

Xue, X., Zhang, R., Yang, R., & Dai, J. (2014). Innovation in construction: A critical review and future research. *International Journal of Innovation Science*, *6*(2), 111–125. https://doi.org/10.1260/1757-2223.6.2.111

Yan, H., Shen, Q., Fan, L. C. H., Wang, Y., & Zhang, L. (2010). Greenhouse gas emissions in building construction: A case study of One Peking in Hong Kong. *Building and Environment*, *45*(4), 949–955. https://doi.org/10.1016/j.buildenv.2009.09.014

Yeh, B., Williamson, T., & Keith, E. (2008). Development of structural insulated panel standards. *Proceedings of the 2008 Structures Congress - Structures Congress 2008: Crossing the Borders*, *314*. https://doi.org/10.1061/41016(314)232

Yin, R. K. (2009). *Case study research: Design and methods (Vol 5)*. Sage Publications Limited.

Young, B. E., Seidu, R. D., Thayaparan, M., & Appiah-Kubi, J. (2020). Modular construction innovation in the UK: The case of residential buildings. *Proceedings of the International Conference on Industrial Engineering and Operations Management*, *0*(March), 806–816.

Yusof, N. A., Kamal, E. M., & Kong-seng, L. (2014). Are Innovations Being Created or Adopted in the Construction Industry ? Exploring Innovation in the Construction Industry. *Sage Open*, *4*(3), 1–9. https://doi.org/10.1177/2158244014552424

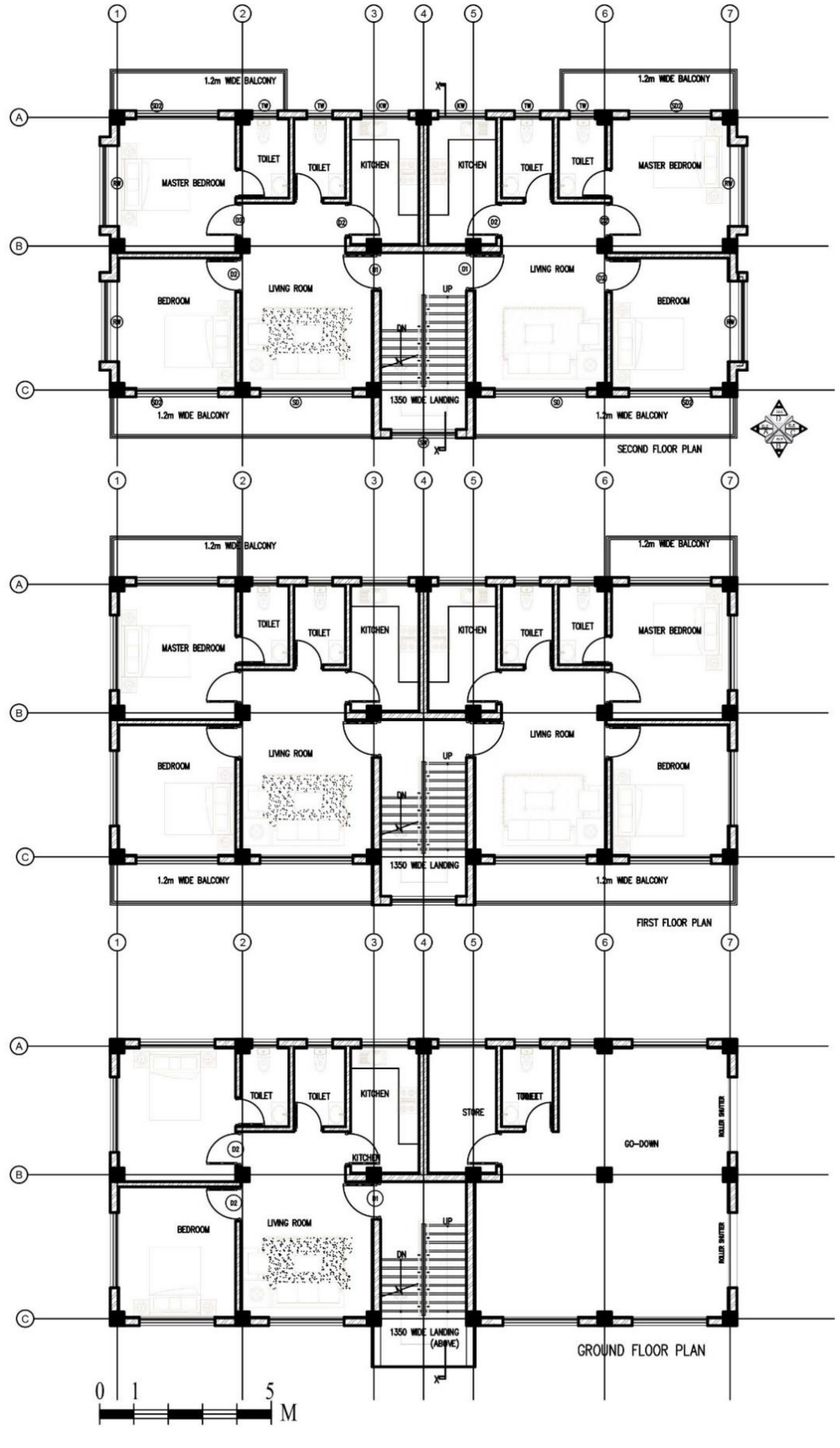
Zhang, S., Pan, Y., Li, N., & Sun, Q. (2014). A comparative study of the direct costs between prefabricated housing system and the traditional construction technology- A case study of precast concrete wall panel. In *Proceedings of the 18th International Symposium on Advancement of Construction Management and Real Estate* (pp. 349–358). Springer. https://doi.org/10.1007/978-3-642-44916-1_35

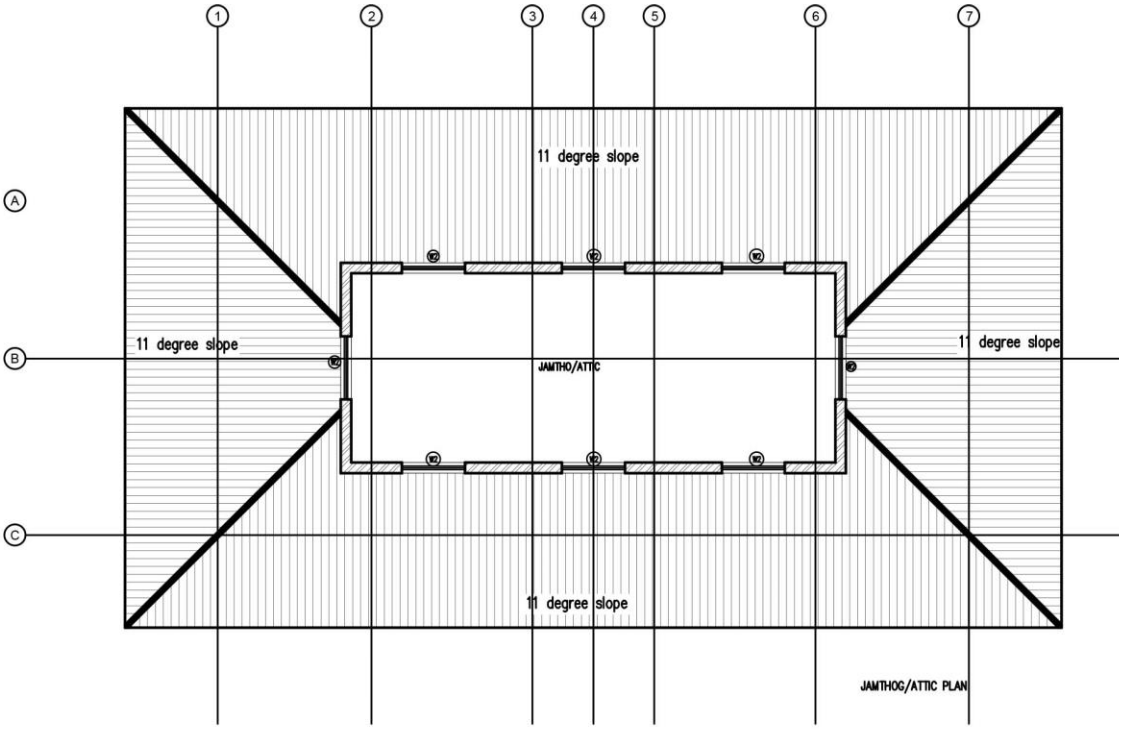
Zhang, X., & Wang, F. (2015). Life-cycle assessment and control measures for carbon emissions of typical buildings in China. *Building and Environment*, *86*, 89–97. https://doi.org/10.1016/j.buildenv.2015.01.003

Zhao, Z., Yang, X., Qu, X., Zheng, J., & Mai, F. (2021). Thermal insulation performance evaluation of autoclaved aerated concrete panels and sandwich panels based on temperature fields : Experiments and simulations. *Construction and Building Materials*, *303*(August), 124560. https://doi.org/10.1016/j.conbuildmat.2021.124560

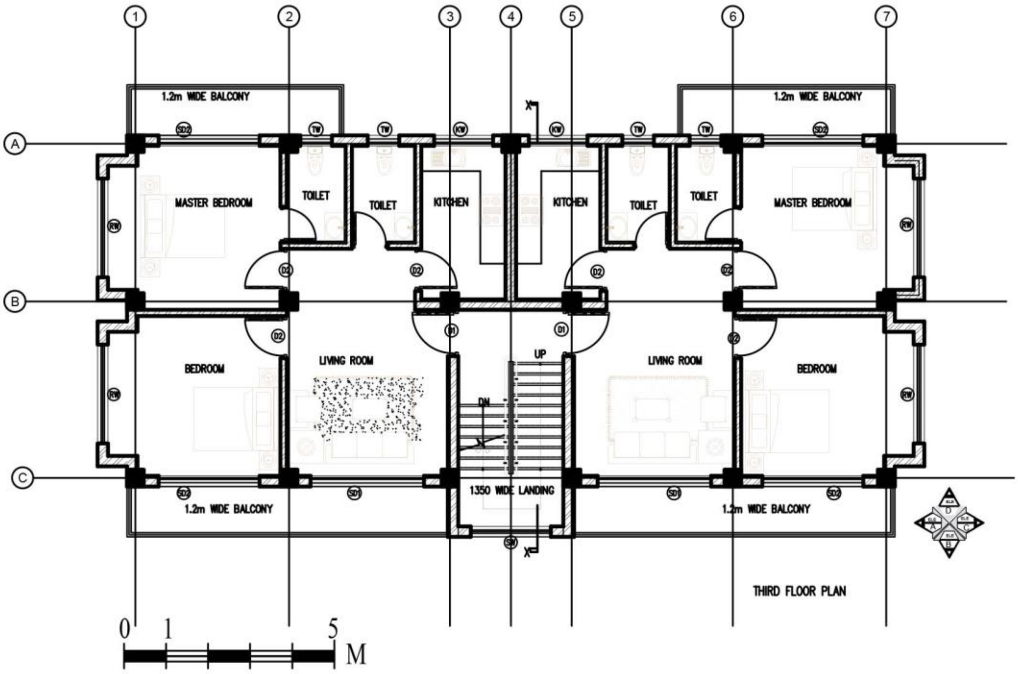
APPENDIX A

CONCRETE BUILDING A (ARCHITECTURE DRAWING)





JAMTHOG/ATTIC PLAN



THIRD FLOOR PLAN

APPENDIX B

CONCRETE BUILDING A (VOLUME CALCULATION)

Sl. No	Assemblage	No	Length (m)	Breadth (m)	Height (m)	Quantity (m3)	Remarks
1	**Floor/Slab**						
	GF roof slab		172.66		0.15	25.899	*Slab volume*
	FF roof slab		179.32		0.15	26.898	*Slab volume*
	SF roof slab		185.56		0.15	27.834	*Slab volume*
	TF roof slab		154.29		0.15	23.1435	*Slab volume*
	Total					**103.7745**	
2	**Column**	68	0.4	0.4	3	**32.64**	*Total column volume*
3	**Beam**						
	Beams supporting GF roof slab					7.92	*Beam volume (calculated from drawing)*
	Beams supporting FF roof slab					8.5536	*Beam volume+ balcony beam projection volume*
	Beams supporting SF roof slab					8.5536	*Beam volume+ balcony beam projection volume*
	Beams supporting TF roof slab					8.5536	*Beam volume+ balcony beam projection volume*
	Total					**33.5808**	
	RCC TOTAL					**169.9953**	*Total RCC volume*
4	**External wall**						
	Ground Floor (GF)		61.25	0.25	2.7	41.34375	*Wall volume by Centre line method*
			3.65	0.25	3	2.7375	*Central wall with 3 m height*
	First Floor (FF)		61.25	0.25	2.7	41.34375	*Wall volume by Centre line method*
			3.65	0.25	3	2.7375	*Central wall with 3 m height*
	Second Floor (SF)		64.55	0.25	2.7	43.57125	*Wall volume by Centre line method*
			3.65	0.25	3	2.7375	*Central wall with 3 m height*
	Third Floor (TF)		67.75	0.25	2.7	45.73125	*Wall volume by Centre line method*
			3.65	0.25	3	2.7375	*Central wall with 3 m height*
	Jamthog/Attic		33	0.25	3	24.75	*Wall volume by Centre line method*
	Substraction (Openings)						
	GF					-12.41	*Volume of Openings*
	FF					-15.76	*Volume of Openings*
	SF					-16.5	*Volume of Openings*
	TF					-16.5	*Volume of Openings*
	Jamthog/Attic					-2.7	*Volume of Openings*
	Substraction (Lintels)						
	GF					-1.245	*Volume of RCC lintel over openings*
	FF					-1.69	*Volume of RCC lintel over openings*
	SF					-1.84	*Volume of RCC lintel over openings*
	TF					-1.84	*Volume of RCC lintel over openings*
	Jamthog (top band/wall plate)					-0.825	
							Total lintel volume for exterior wall is 7.44
5	**Interior wall**						
	GF					12.06	*Total interior wall volume*
	FF					17.28	*Total interior wall volume*
	SF					17.28	*Total interior wall volume*
	TF					17.28	*Total interior wall volume*
	Substraction (Openings)						
	GF					-1.48	*Volume of Openings*
	FF					-2.96	*Volume of Openings*
	SF					-2.96	*Volume of Openings*
	TF					-2.96	*Volume of Openings*
	Substraction (Lintels)						
	GF					-0.093	*Volume of RCC lintel over openings*
	FF					-0.186	*Volume of RCC lintel over openings*
	SF					-0.186	*Volume of RCC lintel over openings*
	TF					-0.186	*Volume of RCC lintel over openings*
						-0.651	*Total lintel volume for interior wall is 0.65*
	Total (Exterior+Interior)					**189.269**	
6	**Staircase**						
	Wall (first landing)		4.9	0.25	3	3.675	
	Wall (second landing)		4.9	0.25	3	3.675	
	Wall (third landing)		4.9	0.25	4.225	5.175625	
	Subtraction (Openings)	3	1.9	0.25	1.8	-2.565	
	Subtraction (Lintels)	3	2.2	0.25	0.15	-0.2475	
	Total (staircase wall)					**9.713125**	
	Staircase RCC					**9.55**	*Volume calculation from building drawing*
	Total (exterior+interior+staircase wall)					**198.982125**	This includes column volume
	Substraction (Column volume)						
	GF					4.05	Column volume in exterior wall
						0.162	Column volume in interior wall
						4.212	
	FF					4.05	Column volume in exterior wall
						0.324	Column volume in interior wall
						4.374	
	SF					4.05	Column volume in exterior wall
						0.324	Column volume in interior wall
						4.374	
	TF					4.05	Column volume in exterior wall
						0.324	Column volume in interior wall
						4.374	
	Total					**17.334**	Total column volume
	WALL TOTAL					**181.648125**	Total wall volume

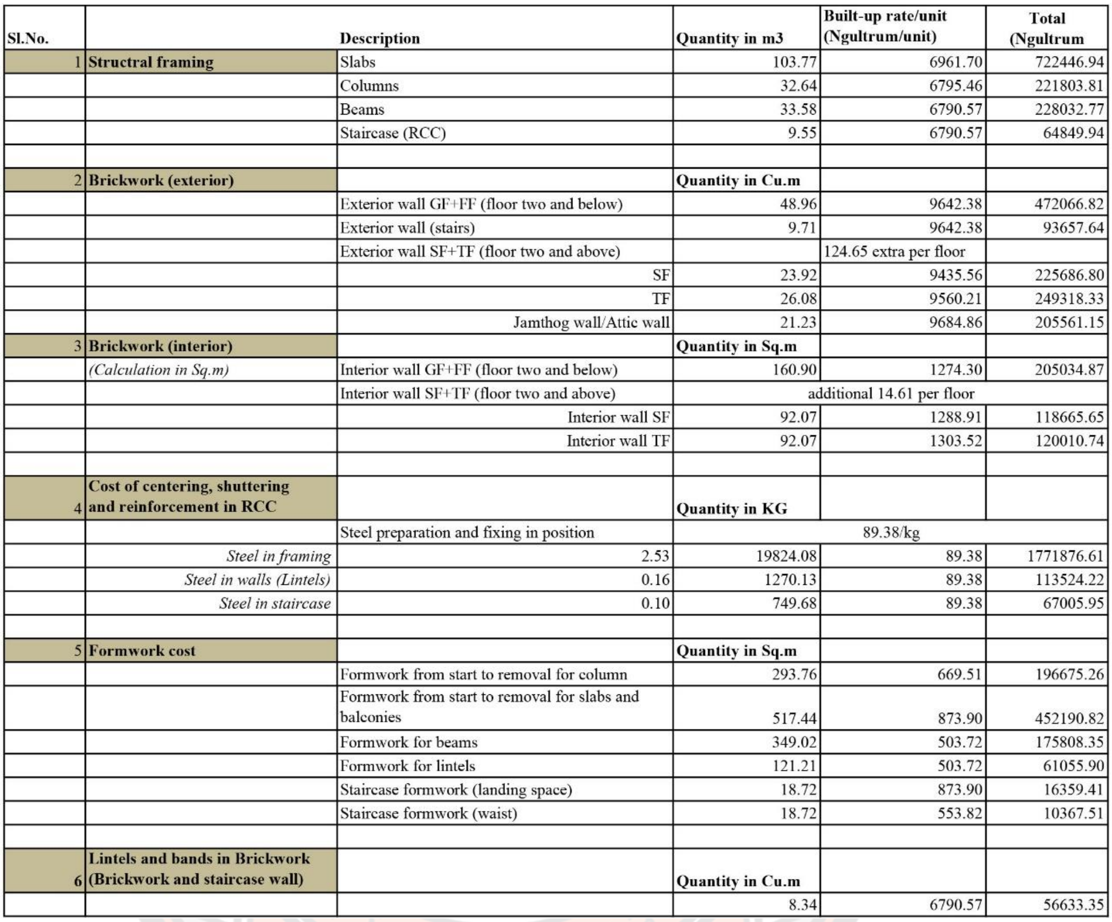
APPENDIX C

CONCRETE BUILDING A (MATERIAL COST)

Sl.no.	**Assemblage**	**Quantity (wet)**	**Quantity (dry)**	**Rate/unit**	**Material rate**	**Assumptions**
	Units	**m3**	**m3**	**Ngultrum (Nu)**	**Ngultrum (Nu)**	
1	**Floor slabs**	103.7745	**158.46**			
	Cement (1/5.5)		28.81	8147.5	234742.31	M20 (1:1.5:3)
	sand (1.5/5.5)		43.22	1124.15	48582.80	
	Aggregates (3/5.5)		86.43	1199.85	103708.70	
	Steel (1%)		1.04	61.09	497657.36	
					884691.17	
2	**Column**	32.64	**49.84**			
	Cement (1/5.5)		9.06	8147.5	73833.06	M20 (1:1.5:3)
	sand (1.5/5.5)		13.59	1124.15	15280.66	
	Aggregates (3/5.5)		27.19	1199.85	32619.31	
	Steel (2.5%)		0.82	61.09	391318.10	
					513051.13	
3	**Beam**	33.5808	**51.28**			
	Cement (1/5.5)		9.3232512	8147.5	75961.19	M20 (1:1.5:3)
	sand (1.5/5.5)		13.9848768	1124.15	15721.10	
	Aggregates (3/5.5)		27.9697536	1199.85	33559.51	
	Steel (2%)		0.671616	61.09	322077.82	
					447319.62	
4	**Brick wall**	181.65				
	Cement mortar(23%)	41.78				
	Cement mortar(wet)	48.05				15% extra for frog filling, brick bonding courses and wastages
	Cement mortar(dry)		**63.90**			
	Total bricks	90824.06		14.167	1286704.49	1Cu.m= 500 bricks, Nu. 14166.7/1000 bricks
	Cement		12.78	8147.5	104126.82	cement mortar ratio of 1:4
	Sand		51.12	1124.15	57467.52	
					1448298.84	
	Lintels & bands (RCC)	8.09	12.35			
	Cement (1/5.5)		2.25	8147.5	18299.92	M20 (1:1.5:3)
	sand (1.5/5.5)		3.37	1124.15	3787.39	
	Aggregates (3/5.5)		6.74	1199.85	8084.87	
	Steel (2%)		0.16	61.09	77592.24	
					107764.43	
	Staircase (RCC)	9.55	**14.58**			
	Cement (1/5.5)		2.65	8147.5	21602.50	M20 (1:1.5:3)
	sand (1.5/5.5)		3.98	1124.15	4470.90	
	Aggregates (3/5.5)		7.95	1199.85	9543.95	
	Steel (1%)		0.10	61.09	45797.65	
					81415.00	

APPENDIX D

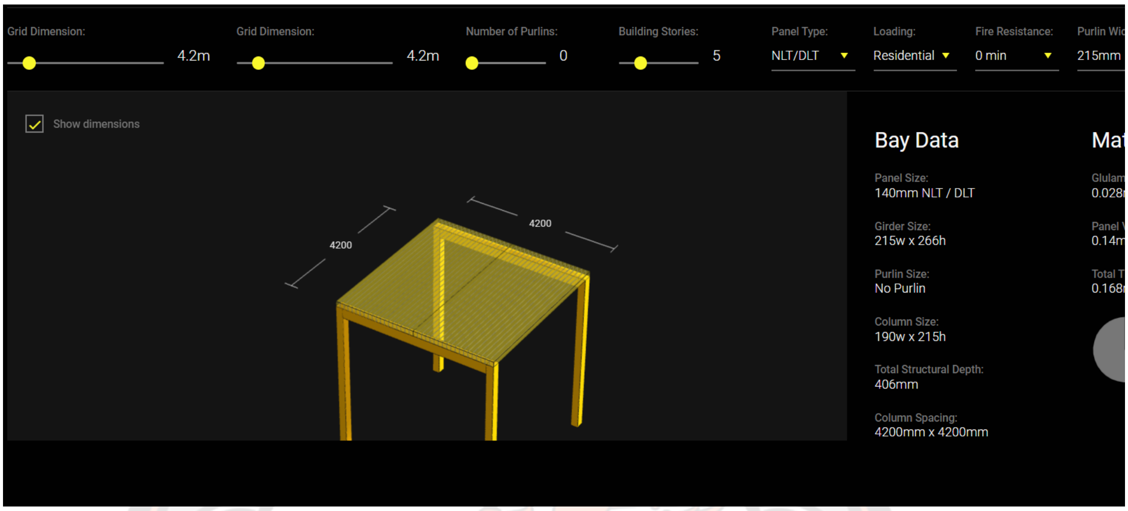
CONCRETE BUILDING A (BUILT-UP COST)



Sl.No.		Description	Quantity in m3	Built-up rate/unit (Ngultrum/unit)	Total (Ngultrum
1	**Structral framing**	Slabs	103.77	6961.70	722446.94
		Columns	32.64	6795.46	221803.81
		Beams	33.58	6790.57	228032.77
		Staircase (RCC)	9.55	6790.57	64849.94
2	**Brickwork (exterior)**		**Quantity in Cu.m**		
		Exterior wall GF+FF (floor two and below)	48.96	9642.38	472066.82
		Exterior wall (stairs)	9.71	9642.38	93657.64
		Exterior wall SF+TF (floor two and above)		124.65 extra per floor	
		SF	23.92	9435.56	225686.80
		TF	26.08	9560.21	249318.33
		Jamthog wall/Attic wall	21.23	9684.86	205561.15
3	**Brickwork (interior)**		**Quantity in Sq.m**		
	(Calculation in Sq.m)	Interior wall GF+FF (floor two and below)	160.90	1274.30	205034.87
		Interior wall SF+TF (floor two and above)	additional 14.61 per floor		
		Interior wall SF	92.07	1288.91	118665.65
		Interior wall TF	92.07	1303.52	120010.74
4	**Cost of centering, shuttering and reinforcement in RCC**		**Quantity in KG**		
		Steel preparation and fixing in position	89.38/kg		
	Steel in framing	2.53	19824.08	89.38	1771876.61
	Steel in walls (Lintels)	0.16	1270.13	89.38	113524.22
	Steel in staircase	0.10	749.68	89.38	67005.95
5	**Formwork cost**		**Quantity in Sq.m**		
		Formwork from start to removal for column	293.76	669.51	196675.26
		Formwork from start to removal for slabs and balconies	517.44	873.90	452190.82
		Formwork for beams	349.02	503.72	175808.35
		Formwork for lintels	121.21	503.72	61055.90
		Staircase formwork (landing space)	18.72	873.90	16359.41
		Staircase formwork (waist)	18.72	553.82	10367.51
6	**Lintels and bands in Brickwork (Brickwork and staircase wall)**		**Quantity in Cu.m**		
			8.34	6790.57	56633.35

APPENDIX E

MTC ALTERNATIVE OF CONCRETE BUILDING A (DESIGN EXPLORATION)



Grid Dimension: 4.2m

Grid Dimension: 4.2m

Number of Purlins: 0

Building Stories: 5

Panel Type: NLT/DLT

Loading: Residential

Fire Resistance: 0 min

Purlin Wi 215mm

☑ Show dimensions

Bay Data

Panel Size: 140mm NLT / DLT

Girder Size: 215w x 266h

Purlin Size: No Purlin

Column Size: 190w x 215h

Total Structural Depth: 406mm

Column Spacing: 4200mm x 4200mm

Mat

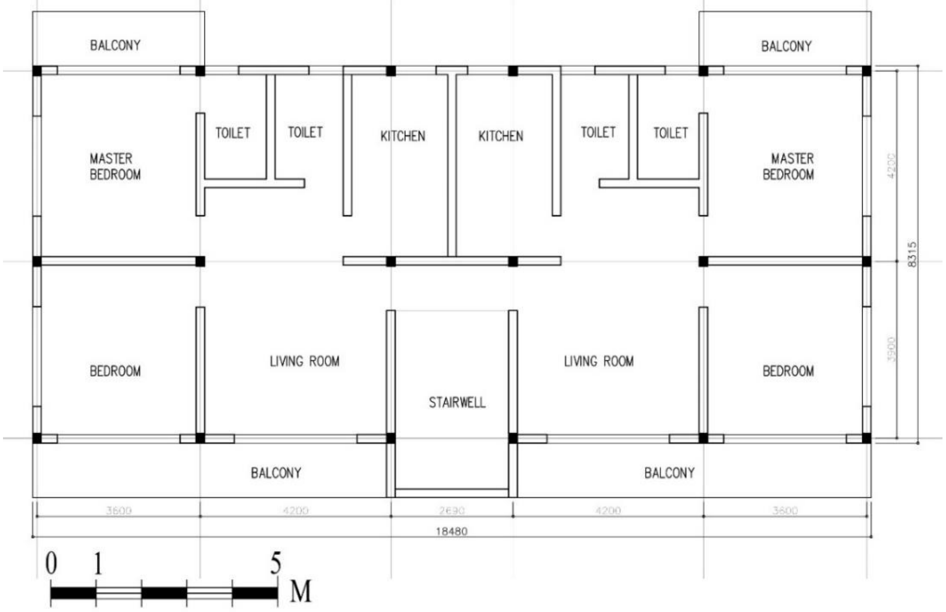
Glulam 0.028

Panel 0.14m

Total T 0.168

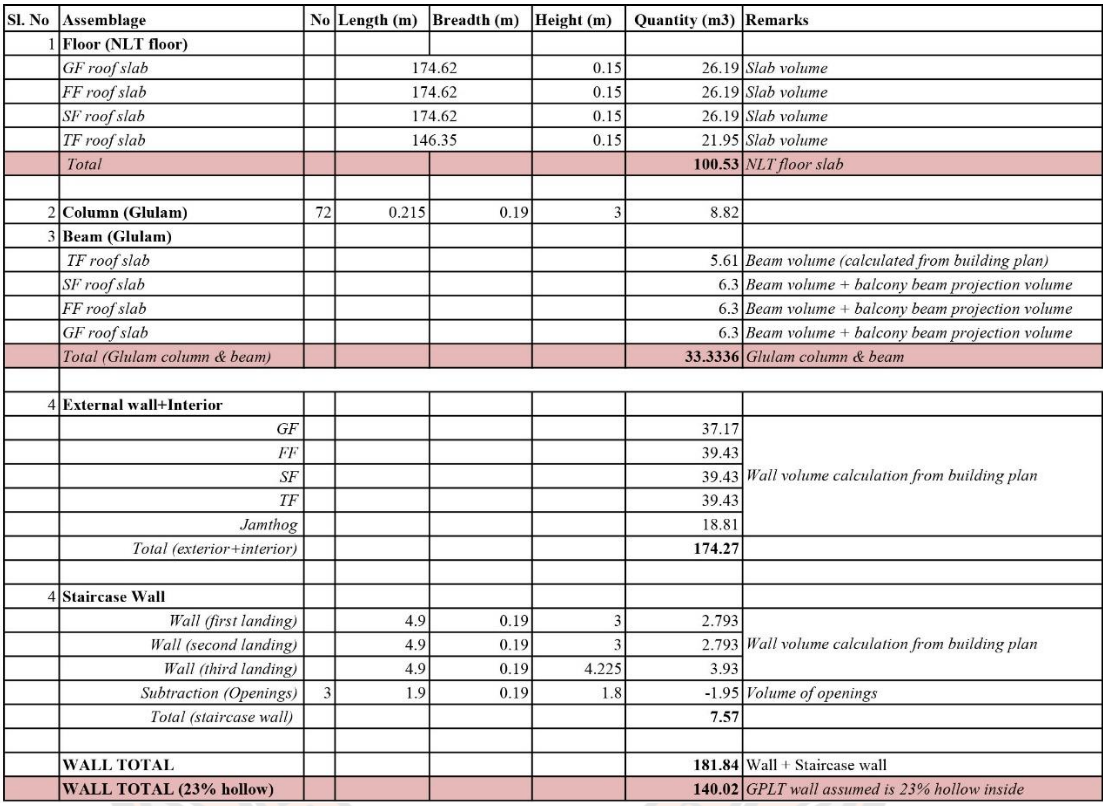
The image above shows the screenshot of design estimates for the MTC alternative from the Timber Bay Design Tool from Fast+ Epp firm. The following are the assumptions/considerations in this estimation:

- Outputs should be considered preliminary and are intended for concept purposes only. Structural engineer of record is responsible for the final design.
- Calculations performed based on CSA O86-14 & BCBC 2018.
- Vibration calculations are preliminary and should be investigated on a case-by-case basis.
- Panels and glulam members have fabrication and shipping constraints that vary between suppliers. Layouts should be reviewed with your selected suppliers.
- Floor panels are assumed to be two-span continuous, equally loaded interior panels.
- Calculations are performed using Douglas Fir species for columns, girders, purlins and GLT panels; Spruce-Pine-Fir species used for CLT/NLT/DLT panels.
- Volume take-offs are preliminary and assume a rectangular building layout; final volumes will vary depending on building shape.



APPENDIX F

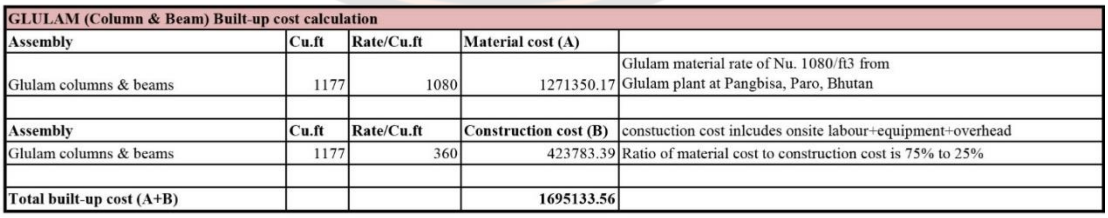
MTC ALTERNATIVE OF CONCRETE BUILDING A (VOLUME CALCULATION)



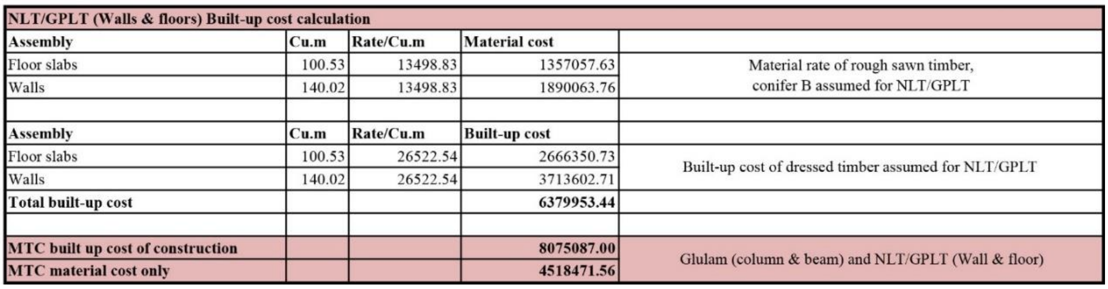
Sl. No	Assemblage	No	Length (m)	Breadth (m)	Height (m)	Quantity (m3)	Remarks
1	**Floor (NLT floor)**						
	GF roof slab		174.62		0.15	26.19	*Slab volume*
	FF roof slab		174.62		0.15	26.19	*Slab volume*
	SF roof slab		174.62		0.15	26.19	*Slab volume*
	TF roof slab		146.35		0.15	21.95	*Slab volume*
	Total					**100.53**	*NLT floor slab*
2	**Column (Glulam)**	72	0.215	0.19	3	8.82	
3	**Beam (Glulam)**						
	TF roof slab					5.61	*Beam volume (calculated from building plan)*
	SF roof slab					6.3	*Beam volume + balcony beam projection volume*
	FF roof slab					6.3	*Beam volume + balcony beam projection volume*
	GF roof slab					6.3	*Beam volume + balcony beam projection volume*
	Total (Glulam column & beam)					**33.3336**	*Glulam column & beam*
4	**External wall+Interior**						
	GF					37.17	*Wall volume calculation from building plan*
	FF					39.43	
	SF					39.43	
	TF					39.43	
	Jamthog					18.81	
	Total (exterior+interior)					**174.27**	
4	**Staircase Wall**						
	Wall (first landing)		4.9	0.19	3	2.793	*Wall volume calculation from building plan*
	Wall (second landing)		4.9	0.19	3	2.793	
	Wall (third landing)		4.9	0.19	4.225	3.93	
	Subtraction (Openings)	3	1.9	0.19	1.8	-1.95	*Volume of openings*
	Total (staircase wall)					**7.57**	
	WALL TOTAL					**181.84**	Wall + Staircase wall
	WALL TOTAL (23% hollow)					**140.02**	*GPLT wall assumed is 23% hollow inside*

APPENDIX G

MTC ALTERNATIVE OF CONCRETE BUILDING A (MATERIAL & BUILT-UP COST)



GLULAM (Column & Beam) Built-up cost calculation				
Assembly	**Cu.ft**	**Rate/Cu.ft**	**Material cost (A)**	
Glulam columns & beams	1177	1080	1271350.17	Glulam material rate of Nu. 1080/ft3 from Glulam plant at Pangbisa, Paro, Bhutan
Assembly	**Cu.ft**	**Rate/Cu.ft**	**Construction cost (B)**	constuction cost inlcudes onsite labour+equipment+overhead
Glulam columns & beams	1177	360	423783.39	Ratio of material cost to construction cost is 75% to 25%
Total built-up cost (A+B)			**1695133.56**	



NLT/GPLT (Walls & floors) Built-up cost calculation				
Assembly	**Cu.m**	**Rate/Cu.m**	**Material cost**	
Floor slabs	100.53	13498.83	1357057.63	Material rate of rough sawn timber, conifer B assumed for NLT/GPLT
Walls	140.02	13498.83	1890063.76	
Assembly	**Cu.m**	**Rate/Cu.m**	**Built-up cost**	
Floor slabs	100.53	26522.54	2666350.73	Built-up cost of dressed timber assumed for NLT/GPLT
Walls	140.02	26522.54	3713602.71	
Total built-up cost			**6379953.44**	
MTC built up cost of construction			**8075087.00**	Glulam (column & beam) and NLT/GPLT (Wall & floor)
MTC material cost only			**4518471.56**	