CRITICAL SUCCESS FACTORS TOWARDS THE INSTALLATION OF MODULAR MASS TIMBER FOR AFFORDABLE HOUSING IN THE US

By

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ABSTRACT

This research thesis investigates Modular Mass Timber (MMT) Construction as a viable solution for addressing the need for affordable and sustainable housing in the United States. The study aims to understand the intricacies of Modular Construction and Mass Timber, and their potential integration into the Affordable Multi-Family Housing market.

It evaluates the critical success factors (CSFs) necessary for the successful implementation of MMT in affordable housing projects, using a robust methodology that incorporates a comprehensive literature review, detailed case studies, expert interviews, and Total Interpretive Structural Modeling (TISM). The research identifies key factors such as sustainability benefits and strategic logistics as important factors in advancing MMT feasibility. The interconnectivity of these CSFs is emphasized as crucial for creating an environment conducive to MMT adoption, with additional focus on construction time, build quality, and operational efficiency. The thesis constructs an interrelationship model among these factors based on expert feedback and offers a strategic implementation guide for future installers and industry stakeholders. Overall, the findings contribute to the existing body of knowledge by providing a targeted implementation strategies and prioritized rubric for enhancing MMT installation in the U.S. affordable housing sector, underscoring the environmental and economic benefits essential for widespread adoption and implementation.

"Dedicated to those who dare to dream, strive to explore, and illuminate the path of life with relentless grit."

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Spartans Will.

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CHAPTER 1: INTRODUCTION

1.1 Overview

In the current landscape of global sustainability challenges and the pressing need for affordable housing, the construction industry stands at a pivotal crossroads. Embracing innovative approaches to material use and construction methodologies is not just an option but a necessity to meet climate goals and address housing crises. The concept of embodied carbon, standing for the comprehensive carbon footprint of building materials from their start to disposal, has become a focal point for reducing greenhouse gas emissions within the sector. Materials such as concrete, steel, and insulation, which significantly contribute to embodied carbon, are under scrutiny, with a push towards employing low-carbon or carbon-storing alternatives like wood, hemp, and bamboo, as well as recycled materials to mitigate environmental impacts (Liebetanz Kai 2022; Weir Madeline et al. 2023). Simultaneously, the housing crisis, worsened by the COVID-19 pandemic, calls for rapid, sustainable solutions. Affordable housing appears as a critical response to the dual demands of growing populations and the need for environmental stewardship, aiming to ensure housing accessibility across income groups while minimizing ecological footprints (Madgavkar A et al. 2023; United Nations 2023).

Enter mass timber and modular construction—two paradigms reshaping the future of construction through their potential for sustainability and efficiency. Mass timber products, like cross-laminated timber (CLT) and glue-laminated timber (GLT), offer renewable, carbon-sequestering options for building, aligning with the global shift towards greener materials (Frank Werner et al. 2007). Modular construction, characterized by off-site manufacturing and on-site assembly, presents a streamlined, less resource-intensive approach, promising significant reductions in construction time and waste, thus contributing to the affordability and accessibility of housing (Adabre et al. 2020; Khan et al. 2022). The amalgamation of these two innovative strategies - Modular Mass Timber (MMT) - appears as a promising solution to the intertwined challenges of climate change mitigation, efficient resource use, and the provision of affordable housing. This thesis aims to explore the Critical Success Factors (CSFs) towards the installation of modular mass timber for affordable housing in the US, navigating the complex interplay between environmental sustainability, economic viability, and social inclusivity in the pursuit of transformative change within the construction industry.

1.2 Modular Construction

Traditional construction methods (CMs) have long been significant contributors to the Architecture, Engineering, and Construction (AEC) industry (Adabre et al. 2020). However, the advent of industrialization in recent decades has ushered in modern methods of construction (MMC), revolutionizing the construction process by making it more convenient, less time-consuming, cost-effective, sustainable, and requiring less labor (Adabre et al. 2020). The emergence of Offsite Construction (OSC) methods, as exemplified by Modular Construction, is illustrative of this shift. Modular Construction involves the planning, design, manufacturing, fabrication, and preassembly of diverse building elements, components, and modules in a controlled environment, commonly referred to as factory production. These components are then transported to the construction site for final installation, helping the rapid creation of a permanent structure (Goodier and Gibb 2007). It is known by various terms worldwide, such as offsite construction, offsite manufacturing (OSM), offsite production (OSP), offsite fabrication (OSF), modern methods of construction (MMC), prefabrication, industrialized construction, volumetric, non-volumetric preassembly, part subassembly, and panelized assembly (Khan et al. 2022).

The concept of modularity underlies Modular Construction, involving the creation of product pieces independently, yet capable of configuration and integration into different systems using similar engineering principles. Modular Construction methods draw from the theories of modularity and modularization. Modularity, defined as breaking down complex systems into smaller components that interact based on specific standards and rules (Carliss Y. Baldwin and Kim B. Clark 2000), suits the construction industry well, allowing each element to be examined in isolation before integration into a complex building system. Modularization, on the other hand, is the pre-manufacturing of a complex system, creating large modules that are further broken down into smaller elements before being transported to the construction site (Amer and Maul 2019). Like assembling Lego bricks, Modular Construction involves stacking different modules on top of each other during the installation process to complete the structure. The rise of Modular Construction in recent years can be attributed to its substantial advantages over traditional construction methods. Researchers like Kamali and Hewage have highlighted the lifecycle benefits of Modular Construction, while Wuni and Shen have documented the critical success factors of Modular Construction projects within the construction industry. This method has found application in various building projects, including houses, hospitals, hotels, offices, retail outlets, universities, and supermarkets (Goodier and Gibb 2007). A 2023 McKinsey & Company report, meanwhile, said that less than 4% of current U.S. housing stock had been built using modular methods. (Blanco Jose Luis et al. 2023)Many researchers believe that Modular Construction stands for the future of the construction industry, offering extensive benefits and addressing challenges posed by traditional construction methods (Blismas and Wakefield 2009).

1.3 Mass Timber

1.3.1 Advantages

1.3.1.1 Advantages in Construction

Mass Timber construction involves the use of elements that are prefabricated off-site. Off-site fabrication, which entails the manufacturing and pre-assembly of building components before their installation at the construction site, harnesses the advantages offered by contemporary factory settings. The production of building system elements employing advanced measurement devices and manufacturing methods yields several benefits, including

Reduced climate impact: According to the Journal of Building Engineering, the adoption of mass-timber construction has the potential to diminish the global warming impact of buildings by as much as 26.5% (Pierobon et al. 2019).

Minimized material waste: This is achieved through a precise manufacturing process (Abed et al. 2022).

Reduced on-site time and energy waste: This is helped by the use of pre-assembly systems.

Optimized material value: Modern measurement devices, such as acoustic grading and machine grading, have the capability to predict the grade of timber, thereby enhancing its overall value.

Mass timber construction has been proven to reduce construction durations on projects by as much as 20% in comparison to more conventional methods, a factor particularly relevant when the timing of building approvals impacts returns on investment (Abed et al. 2022). Beyond its positive impact on forests, Cross Laminated Timber (CLT) offers various advantages within the construction industry. It stands out as a promising construction material due to its demonstrated energy efficiency, environmental friendliness, suitability for constructing relatively dense built environments, and ability to accelerate construction timelines. CLT serves as a thermal mass, storing heat during the day and releasing it at night, thereby reducing overall building energy consumption (Laguarda-Mallo & Espinoza, 2014). Furthermore, CLT is a renewable material that sequesters carbon instead of emitting it, as seen with concrete (Laguarda-Mallo et al. 2016). A key attribute of CLT is its high strength-to-weight ratio, resulting in smaller building foundations for comparable structural capabilities, enabling the construction of added floors with the same structural weight (Laguarda-Mallo et al. 2016). Additionally, CLT can be prefabricated in a controlled environment, helping safe construction (Abed et al. 2022).

1.3.1.2 Advantages in Forest Management

Mass Timber brings added value to the industry by employing lower-quality timber in applications of higher value. Cross Laminated Timber (CLT) presents a distinctive opportunity to use less valuable timber sourced from various origins, including less commonly used species, trees affected by disease or infection, and relatively young trees with smaller diameters (Laguarda-Mallo et al. 2016). CLT can be produced using "junk" trees with diameters as minimal as 4 inches. The extraction of such lower-value timber has been recognized as a practical strategy to enhance the value and health of forests (Quesada et al. n.d.). While CLT is commonly manufactured from spruce, it can also utilize pine, larch, and fir species, which are more susceptible to fire. The establishment of robust markets for such timber can contribute to a reduction in fire hazards to some extent and aid in effective forest management.

1.3.2 Barriers in adoption of Mass Timber

The decision-making process for selecting structural materials occurs early in the design phase, with cost being a critical factor alongside considerations of structural and fire performance, market availability, and compliance with building codes (Laguarda-Mallo et al. 2016). The economic performance of construction materials ranks among the top considerations for engineers, with a national survey of U.S. structural firms revealing that 88.5% of respondents considered it "extremely important," "very important," or "important" (Laguarda-Mallo et al. 2016). In multifamily housing, the choice of the right structural system is a challenge to professionals and clients (Douglas 2017). To make informed decisions about building materials, architects and engineers need awareness of new materials and an understanding of factors influencing structural material choices.

In the case of Cross Laminated Timber (CLT), the situation is paradoxical. A nationwide survey shows low to moderate awareness of CLT in U.S. engineering firms, with first costs and building code compatibility perceived as major barriers to adoption (Laguarda-Mallo et al. 2016). However, CLTs (Cross Laminated Timber) have proved cost competitiveness by reducing onsite labor costs and construction time by up to 30% (Laguarda-Mallo et al. 2016). This underscores an uncertainty about the cost competitiveness of CLT, contributing to its unfamiliarity in the industry.

Despite the added values of sustainability, strength, and aesthetic appeal in mass timber construction, the absence of qualitative or quantitative data on its performance acts as a barrier to adoption (Ryan 2016). Additionally, there is no standardized method for collecting data on mass timber projects, hindering the development of empirically supported arguments. (Schmidt et al. 2023) found significant challenges, including a lack of understanding of fire safety, regulations, performance, application specifics, and local manufacturers and suppliers. The research found that prior experience builds confidence in mass timber construction but highlighted a significant lack of awareness and involvement among U.S. construction practitioners. About 55% of participants showed no experience with mass timber construction projects. Qualitative data analysis revealed barriers such as a lack of experience in timber construction, poor coordination among project parties, design-related difficulties, and the prohibitive cost of mass timber panels (Ahmed and Arocho 2020).

1.4 Housing Affordability

The interpretation of the term "affordable" is subjective and varies among different parties. Diverse perspectives on the definition of 'Affordable Housing' are clear in many studies. While various measures are employed to define affordability, income is a prominent factor, often assessed through the expenditure-to-income ratio. In the United States, the widely accepted standard is the 30 percent housing cost to income ratio as a simple "rule of thumb" for evaluating housing affordability (Michael Stone 2010). However, among the various housing types in the market, only a limited number are considered affordable. Housing affordability is described in studies as a complex relationship involving income, expenditure, and many other considerations. These factors encompass, but are not restricted to, the financial cost structure, availability, occupational requirements of relevant demographics, distribution of housing processes, and government policies (Thompson and Yang 2015) ;(Abdul Hamid et al. 2018). Apart from financial considerations, factors such as the location and quality of a house are crucial in defining affordable housing (Clapham David et al. 2012). While the primary aim of Affordable Housing is to provide housing for low or moderate-income households, effective and cost-saving design and construction methods have struggled to meet the increasing demand. This highlights the deficiencies inherent in current affordable housing design and construction processes, leaving stakeholders with limited or no solutions. Given this affordable housing crisis, there is a pressing need to transform the way affordable housing is built, making it more financially practical and environmentally friendly. Affordable housing should not only be economically sustainable but should also minimize residents' living costs. However, as noted by Chan and Adabre, "not all that is affordable can be counted as sustainable." Hence, bridging this gap to incorporate sustainability into affordable housing is crucial, especially since the building sector contributes significantly to energy consumption (30%) and carbon emissions (30%) (Architecture 2030 2023). Despite many studies on affordable housing, the integration of sustainable and innovative methods has been lacking (Moghayedi et al. 2021). Sustainable housing involves the use of eco-friendly materials and methods throughout design, planning, and operational stages, incorporating green practices. Not only can sustainability enhance the well-being of residents, but it also reduces environmental impact (Atta et al. 2021).

Examining affordable housing through the lens of sustainable innovation is vital for designing resilient urban spaces and durable housing (Sunday et al. 2021). However, there has been insufficient empirical exploration of innovative and modern techniques for affordable housing. Deploying innovative construction methods with a focus on affordability and sustainability is crucial for creating inclusive and cohesive sustainable communities (Atta et al. 2021). One of the UN's SDGs is to provide affordable housing for the entire relevant population, but achieving this target is still an aspiration (United Nations 2023). Despite ongoing efforts by governments and organizations to mandate and provide affordable housing, challenges persist. The absence of a universally accepted definition of affordable housing stays a contentious issue among stakeholders and in scholarly articles. Researchers have found various criteria for success (Adabre et al. 2020) and barrier (Hamid et al. 2018) in achieving affordable housing. Critical success factors (CSFs) and barriers have been categorized into environmental, social, technical, economic, and institutional subcategories (Moghayedi et al. 2021) ;(Adabre et al. 2020). The problem of insufficient delivery of adequate affordable housing persists globally among developed and developing countries, as reported by the (United Nations 2023). Approximately 1.6 billion people live in inadequate houses in unhygienic micro-environments. Housing policies and authorities should consider approaches that deliver better households with low cost, high quality, improved productivity, and environmental friendliness to address this challenge.

1.5 Modular Mass Timber (MMT) and Affordability

The advantages of Mass Timber, such as sustainability, strength, and aesthetic appeal, have been well-established. Timber architecture is experiencing a resurgence in a technologically impressive manner, leaving room for new developments in terms of higher, larger, denser, faster, and simpler solutions (Carvalho et al. 2020). However, its traditional construction process has limitations in terms of efficiency, speed, and cost-effectiveness. In contrast, modular construction techniques enable the prefabrication of Mass Timber components off-site, reducing on-site construction time and minimizing waste. This leads to faster and more cost-effective construction, promoting the use of sustainable materials like Mass Timber.

Modular construction techniques offer several positive outcomes when combined with Mass Timber construction:

- **Speed of construction:** Modular construction allows for faster construction times compared to traditional methods. Prefabricated Mass Timber components can be manufactured and assembled off-site simultaneously with construction site preparation, contributing to economic drivers such as speed and robustness (Fernandes Carvalho et al. 2020a).
- **Reduced site disruption:** With a sizable part of construction work completed off-site, on-site disruption is minimized. The precision-manufactured components, materials, and systems bring advantages such as superior quality control, improved

energy performance, reduced onsite deliveries, noise, pollution, and less disruption to communities (Yip et al. 2022).

- **Modular Advancement:** The goal of minimizing onsite work and maximizing prefabrication, along with high-quality control, fine-tunes the "plug-and-play" concept. This involves offsite assembling of units with installed mechanical, electrical, and plumbing services, connected directly into the mains on site (Fernandes Carvalho et al. 2020a). This modular construction model becomes economically practical with greater product repetition, especially for large-scale programs involving replicable units like hotels, nursing homes, student accommodation, labs, offices, and multifamily residences.

Furthermore, there is a significant housing shortage globally, contributing to unfulfilled demand for shelter. Modular construction methods, with their reduced construction time, can address this requirement effectively. Studies exploring the application of Modular construction in affordable housing emphasize its benefits in both developing and developed countries. Utilizing manufacturing methods such as last planner, lean, and six sigma, along with techniques related to Industry 4.0, could augment the process of affordable housing delivery. Combining the benefits of Mass Timber with the efficiency of modular construction creates an opportunity for the construction industry to develop a more sustainable and cost-effective method of building construction. The integration of Modular Construction and Mass Timber has been discussed in detail in the next section (1.5.2) of this study.

This study focuses on multi-family housing within the context of enhancing sustainability, efficiency, and accessibility and underscores a pivotal approach to addressing the intertwined challenges of environmental impact and housing affordability. Multi-family constructions inherently perfect the use of land, materials, and energy, offering a resource-efficient solution critical for mitigating environmental footprints and elevating the availability of cost-effective living spaces. The compatibility of modular mass timber construction with multi-family projects lies in the scalability and repetition of these endeavors, enabling a more streamlined off-site manufacturing process that significantly reduces waste and perfects resource use. This method not only advances environmental conservation efforts by minimizing the construction sector's carbon footprint but also plays a crucial role in enhancing housing affordability through reduced production and assembly costs.

Moreover, multi-family units prove superior land and energy efficiency compared to single-family homes, particularly in urban environments where land scarcity and prohibitive costs pose significant challenges. The design efficiencies, including shared walls, contribute to minimized per-unit land use and improved insulation, leading to decreased energy requirements for heating and cooling. Such efficiencies not only lower operational carbon emissions but also reduce utility expenses for residents, thereby addressing urgent needs for affordable housing in densely populated areas. The deployment of modular mass timber in multi-family housing construction could potentially set new industry benchmarks for sustainability and efficiency, influencing broader adoption across various construction projects and contributing to long-term environmental sustainability and development goals.

1.5 Research Needs, Objectives and Methodology

1.5.1 Understand the Research Needs

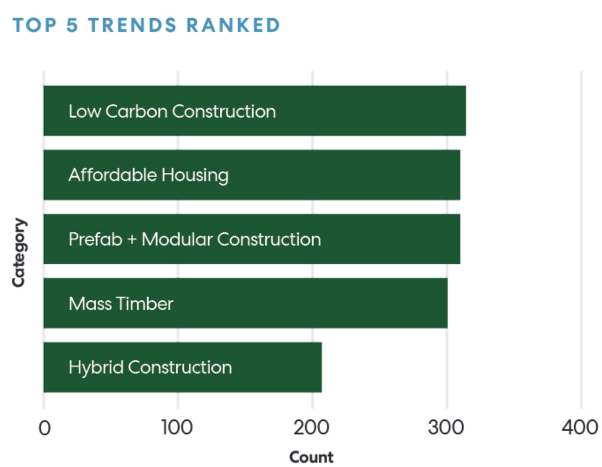

Figure 1 Top 5 Trends (ThinkWood 2022)

In January 2022, a survey conducted by Think Wood (ThinkWood 2022) sought insights from 500 professionals including architects, engineers, developers, and contractors to gauge emerging trends in design and construction for the year.

The top three trends found,

- low carbon construction,
- affordable housing, and
- prefabrication/modular construction,

were closely ranked in popularity, emphasizing the need for a multifaceted approach to address design challenges. The intersectionality of these trends, clear in the growing number of timber projects, presents a positive outlook for the upcoming year.

The scarcity of housing to meet the needs of expanding urban populations is a significant challenge faced by major cities today. Modular housing is gaining considerable attention due to its substantial potential, particularly in terms of adaptability to constrained sites, rapid delivery, reduction of noise, waste, pollution, and other environmental considerations, as well as its ability to generate new employment opportunities. Beyond affordable multifamily housing, modular construction is becoming increasingly relevant for emergency housing, aligning with global human rights considerations and ethical awareness of climate change. With their contextual flexibility and swift delivery, plug-in modules hold promise in providing quality and dignified shelter for large communities of refugees.

Federal Reserve data reveals a surge in home sales, accompanied by a decline in active housing listings and a significant increase in the median home sale price. As of January 2024, the number of active housing listings in the U.S. was 664,716, being a 50% decrease from the 1,238,633 million listings in July 2019, just before the impact of the coronavirus on the U.S. economy (FRED 2024).

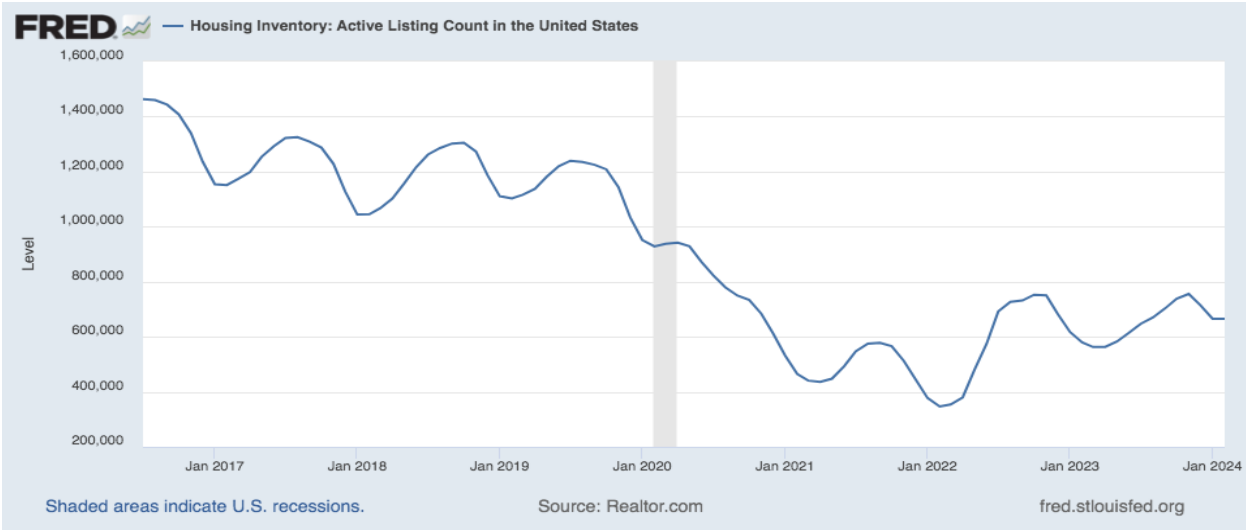

Figure 2 Active listing count in the US (FRED 2024)

Around the same time, the national median sale price for a single-family home jumped 25% from $327,100 in the fourth quarter of 2019 (the last full quarter unaffected by the COVID-19 recession) to $417,700 in the third quarter of 2023, the most recent data available. The greatest increases were in the West, Midwest and Northeast (FRED 2024).

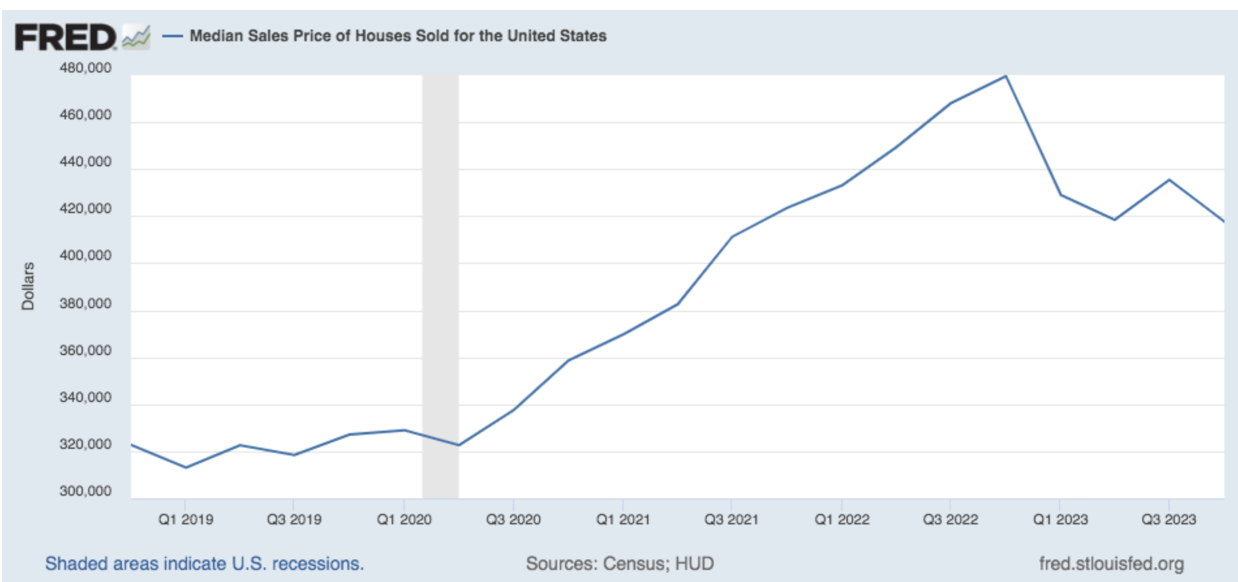

Figure 3 Median Sales Price of the houses sold for the US (FRED 2024)

Renters across the U.S. have seen the average rent rise 18% over the last five years, outpacing inflation. The Consumer Price Index in Jan 2019 was 331.605 and in Jan 2024 it was 413.695.

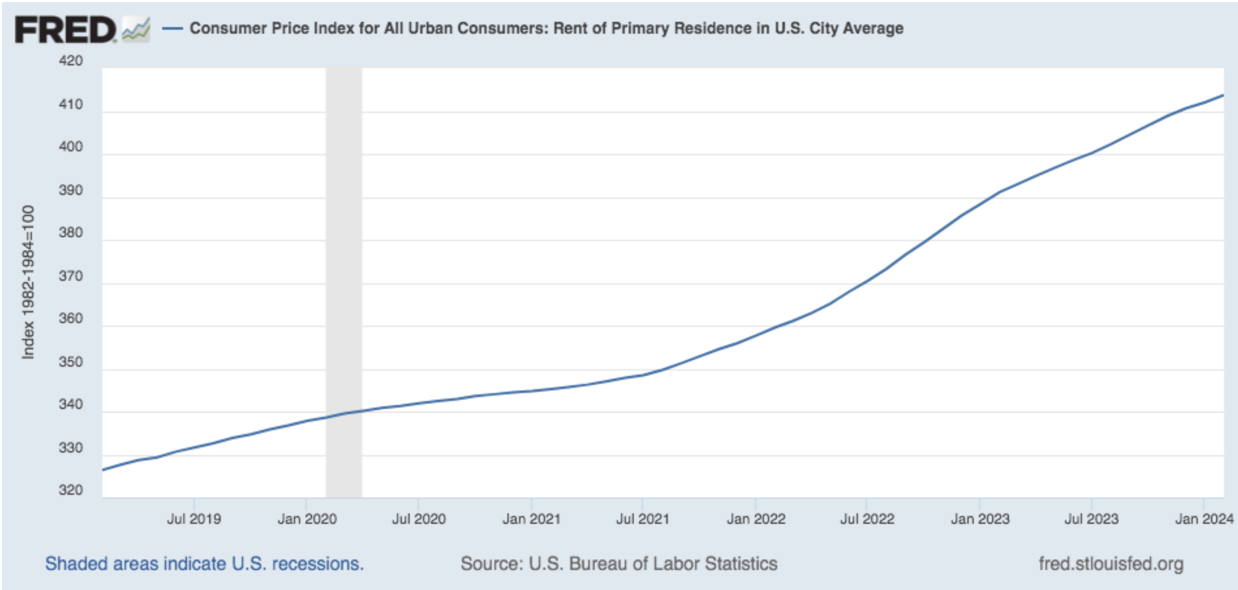

Figure 4 Rent of Primary Residence in the US (FRED 2024)

The urgency for research on affordable housing options in the USA is critical, given the ongoing housing crisis with respect to the active listings, hike in Median Sales Price and increasing rent of the primary residence in the US. The National Low Income Housing Coalition's report (NLIHC 2023) shows a shortage of 7.3 million affordable and available rental homes for extremely low-income renters in the United States. This shortage has contributed to a rise in homelessness and housing insecurity, worsened by the COVID-19 pandemic, leading to the risk of eviction for millions of Americans due to job losses and financial instability. Escalating housing costs outpacing income growth pose challenges for low-income families in finding affordable housing. Addressing the affordable housing crisis requires research to find effective solutions, including increased funding for affordable housing programs, implementation of regulations to prevent gentrification, and the development of advanced construction techniques for building affordable and efficient houses. Tackling the affordable housing crisis is crucial to ensuring that all Americans have access to safe and affordable housing (Aurand et al. 2024).

1.5.2 Why Modular Mass Timber (MMT)?

The integration of Modular Construction (MC) and Mass Timber (MT) into a unified strategy for addressing the United States' affordable housing crisis stands out for its unique combination of speed, sustainability, and scalability. Unlike traditional construction methodologies, which are often hindered by lengthy timelines and higher labor costs, Modular Construction streamlines the building process. It enables housing units to be prefabricated in controlled environments, which significantly speeds up construction times, reduces waste, and cuts overall costs. This efficiency is crucial for quickly addressing the growing demand for affordable housing.

Mass Timber further complements Modular Construction by adding environmental sustainability and durability to the mix. As a construction material, Mass Timber is renowned for its carbon-sequestering capabilities, making it a cornerstone for green building practices. Its compatibility with prefabrication aligns perfectly with Modular Construction, allowing for the efficient production of durable, fire-resistant, and aesthetically pleasing housing units. This combination promotes not just faster but also environmentally responsible construction practices.

Together, MMT capitalizes on the strengths of both Modular Construction and Mass Timber, creating a synergistic effect that other technologies do not replicate. The rapid assembly and environmental sustainability of MMT provide a comprehensive solution to the multifaceted challenges of affordable housing. It's the distinct qualities of MMT—efficiency from Modular Construction and the sustainability of Mass Timber—that enable this approach to overcome the conventional barriers of cost, time, and environmental impact in the affordable housing sector. This positions MMT not just as an innovative construction method but as a transformative approach that could significantly alleviate the affordable housing shortfall with speed, sustainability, and scale at its core.

1.5.3 Research Goal

The research goal of this thesis, titled "Critical Success Factors (CSFs) towards the Installation of Modular Mass Timber for Affordable Housing in the US," is to understand, find and analyze the key factors that contribute to the successful implementation of modular mass timber construction methods in the development of affordable multi-family housing in the United States.

This goal encompasses evaluating how modular mass timber can address the dual challenges of reducing the environmental impact of construction practices and meeting the growing need for affordable housing. Through a comprehensive examination of the economic, environmental, technical, and regulatory dimensions, the research aims to set up an implementation strategy that can guide installers, policymakers, architects, and builders in perfecting the use of modular mass timber. Ultimately, this study looks to contribute to the body of knowledge and an advancement of sustainable construction practices that not only support the reduction of greenhouse gas emissions but also enhance the accessibility of quality housing, thereby aligning with national climate goals and the pursuit of urban sustainability.

1.5.4 Research Methods, Objectives and Outputs

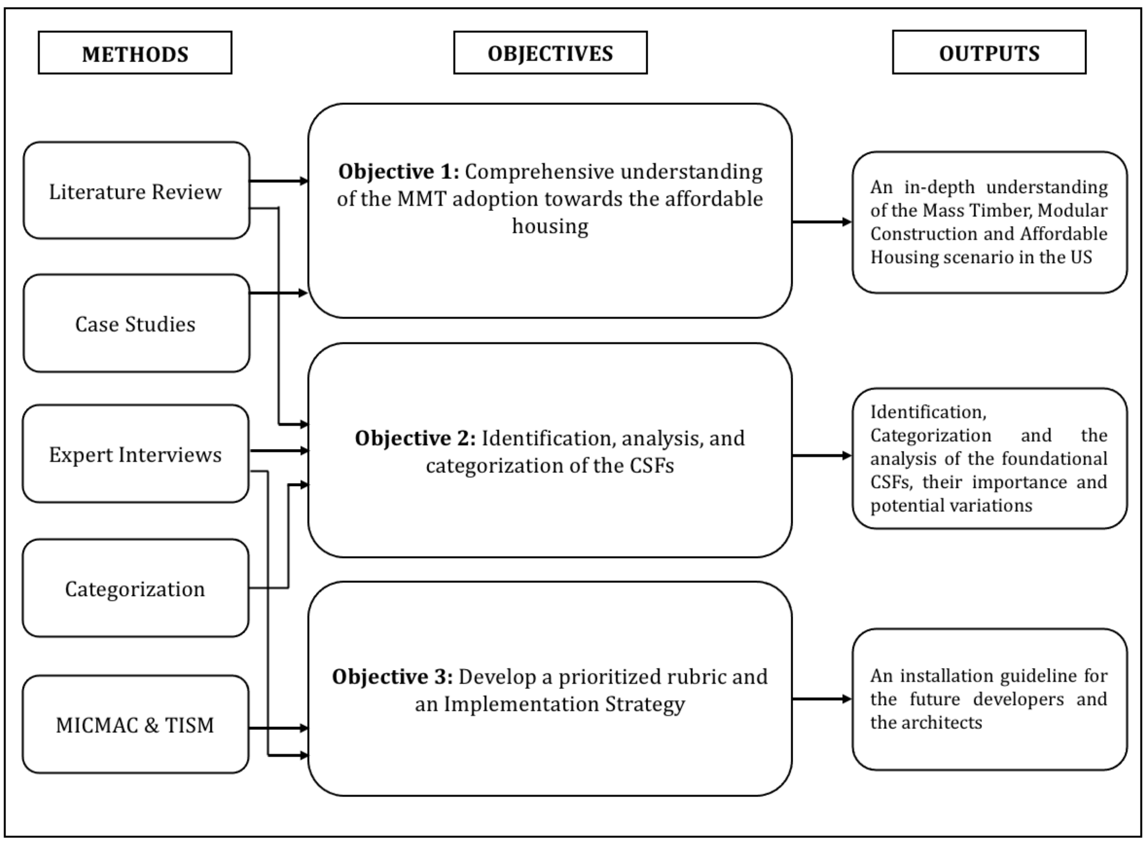

Figure 5 Research Methods, Objectives and Outputs

Objective 1: *Comprehensive understanding of the Modular Mass Timber (MMT) adoption towards the affordable housing*

- **Research Method:** Conduct an in-depth exploration of Mass Timber construction and Modular systems, focusing on their potential applications in affordable housing within the USA. This analysis should cover engineering, design flexibility, and economical sustainability aspects of both Mass Timber and Modular construction techniques.
- **Literature Review:** Conduct a thorough review of existing literature on modular mass timber and its applications in affordable housing. Analyze scholarly articles, papers, case studies and reports to gain insights into the development, status, and potential future trends.
- **Case Studies:** Examine successful case studies of modular and mass timber projects in affordable housing in the US. Evaluate their design, installation, cost-effectiveness, and overall impact on communities.
- **Interviews and Surveys:** Gather perspectives from industry experts, specialists, architects, market analysts, builders, and developers involved in modular or mass timber projects. Use interviews and surveys to collect qualitative data on the benefits and challenges associated with this construction method.

Objective 2: *Identification, analysis, and categorization of the Critical Success Factors (CSFs)*

- **Research Methods:** Synthesize findings related to the unique challenges and success factors in this context. Gather insights into the perceived critical success factors, their importance, and potential variations across different projects. And categories these factors.
- **Literature Review on CSF:** Conduct an extensive literature review to find existing research on Critical Success Factors (CSF) for construction projects, with a specific focus on modular mass timber in affordable housing.
- **Expert Interviews and Surveys:** In this research phase, an extensive approach will be employed to connect with industry experts, encompassing architects, engineers, builders, and stakeholders actively involved in modular mass timber projects. The

data collection methods will primarily involve conducting expert interviews and surveys. The recruitment process will be enriched by incorporating the 'Snowball' sampling method (Coleman James 1958), a technique wherein research participants are not only the subjects of the study but are also invited to aid researchers by finding added potential participants. This iterative process enhances the inclusivity and diversity of perspectives within the study.

- **Data Analysis and Categorization:** Systematically analyze the collected data to find recurring themes and patterns related to critical success factors. Categorize these factors based on their nature, such as design-related, regulatory, financial, or community acceptance factors.

Objective 3: *Develop a prioritized rubric and an Implementation Strategy*

- **Research Method:** Further, use this rubric to assess case studies, compare different construction methods, and propose recommendations for perfecting Modular Mass Timber solutions in the affordable housing sector. Develop strategic implementation guidelines for the installers, architects and developers. This guideline would encompass criteria such as cost-effectiveness, ease of installation, material manufacturing and supply, best management practices, and compliance with the housing policies.
- **Literature Review on Evaluation Criteria:** Conduct a literature review focusing on Total Interpretive Structural Modelling (TISM) and Apply Matrice d' Impacts Croises-Multipication Appliqué a Classement (MICMAC) methodologies and their combined application in evaluating construction methods. Find studies that have successfully used both approaches and extract insights into the criteria used for evaluation.
- **Expert Elicitation through TISM:** Utilize TISM to elicit expert opinions on the factors influencing the prioritization of modular mass timber construction in affordable housing. Develop a structured questionnaire based on TISM principles to collect and analyze the hierarchical relationships among criteria. The TISM model will act as a prioritized rubric that highlights the inter-relativity and its implications for an individual CSF.

- **MICMAC Analysis:** Apply Matrice d' Impacts Croises-Multipication Appliqué a Classement (MICMAC) analysis to find the driving and dependent factors among the criteria found through TISM. MICMAC analysis is used to classify the factors and confirm the interpretive structural model factors in the study to reach their results and conclusions (Ahmad et al. 2019). Classify factors as autonomous, linkage, dependent, or independent using the MICMAC framework, providing a deeper understanding of the dynamics within the system and distribution of the impact.
- **Implementation Strategies:** This chapter presents a comprehensive overview of the intervention strategies employed in this study, outlining a systematic method that prioritizes individual Critical Success Factors (CSFs). These responses are derived mainly from expert interviews and literature studies. It delves into the interconnectedness of these factors and elucidates the practical applications of our findings within the industry. This structured approach ensures a nuanced understanding of each CSF, easing the development of effective, targeted interventions. The figure below depicts the inter-relativity of the critical factors in a colored matrix form.

1.6 Research Scope and Limitations

1.6.1 Research Scope

This research delves into the exploration and analysis of critical success factors (CSFs) pivotal for deploying modular mass timber technologies in the creation of affordable multi-family housing across the United States. This research looks to thoroughly examine the diverse factors that affect the effective implementation of innovative construction methods, covering a spectrum from economic feasibility and environmental benefits to adherence to regulations and technical viability. By focusing on multi-family housing, the study inherently addresses the pressing urban challenge of housing affordability and availability while simultaneously striving for a reduction in the construction industry's environmental footprint.

The scope of this investigation is specifically tailored to understand how modular mass timber can be effectively used to meet the demands of both sustainable construction and the urgent need for affordable living spaces in densely populated areas. Through a multifaceted analysis, this thesis looks to contribute actionable insights and strategies for stakeholders across the construction sector, including developers, policymakers, architects, and builders. By finding key enablers and barriers, the research endeavors to provide a foundational blueprint that supports the scaled application of modular mass timber in the pursuit of achieving broader environmental and social housing aims within the U.S. context.

1.6.2 Research Limitations

1. This study will focus exclusively on the use of modular mass timber for affordable housing in the US and will not explore other construction materials, technology or affordable housing models.
2. This research does not comment/review/propose any specific government policies or initiatives for adoption of Modular Mass Timber towards affordable housing.
3. The research though is in contact to following areas will not primarily focus on them. These includes,

- Labor hour productivity analysis
- operational energy performance
- construction energy and carbon performance
- waste factors in construction
- schedule per SF
- labor per SF
- incidents per SF
- change orders per SF and,
- defects per SF

4. As per the limitations of the research scope, following items will not be covered,

- Architectural or engineering plans for the construction of modular mass timber affordable housing units will not be provided.
- Social or political implications of using modular mass timber for affordable housing will not be addressed.
- An analysis of the economic or political feasibility of implementing government policies that promote the use of modular mass timber for affordable housing will not be provided.

1.7 Research Outcomes

The following are planned outcomes of this study:

1. This study is intended to provide a comprehensive introduction and understanding of the Mass Timber, Modular Construction and Affordable Housing scenario in the US.
2. This study will find and analyze the foundational CSFs derived from the literature and expert interviews, discuss their importance and inter-relativity, and potential implications for promoting Modular Mass Timber adoption in Affordable Housing.
3. This study will develop a prioritized rubric and an implementation strategy that will be used as a design guideline for the future installers, architects as well as the developers.

CHAPTER 2: LITERATURE REVIEW

2.1. Introduction

The primary aim of this chapter is to examine the background of the study area comprehensively, offering a thorough review of relevant information. This is intended to enhance understanding of the study area and set up proper methodologies for the prioritized rubric. The topical outline of this chapter is illustrated in Figure 6.

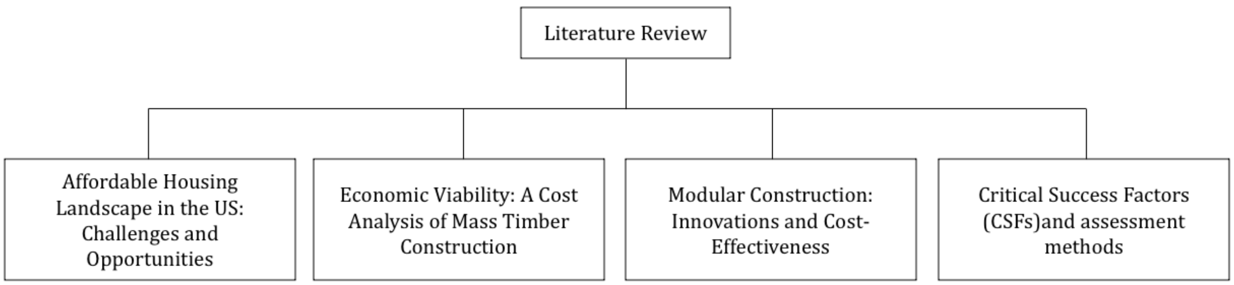

Figure 6 Literature Review Outline

Structured to cover aspects like background, challenges, opportunities, effectiveness, economic viability, and validity and reliability of modular mass timber adoption in affordable housing, this chapter adopts a systematic approach. The review initiates with an exploration of the current state of affordable housing in the US, addressing challenges and opportunities concerning the integration of modular mass timber. The cost implications of incorporating mass timber in construction projects, focusing on economic viability and potential benefits for affordable housing, are then scrutinized. Following this groundwork, the review delves into the modular construction approach, examining its cost-effectiveness and discussing innovations that can contribute to making modular construction a viable option for affordable housing. Finally, the review explores specific key performance indicators and assessment methods related to the adoption of modular mass timber in affordable housing, providing insights into the evaluation criteria for successful implementation.

The initial section of this chapter underscores the scenario of affordable housing in the US, highlighting the research need and urgency. Given the critical concern of affordable housing in the United States and the increasing demand for innovative solutions, this section explores the current landscape, addressing challenges and opportunities. By recognizing the unique demands of affordable housing, the potential for adopting modular mass timber construction methods as a sustainable and cost-effective solution is considered.

The later section of this review places a strong emphasis on the economic viability of Mass Timber Construction. Integral to integrating modular mass timber into affordable housing initiatives is a comprehensive cost analysis. This section evaluates the economic feasibility of incorporating mass timber construction, analyzing factors like material costs, installation expenses, and long-term financial implications. A clear understanding of the economic viability is essential for the successful adoption of mass timber construction in affordable housing projects.

The third section focuses on studies investigating the feasibility, innovations, and effectiveness of Modular Construction. As a promising approach to address the challenges of traditional construction methods, modular construction's innovations and cost-effectiveness are explored. By examining advancements in modular techniques, the aim is to find how these innovations contribute to the overall efficiency and affordability of housing projects, particularly when incorporating mass timber.

The fourth section of this review is dedicated to assessing the effectiveness of modular mass timber adoption in affordable housing. Finding and evaluating Critical Success Factors (CSFs) is imperative for understanding the success of projects. This section focuses on the specific CSFs related to the integration of modular mass timber, providing a framework for project evaluation. Addressing these critical factors is crucial to ensuring a comprehensive approach to the adoption of modular mass timber in the affordable housing sector.

2.2 Affordable Housing Landscape in the US: Challenges and Opportunities

2.2.1 Affordable Housing in the US: A review

The issue of affordable housing has become a significant and pressing concern in the United States in recent times. The affordability of housing is a critical challenge, particularly for low-income individuals and families, especially in urban areas where housing costs are high, and job opportunities and wages are often limited. Numerous factors contribute to the challenge of affordable housing, encompassing escalating construction expenses, restricted government funding, increasing mortgage interest rates, stringent land laws, and zoning regulations. This literature review aims to assess the current state of the affordable housing crisis in the US, analyze contributing factors, and evaluate proposed solutions.

According to the National Low Income Housing Coalition, there is a severe shortage of rental homes in the US that are both affordable and accessible to individuals with extremely low incomes—those earning at or below the federal poverty guideline or 30% of the median income for their area. The data shows that for every 100 renter households with extremely low incomes, only 33 affordable and accessible rental homes are available. This scarcity is prevalent across all states and major cities, with the shortage ranging from 17 affordable homes for every 100 extremely low-income renter households in Nevada to 58 in South Dakota. Notably, in 12 of the 50 largest metropolitan areas in the US, there is a deficit exceeding 100,000 units of affordable and unoccupied homes for extremely low-income renters (Aurand et al. 2024).

2.2.2 Challenges and Opportunities

The challenge of affordable housing in the United States is influenced by many factors, notably the escalating costs associated with construction and materials. Recent data from the U.S. Census Bureau shows a 17.5% year-to-year increase in construction costs, the most significant since 1970 (US Census 2023). Building materials costs surged by 20.4% compared to the previous year and have risen by 33% since the onset of the pandemic. Additionally, the price index for services related to home construction, such as transportation, trade services, and warehousing, has seen a 15.2% increase since the beginning of the year and an 18.5% year-over-year increase (NAHB 2022).

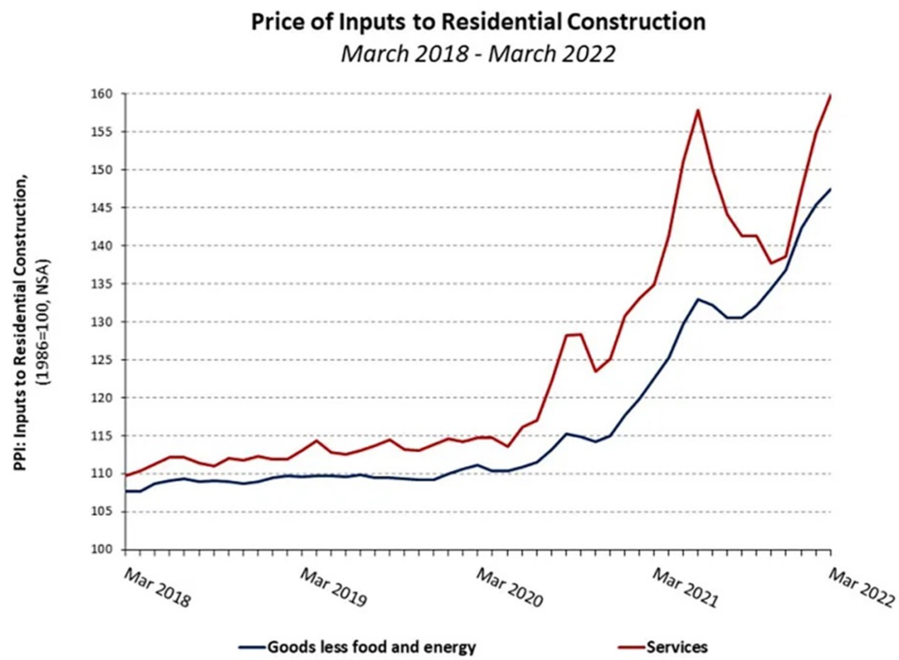

Figure 7 Material Costs (NAHB 2022)

Diane Yentel, President and CEO of the National Low Income Housing Coalition, highlights that systemic inequalities and insufficient federal support place seven out of ten renters with the lowest incomes at a critical risk of housing insecurity.

Addressing the shortage of affordable housing requires local governments to act by reducing regulatory barriers hindering the construction of small, low-cost homes on expensive land. Many U.S. cities limit construction to single-family detached houses on approximately three-quarters of the land, making townhouses, duplexes, and apartment buildings illegal in those areas. Even where multifamily construction is allowed, zoning regulations, such as building height restrictions and minimum lot size requirements, pose financial challenges that hinder new housing development (Schuetz 2020).

The restrictive zoning regulations become a significant factor contributing to the affordable housing problem, especially in high-opportunity areas. To increase affordable housing availability, local governments must address these regulatory barriers by reducing restrictions on constructing small, low-cost homes on expensive land.

Various solutions have been proposed, including added government funding for affordable housing initiatives, such as expanding programs like the Low-Income Housing Tax Credit

(LIHTC) or creating innovative funding programs (Aurand et al. 2024). Reforming zoning regulations is another suggested solution, involving changes like reducing minimum lot sizes, implementing comprehensive zoning overhauls, creating floating zones, allowing multifamily housing in more areas, and reducing parking requirements (Fertitta 2023).

An innovative construction technique proposed as a potential solution is modular mass timber. Compared to traditional methods, modular construction offers benefits like faster construction timelines, cost and time predictability, and reduced waste. Modular structures, employing engineered wood panels like Cross Laminated Timber (CLT), provide an efficient construction method (Bhandari et al. 2023b). However, careful evaluation is needed, as there are added costs associated with this approach, including material, manufacturing, transportation, assembly, and installation costs.

In summary, the United States faces a critical challenge of affordable housing shortage, influenced by factors such as rising construction costs, limited government funding, and restrictive zoning regulations. Proposed solutions encompass increasing government funding, reforming zoning regulations, and adopting innovative construction techniques like modular mass timber.

2.3 Economic Viability: A Cost Analysis of Mass Timber Construction

2.3.1 Cost Analysis of Mass Timber Construction

Examining the cost trends appearing from a decade of mass timber projects in the United States reveals a general premium for such projects, typically up to 15 percent. However, the median project premium, showing the added cost associated with mass timber, was less than 2 percent, and this gap is narrowing as teams and markets gain more experience. When mass timber substitutes for concrete and steel construction, the cost savings tend to be greater than when replacing light framing. The analysis categorizes cost information into three macro systems integral to every building: the superstructure, the substructure, and the environment. The most significant cost savings are seen in the superstructure's construction schedule, leading to a substantial reduction, up to 25 percent, in the total construction schedule. This reduction translates to savings in overhead, carrying costs, earlier occupancy, and decreased risk. Contractors report noteworthy cost savings in general conditions, even with increased coordination. Mass timber presents distinctive advantages, challenges, and potential across these three categories (Dawson 2023).

In recent years, mass timber construction has gained popularity as a sustainable and efficient alternative to conventional materials like concrete and steel. Despite the feeling of a premium associated with mass timber projects, the median project premium is less than 2 percent, highlighting a decreasing trend as teams and markets become more adept. 'Mass Timber doesn't have to radically change design concepts used with other materials; we can accomplish what we're already familiar with in steel and concrete' (Chung 2017). However, a critical aspect influencing the adoption of mass timber construction is the cost analysis of the material. This review delves into recent research on the cost analysis of mass timber construction, exploring the cost comparison between mass timber and traditional materials, along with factors affecting mass timber construction costs.

One study, "Comparing cross laminated timber with concrete and steel: a financial analysis of two buildings in Australia" by (Cazemier 2017), compares the cost of mass timber with conventional construction. The research method leans predominantly towards quantitative analysis, incorporating a small qualitative element to examine the role of financial institutions in funding a Cross-Laminated Timber (CLT) project. The study evaluates two buildings in terms of final development margin, development profit, return on equity, and Equity Internal Rate of Return. EstateMaster and Nitro software were used for the analysis, considering a construction program of 21 months, reduced to 15 months with CLT, resulting in a 30-40% reduction in construction time. The adjusted construction cost affected development profit, margin, ROE, and Equity IRR, with increased equity injection but decreased development profit, margin, and ROE, while Equity IRR showed an increase.

Table 1 Reference versus Study CLT (Cazemier 2017)

	Reference	CLT (Study)	Variance	Comment
Equity Injected	$9,155,459	$9,591,991	+4.77%	Due to higher contingency
Development Profit	$15,422,695	$13,889,852	-9.94%	needed in feasibility, increased
Development Margin	27.65%	24.24%	-12.33%	construction cost, less interest
ROE (Return on Equity)	168.45%	144.81%	-14.03%	and holding costs.
Equity IRR (Internal Rate of Return)	**33.46%**	**36.58%**	**+9.32%**	Increase IRR due to reduced construction time

To gain insights into the cost comparison between CLT and Concrete-Steel buildings, an assessment was conducted involving five construction options:

(1) Original construction using concrete, structural steel, and light-steel framing;

(2) and (3) Basic CLT alternatives, wherein CLT panels from two different manufacturers replaced the main structural concrete elements (walls and roofs);

(4) and (5) Green options, involving the replacement of concrete with CLT panels, substitution of structural steel beams with glulam beams, and exchange of light-steel frame construction with wood-frame construction. A concise summary of the outcomes derived from the cost estimation analysis is presented in the table below.

Table 2 Cost estimation analysis (Burback and Pei 2017; Laguarda-Mallo et al. 2016)

Element	Concrete/ Steel option	CLT options			
		Basic CLT option 1	Basic CLT option 2	Green option 1	Green option 2
	(Concrete walls/roof, steel beams, light-steel frame)	(CLT walls/roof, steel beams, light-steel frame)		(CLT walls/roof, glulam beams, wood-frame)	
Structural Walls	$1,071,680	$624,417	$414,901	$624,417	$414,901
Concrete Slab	$256,416	$256,416	$256,416	$256,416	$256,416
Roof System	$600,975	$427,809	$289,339	$427,809	$289,339
Interior Walls*	$155,304	$155,304	$155,304	$297,666	$297,666
Steel Beams	$506,575	$506,575	$506,575	-	-
Glulam Beams	-	-	-	$29,022	$29,022
Extra CLT Walls	-	-	-	$115,407	$84,977
Extras for CLT**	-	$595,241	$595,241	$654,768	$654,768
TOTAL $	2,590,950	2,565,763	2,217,777	2,405,506	2,027,091
SQFT	40,065	40,065	40,065	40,065	40,065
Cost per sqft	$64	$64	$55	$60	$50

* Interior walls for concrete and basic CLT options are in light-steel frame construction. Interior walls for CLT Green options are in wood-frame construction.

** Extras for CLT includes labor cost and connectors for CLT

Findings suggest that opting for CLT panels instead of cast-in-place concrete for walls and roofs alone can result in cost savings (ranging from $1 to $9 per square foot, contingent on the CLT manufacturer).

The overall construction cost savings could be more substantial when factoring in the reduced construction time (approximately 4 months less for CLT structures compared to traditional concrete/steel alternatives).

Opting for an environmentally friendly alternative that incorporates glulam beams (in lieu of steel beams) and wood-frame construction (instead of light-steel frame construction) leads to even more noteworthy cost reductions (ranging from $4 to $15 per square foot, depending on the CLT manufacturer).

Construction time sees a reduction of 61.1% when transitioning from concrete and structural steel/light-steel frame structures to glulam elements and wood-frame structure.

Moreover, in a comparison with other types of prefabricated materials (e.g., precast concrete) that could yield similar construction time savings, CLT remains more cost-effective due to lower material costs (ranging from $5 to $20 per square foot for CLT panels, compared to $14 to $40 per square foot for a "tilt-up" concrete solution) and lower weight (29 lb./square foot for wood compared to 150 lb./square foot for concrete), resulting in smaller and shallower foundations (Laguarda-Mallo Maria Fernanda and Espinoza Omar 2018).

Table 3 Cost comparison of different construction options (Burback and Pei 2017)

Project task	Traditional LFW option ($)	All CLT option ($)	Optimized CLT option ($)
Preparation	153,300	153,780	153,780
Foundation	29,780	29,780	29,780
Frame work	44,220	153,270	120,270
Exterior work	31,295	31,295	31,295
Interior work	42,930	44,860	44,860
Interior work final	50,560	51,360	51,360
Final details	41,000	45,200	45,200
Total	393,085	509,545	476,545

In this research, a comparative cost analysis was conducted for three distinct design options using the same floor plan for a single-family residence: traditional light-framed wood, all cross-laminated timber (CLT), and an optimized CLT variant. The study aimed to quantify the cost disparities among these options and assess the construction cost potential of CLT for single-family homes. The optimized CLT design incorporated a three-layer structure and replaced interior non-load-bearing walls with light-framed walls. The cost assessments for all three options factored in material, labor, and time considerations throughout the construction process. Despite CLT installation being considerably faster than traditional framing, the overall schedule impact was found to be relatively modest (an 18% decrease in time). The study did not explore a mixed design that might reduce costs. It suggested that, given the novelty of CLT manufacturing, prices for this material could decrease as industry volume increases. The study also highlighted the need for added research to evaluate CLT performance during hazardous events. If CLT could substantially mitigate potential damage to building structures and contents, it might become a preferred construction style for residential buildings in hazard-prone regions (Burback and Pei 2017).

Alternate perspectives are presented in the study " Feasibility study to estimate the environmental benefits of utilizing timber to T construct high-rise buildings in Australia " by (Li et al. 2019). This research focuses on the cost analysis of CLT construction in Australia, comparing it with conventional construction. Numerous factors affecting costs, including construction time, material costs, and construction methods, were considered. The findings show that CLT construction costs are higher than conventional construction, but the increased cost is offset by the reduction in construction time. The study suggests that proper cost management and the use of prefabrication can contribute to reducing CLT construction costs.

According to a study conducted by the imarc group, the 2021 CLT market in North America is valued at $129.3 million and is expected to grow to $360.2 million by 2027 (imarc 2021). The slow adoption of CLT in the US can be attributed to several factors, including limited CLT supply leading to high material premiums, building codes not fully leveraging CLT's potential, a lack of training for professionals, and disincentives for developers and builders due to higher upfront costs. For instance, a study on a 12-story, 8,360-square-meter mass timber building in Portland, Oregon, found that the upfront cost of using CLT was 26% higher than steel and concrete. However, there was a 2.4% decrease in the total life cycle cost of the building (Gu et al. 2020).

Table 4 60-year study period life-cycle cost (Gu et al. 2020)

Total Life-Cycle Cost ($)			
	Mass Timber Building	Concrete Building	Difference %
Building	1,90,71,250	1,51,03,437	26.3
Energy	23,23,166	23,23,166	0
Water	81,83,069	81,83,069	0
M&R	39,17,780	39,21,900	0
EoL	76,28,500	30,20,687	152.5
Total	2,58,66,765	2,65,10,884	2.4

Table 4 depicts 60-year study period life-cycle cost for the two high-rise buildings with base assumption. TLCC = total life-cycle cost; M&R = maintenance and repair; EoL = end-of-life. (Adopted from *(Gu et al. 2020)*)

Table 4 of the study shows that the first expenses are balanced by the salvage value of CLT buildings at the end of their life. To summarize, recent investigations propose that the expense associated with mass timber construction can be competitive compared to traditional construction methods. Nevertheless, the cost assessment is contingent on numerous factors, including the building's size and complexity, construction duration, material expenses, and the construction approach employed. Implementing effective cost management strategies, such as incorporating prefabrication, can contribute to lowering the overall cost of mass timber construction.

2.3.2 Case Study on Affordable Mass Timber Building Project: Sonrisa (1322 O Street)

Sonrisa, found at 1322 O Street, Sacramento, CA, forms 58 micro-unit apartments and features 1,300 square feet of community space on the ground floor. All units are appointed as affordable, catering to low and very low-income levels. Positioned just one block south of the State Capitol, the project uses an underutilized infill site, offering excellent accessibility to public transit, walkability, and proximity to employment opportunities and services. As the pioneering project to begin construction under Executive Order N-06-19 for Affordable Housing Development, Sonrisa emphasizes affordable housing development on surplus State-owned property while embracing sustainable, innovative, and cost-effective construction methods. The construction of the five-story building, classified as Type-IIIB, incorporates cross-laminated timber for the horizontal elements, supported by a concrete mat slab foundation.

The feasibility of the project is eased by a multifaceted approach to public financing, including a development ground lease with the CA Dept. of General Services, a Capitol Area Development Authority loan, tax credits and bonds, and a CA Dept. of Housing and Community Development Transit-Oriented Development (TOD) Program loan. Sonrisa appeared as one of the most competitive TOD Program applicants, securing a $10 million award. Additionally, the project sponsor collaborated with SacRT on two companion TOD infrastructure grant applications, resulting in over $2 million in grants to advance the Light Rail Modernization Project at the 13th Street and Archives Plaza stations.

Unit Mix:

Fifty-eight (58) 267 SF small-studio units

Table 5 Affordability Mix & Unit Breakdown (Funston Renee 2023)

Rent Level	No. of Units	Rents	% of Total Units	2022 Max Income
40% AMI	22	$710	38%	$28,400
50% AMI	28	$887	48%	$35,500
60% AMI	7	$1,065	12%	$42,600
Mgr.'s Unit	1	—	2%	—
Total	**58**	—	**100%**	—

Applicants are subject to income maximums and must meet income and asset guidelines to qualify.

Table 6 Income limits (Funston Renee 2023)

Rent Level	1-Person Household 2022 Max Annual Income	2-Person Household 2022 Max Annual Income	2022 Household Rent (Utility Allowance to be deducted from this amount)
40% AMI	$28,400	$32,440	$710
50% AMI	$35,500	$40,550	$887
60% AMI	$42,600	$48,660	$1,065

The information outlined in the case study highlights the cost-effectiveness of constructing with mass timber, proving that the rental rates for households across different income brackets align with their financial capabilities. The largest rental amounts for households at 40%, 50%, and 60% of the area median income (AMI) all fall below $1,100, a generally recognized affordability threshold for low and moderate-income households. Additionally, the potential cost savings throughout the building's life cycle further emphasize its economic viability, positioning it as a more economical choice in comparison to traditional construction materials. Consequently, the case study underscores that mass timber construction presents an affordable and sustainable housing alternative for low and moderate-income households.

2.4. Modular Construction: Innovations and Cost-Effectiveness

The use of modular mass timber construction in the construction industry has garnered substantial attention due to its potential for swift construction, cost-effectiveness, sustainability advantages, and enhanced workplace safety. According to the Modular Building Institute (MBI), modular construction projects have the potential to reduce construction schedules by up to 50 percent. The modularization of an entire structural system offers advantages for on-site safety, schedule efficiencies, and precision, appealing broadly to installers, building owners, and designers (MBI 2023). Regardless of the upfront costs, if implemented correctly it will prove to be a more cost-efficient way to create value in the long term (AIA 2023). The later literature review aims to offer a comprehensive analysis of these benefits based on data presented in various reports.

Modular construction has been on the rise in the North American construction industry, with the multifamily market consistently leading the industry for the third consecutive year (MBI 2023). In 2022, a review of 62 projects revealed an average size of 24,057 square feet and an average cost per square foot of $278.84. Most projects formed one to three stories, with only nine projects being four stories or taller. Wood-frame structures were the predominant primary structural material, followed by steel and concrete structures. Among 29 projects where the project delivery method was found, design-build projects were the majority. It is considered a best practice to involve modular manufacturers as early as possible in the decision-making process. Modular construction projects accounted for approximately 6.14% of the total square footage for new construction in North America in 2022 (MBI 2023).

Significant cost savings are associated with modular mass timber construction, with the potential for an overall schedule reduction of up to 50 percent (AIA, 2023). Site coordination and installation approaches can significantly impact estimated costs, emphasizing the importance of selecting a construction partner familiar with the time and cost savings offered by mass timber in early cost models or bids (Dawson 2023). Companies specializing in structural mass timber panel manufacturing often provide integrated packages, encompassing architectural and engineering design, modelling, project management, and construction services, supporting clients who choose external designers and/or contractors (Dawson 2023).

The 2020 Smart Market Report on Prefabrication and Modular Construction by Dodge Data & Analytics delved into the impact of modular construction on project budget performance. The report revealed that 91 percent of all general contractors considered modular construction to have a favorable impact on project budget performance, with 48 percent showing cost reductions of more than 10 percent. Most respondents (68 percent) cited a positive budget impact exceeding 5 percent.

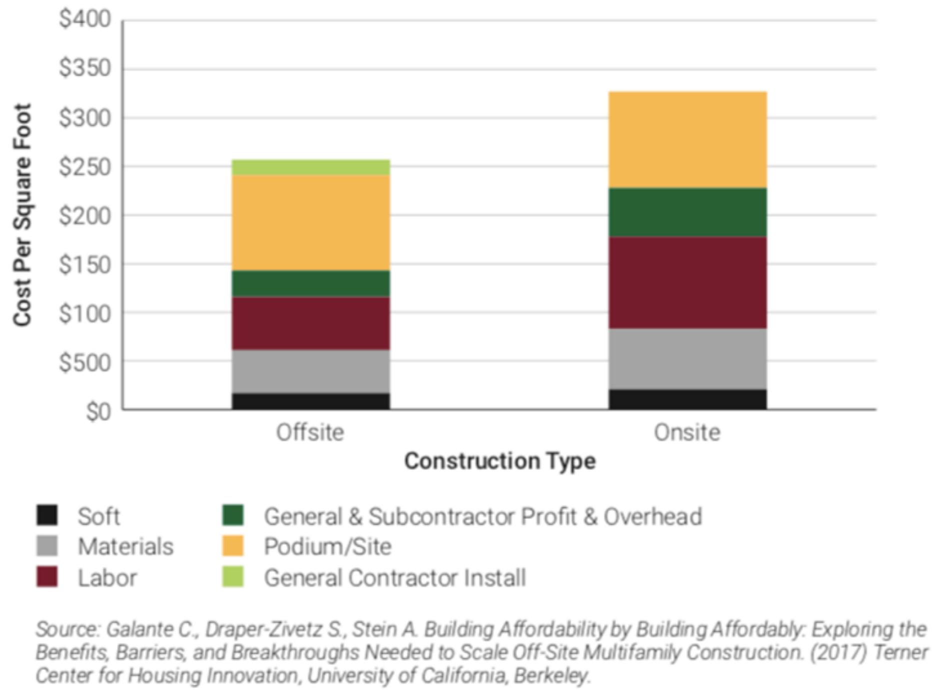

Figure 8 Construction Type (Galante Carol et al. 2017)

The Terner Center (2017) has highlighted that modular construction has the potential to bring about a minimum 20 percent reduction in construction costs and a shortening of construction times by up to 40 percent, resulting in large savings for consumers. These savings are primarily attributed to reductions in labor time and costs, economies of scale in material use, and procurement savings. Modular construction also offers cost predictability (Galante Carol et al. 2017). The shortened construction schedule, upfront materials purchases, and consistent, reliable labor in modular projects act as a hedge against uncertainties in the construction market. This aligns with the findings of the McKinsey & Company (2019) report on modular construction, which set up a consistent record of accelerating project timelines by 20-50 percent, leading to faster returns on investment (Bertram et al. 2019).

Additionally, modular construction contributes to enhanced workplace safety, promoting greater employee longevity and increased productivity. The 2020 Dodge Smart Market Report on Modular Construction and Prefabrication addressed the aspect of workplace safety, with 89 percent of architects, engineers, and contractors noting safety benefits associated with modular construction (Dodge Construction Network 2020a). Among large contractors generating revenues exceeding $100 million annually, half said that modular construction had a "very high" impact on safety, and 100 percent of respondents showed a medium, high, or very high impact on worker safety. Literature also suggests that the modular construction industry has broader access to a larger pool of potential workers, including those who may not sustain the physical demands of a job site over an extended period. This inclusivity can lead to a less physically demanding job and an improved quality of life for workers.

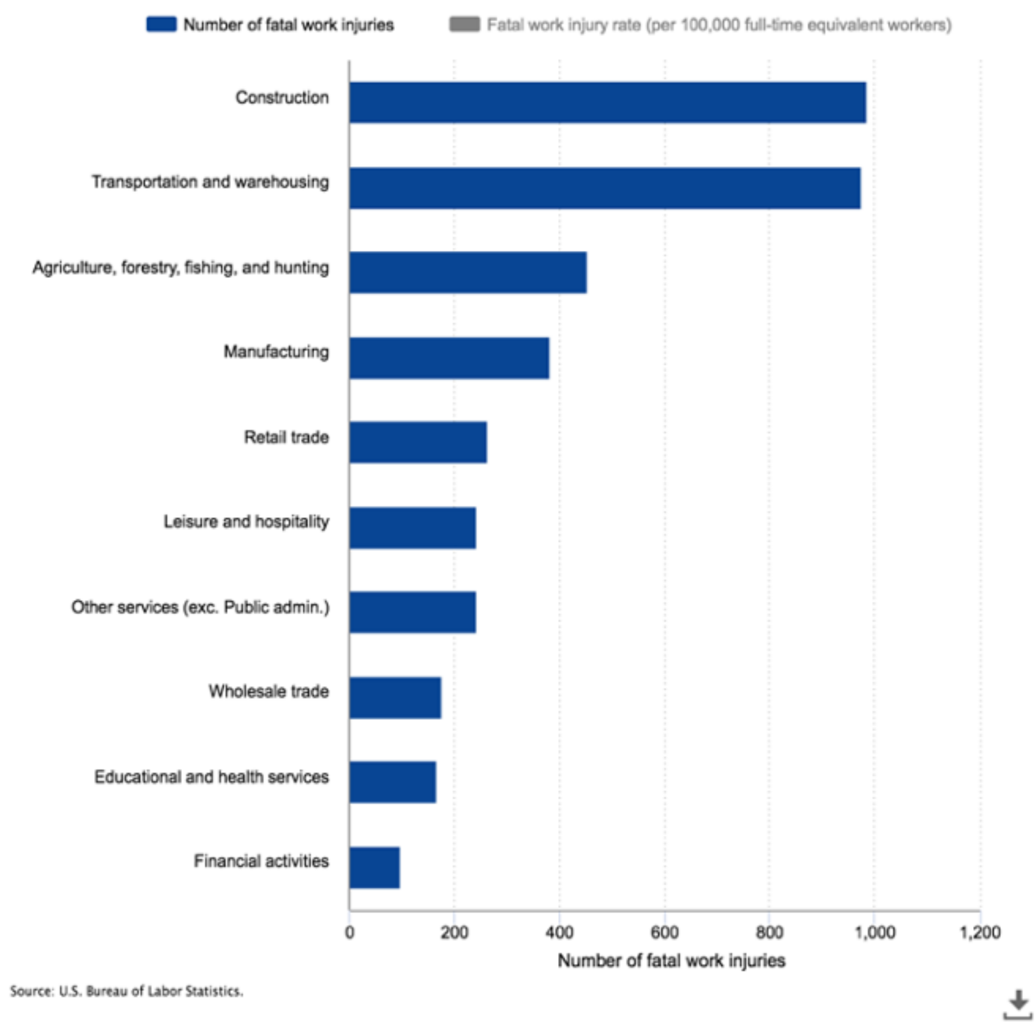

Figure 9 Number and rate of fatal work injuries (Source: (USBSL 2022))

Additionally, NRB Modular Solutions asserts that employing modular construction methods for residential homes yields a substantial positive environmental impact compared to conventional construction. Their study reveals that modular homes use approximately 20%

less material overall, resulting in reduced waste during construction. Modular homes generate about 75% less wood and drywall waste per project in comparison to conventional construction. Furthermore, the factory's energy consumption during modular construction projects proves to be more efficient than on-site energy use for conventional construction. These findings suggest that modular mass timber construction stands out as a cost-effective and environmentally friendly alternative to traditional methods (Quale John et al. 2012).

The implementation of modular construction techniques has proved substantial cost savings compared to traditional methods. For instance, the 5830 Third St. project in San Francisco by Holliday Development, featuring 136 units, achieved a 20 percent cost reduction over conventional construction. Similarly, Lowney Architects priced a 96-unit supportive housing project in San Francisco in 2017, and the factory-built cost was 15 percent lower than the site-built cost. Broad Sustainable Buildings (BSB) reported even more significant savings in its T30 high-rise project, with approximately 30 percent cost savings at $93 per square foot compared to the average traditionally constructed Chinese high-rise at $130 per square foot (WSP 2018). These observed cost savings underscore the potential advantages of integrating modular construction methods, including mass timber, in the affordable housing sector, enabling developers to deliver more cost-effective housing solutions to those in need.

Furthermore, the comprehensive review of the literature unveiled numerous studies investigating the cost analysis of modular construction. These studies fall into four overarching themes:

1. **Comparing modular construction costs to traditional construction:**

Numerous studies have undertaken a comparative analysis of the cost between modular and traditional construction methods. For instance, an evaluation of modular buildings in Australia proved a 25% reduction in labor costs and a 40%-time reduction during the construction phase compared to conventional building construction (Li et al. 2019). Similarly, (Mills Rob 2017) concluded that the cost of modular construction was 10-20% lower than traditional construction.

2. **Finding factors influencing the cost of modular construction:**

Several studies delved into the factors influencing the cost of modular construction. (Abdul Nabi and El-adaway 2020) modelled key risks affecting cost and schedule performance, revealing that poor coordination, delayed design changes, inefficient scheduling, contractual risks, and inexperienced laborers significantly affect modular construction cost and schedule performance. Meanwhile, (Yang and Kao 2012) found raw material costs, labor, and equipment as large factors affecting the cost of modular construction.

3. **Analyzing the cost-effectiveness of modular construction:**

A study by Smith and Rice scrutinized the cost-effectiveness of modular construction. The findings showed that modular construction was more cost-effective than traditional methods, resulting in on average 11% reduction in construction costs and a 42% reduction in construction schedule (Smith and Rice 2015).

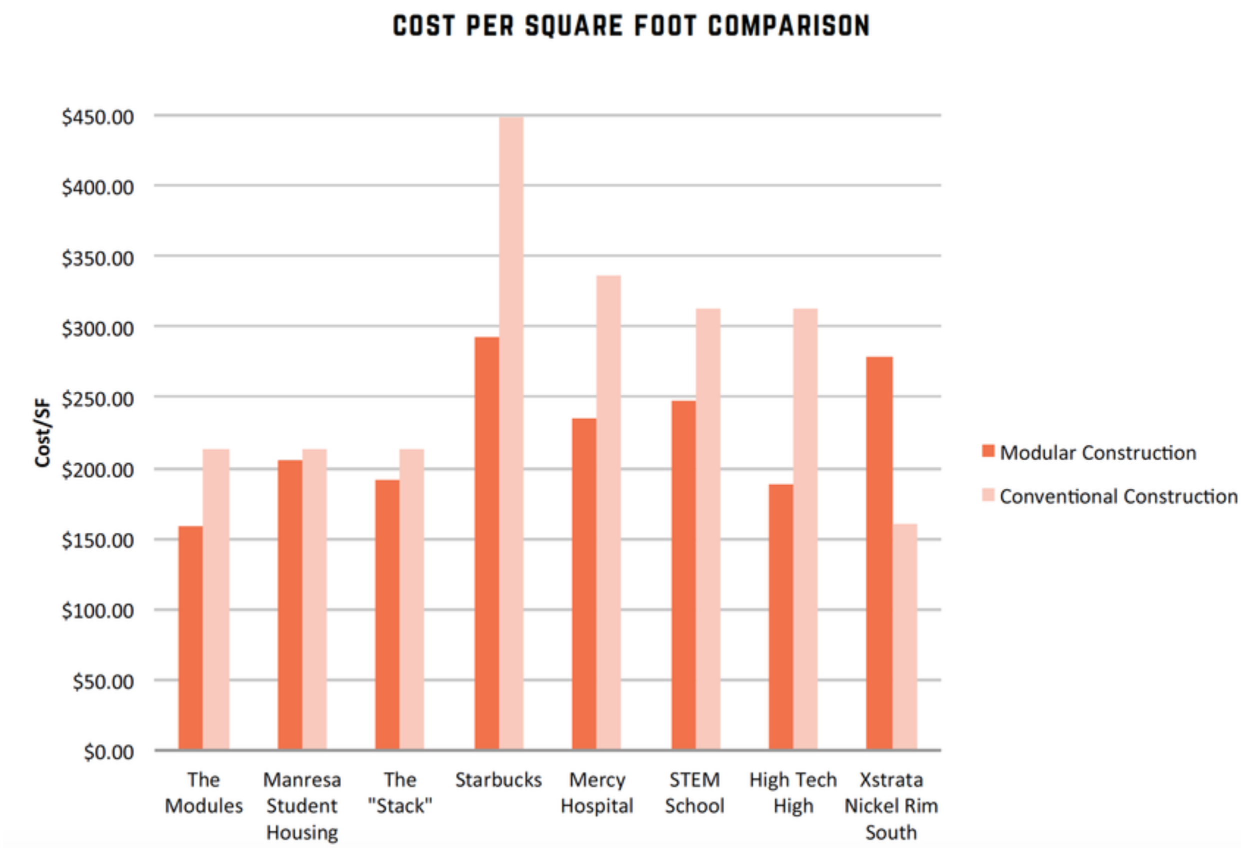

Figure 10 Cost Per Square Foot Comparison (Smith and Rice 2015)

4. **Case studies:**

Numerous studies explored the cost analysis of modular construction through case studies.

Recent modular projects have already set up a solid record of accomplishment of accelerating project timelines by 20 to 50%. The modular approach also has the potential to yield significant cost savings up to 20% (Bertram Nick et al. 2019).

In summary, modular mass timber construction presents opportunities for cost savings, sustainability benefits, and design flexibility in the building industry. Emphasis has been placed on the use of cross-laminated timber panels and off-site fabrication techniques to achieve these advantages, with the potential for overall schedule savings of up to 50 percent. Selecting a construction partner well-versed in the time and cost savings offered by mass timber is crucial for realizing these benefits in first cost models or bids. Additionally, integrating Design for Disassembly principles can enhance the building's value at the end of its lifecycle.

2.5. Critical Success Factors (CSFs) and assessment methods for Modular Mass Timber Adoption in Affordable Housing in the US

The use of Modular Mass Timber construction is on the rise within the affordable housing sector in the United States, driven by its cost-effectiveness, sustainability, and construction efficiency. As this construction method gains prominence, it becomes imperative to set up Critical Success Factors (CSFs) and assessment methodologies to gauge the effectiveness and efficiency of modular mass timber construction in the context of affordable housing. This literature review aims to delve into existing research on CSFs and assessment approaches specifically tailored for modular mass timber construction in affordable housing projects in the US.

CSFs play a pivotal role in evaluating the performance of Modular Mass Timber construction, offering a framework for assessing overall building performance, both off-site and on-site. Stakeholders in a project can use these factors to evaluate the sustainability of modular mass timber construction for affordable housing. Such a framework also eases comparisons between the performance of modular construction and conventional practices, offering valuable insights into the benefits of modular construction methods. Additionally, key performance indicators for modular mass timber construction, such as structural stability, seismic performance, and post-disaster relief performance, have been found (Bhandari et al. 2023a). Various aspects of modular construction, including seismic resistance, thermal behavior, acoustic performance, energy consumption, and sustainability, have been scrutinized in research studies.

Specific studies have examined the structural behavior of modular buildings, emphasizing connections and responses. For instance, (Thai et al. 2020) explored the structural behavior of high-rise steel volumetric modular buildings, focusing on inter-modular connections and their role in robustness and preventing progressive collapse. (Lacey et al. 2018) reviewed 13 modular steel buildings, concentrating on structural design, loads, connections, and structural response. In the realm of steel modular buildings, (Lawson Robert et al. 2014) offered detailed insights into module configuration, structural features, eco-friendliness, financial advantages, fire retardancy, and noise insulation. However, these studies primarily centered on modular structures made of steel, leaving a gap in the comprehensive analysis of connection systems and structural effectiveness, particularly in modular Cross-Laminated Timber (CLT) buildings.

In the limited studies specifically focused on modular CLT construction, (Gijzen 2017) investigated the applicability of a standardized modular CLT system for tall buildings, featuring CLT walls and ceiling components with a concrete floor slab. However, this research, while valuable, has a narrow scope, concentrating on modules within a specific volume.

In conclusion, the growing popularity of modular mass timber construction in affordable housing needs the establishment of CSFs and assessment methods. Existing literature shows that CSFs for this construction approach encompass construction and material cost, energy efficiency, carbon footprint, waste reduction, labor productivity, structural stability, seismic performance, fire resistance, and acoustic performance. Assessment methods include methodologies for evaluating affordability, structural stability, carbon footprint, and data analysis approaches for best construction system selection. This study advocates for the development of a standardized CSFs rubric and assessment methods applicable to the evaluation of modular mass timber construction for affordable housing in the US.

CHAPTER 3: RESEARCH METHODOLOGY

3.1. INTRODUCTION

This chapter presents a discussion of the research methods used in this study. Chapter 1 sets up the study's context by delving into the background and introducing the research area. Concurrently, Chapter 2 performs a comprehensive review of the literature, focusing on the critical success factors related to the cost analysis of Mass Timber and Modular Construction. Building upon the groundwork laid by these first chapters, the present chapter elucidates the research approach and method. Additionally, it outlines the aims, clarifies the connection, and underscores the contribution of these chapters to the broader research endeavor. This research includes three main aims as described in figure 11. The conduct of the research and connection to the project is presented in this chapter.

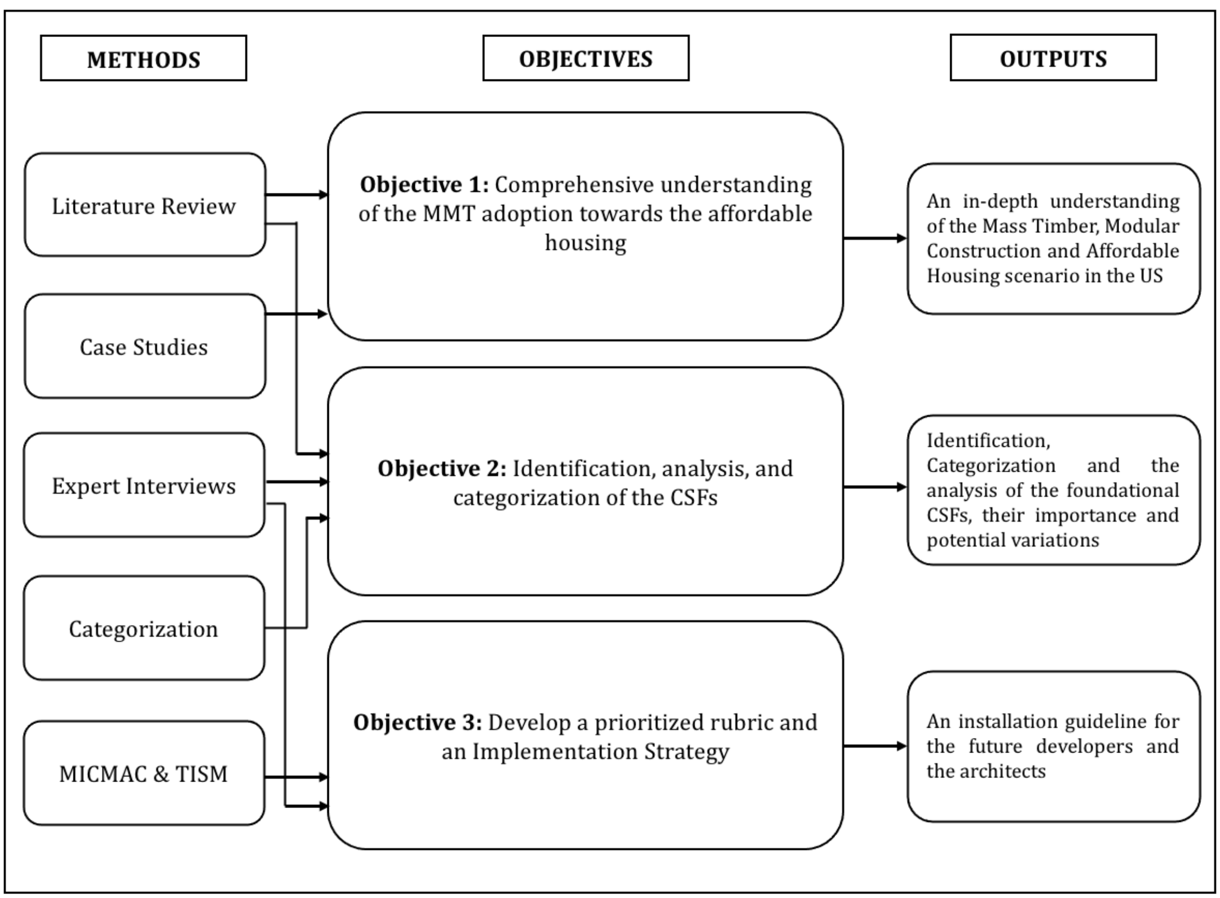

Figure 11 Research Methods, Objectives and Outputs

Objective 1 strives to provide a comprehensive overview of Mass Timber and Modular Systems tailored for affordable housing applications in the USA. This involves a thorough exploration of Mass Timber construction and Modular systems, with a specific emphasis on their potential utility in affordable housing. The study delves into engineering aspects, design flexibility, and economic sustainability inherent in both Mass Timber and Modular construction methods. Chapter 2 succinctly summarizes the existing literature on the cost analysis of Mass Timber and Modular construction, setting up a link between the two for constructing affordable housing in the USA.

Objective 2 advances by deepening the comprehension of the technical, economic, and policy dimensions of employing Modular Mass Timber in affordable housing. This includes an investigation into the technical intricacies of Modular Mass Timber construction, encompassing assembly processes, material properties, installation, and compliance with building codes. The economic viability of integrating Mass Timber and Modular systems is scrutinized, with a focus on costs, efficiency, and scalability. Additionally, the study analyses findings related to unique challenges and success factors in this context. Perceived critical success factors, their significance, and potential variations across diverse projects are systematically gathered and categorized. The study also evaluates existing policy frameworks and regulations pertinent to Mass Timber and Modular construction within the context of affordable housing policies in the USA.

Objective 3 involves the formulation of a prioritized rubric and an implementation strategy designed for assessing critical success factors associated with affordable modular mass timber projects. This rubric and strategies encompass inter-relativity of the CSFs and their individual practical implications.

3.2 RESEARCH OBJECTIVES

3.2.1 Objective 1 – Comprehensive Introduction to the Modular Mass Timber Adoption in Affordable Housing

The purpose of the work conducted in Objective 1 was to construct a greater understanding of the Affordable Housing scenarios in the US and to gain insight into the factors involved in the successful adoption of Modular Mass Timber. The work in this aim was started through a comprehensive review of the literature which provided the necessary theoretical and current state-of-knowledge underpinnings for the study. Reviewing the literature and understanding the current state provided a vision towards the need of this research and concrete reasons to study the Critical Success Factors towards the Installation of Modular Mass Timber for Affordable Housing Projects in the US. This research is focused on the Critical Success Factors involved in the 'Installation' process of Modular Mass Timber projects. Four categories of literature were reviewed to provide proper context for the research: (1) Affordable Housing Scenarios in the US, (2) Critical Success Factors involved in Modular/ Mass Timber/ Affordable Projects, (3) Modular construction statistics and analysis, (4) Mass Timber statistics and analysis.

The literature was reviewed primarily within the context of an introduction to the crucial factors involved in the context of Affordable or Modular or Mass Timber projects individually. Fig. 12 shows the research outline of the methods and outputs with interoperability of objectives.

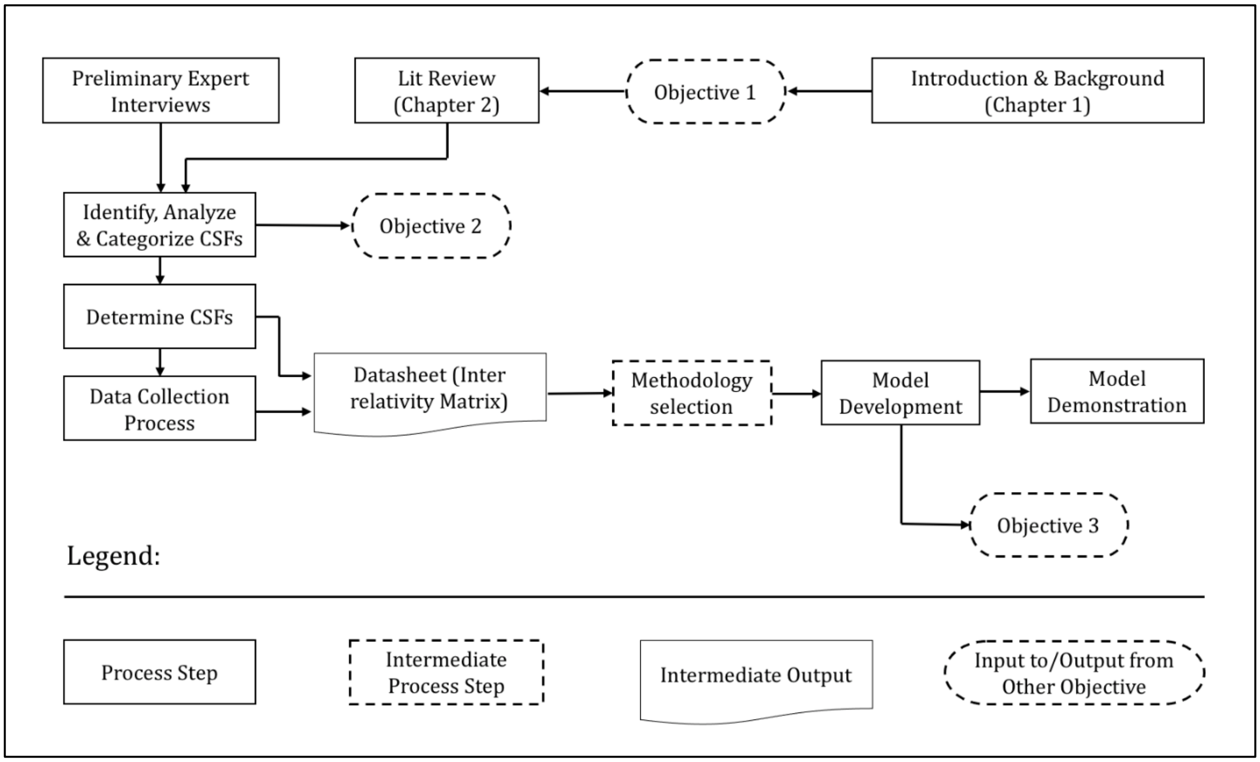

Figure 12 Research Outline of Methods and Outputs

The contribution of affordable housing study was to create a deeper understanding of the current market condition and the research need. This observation provided familiarity with the current market backlog, challenges and opportunities and is represented in section 2.2.2 of chapter 2. Study of the statistics and analysis of Mass Timber and Modular construction provided necessary inputs for the success factors identification step. Furthermore, literature on the Critical Success Factors involved in Modular/ Mass Timber/ Affordable Projects, provided insights for the variables to be decided in Objective 2.

The primary deliverable of the work conducted in objective 1 was a comprehensive background of the Building Materials, Housing crisis and affordability, Introduction to the Modular and Mass Timber construction technologies. Challenges and opportunities in affordable housing landscape, economic viability of the Mass Timber, Innovations and cost-effectiveness in the Modular Construction and corresponding critical success factors are presented in Chapter 2. These deliverables served as an input to the work undertaken further in Chapter 2, which identified, analyzed and categorized the critical success factors involved.

3.2.2 Objective 2 - Identification, Analysis and Categorization of the Critical Success Factors (CSFs)

The primary purpose of this objective was to create a base needed for the development of prioritized rubric which includes three steps; 1) Identification of Critical Success Factors (CSFs), 2) Data Collection, Analysis and Categorization of the CSFs, and 3) Research Methodology Selection. This objective advances on the groundwork performed in Objective 1 by comprehensive introduction and sets a stage for objective 2 by addressing data collection process and suitable technique for prioritized rubric development.

3.2.2.1 Identification of the Critical Success Factors (CSFs)

The primary aim of this objective was to delineate a comprehensive list of Critical Success Factors (CSFs) that are pivotal in the adoption of Modular Mass Timber (MMT) for Affordable Housing projects. This endeavor was designed to generate a foundational dataset, after it was used to populate a spreadsheet for detailed analysis. The genesis of this dataset was a methodical literature review and content analysis encompassing 40 scholarly articles, which meticulously explored the CSFs influencing MMT adoption in the realm of affordable housing. This rigorous examination led to the extraction of 78 distinct factors considered significant within the scope of this investigation.

After the extraction process, these factors underwent a clustering phase, adhering to a classification schema informed by preceding scholarly contributions in this field (Khan et al., 2022). This essential categorization distilled the myriad factors into eight pivotal clusters, namely: “Cost,” “Time,” “Quality,” “Efficiency,” “Demand,” “Sustainability,” “Social,” and “Legislation.” These categories were not only reflective of the multifaceted nature of the CSFs but also aligned with the established frameworks in existing literature, thereby ensuring a coherent and structured analysis.

Each cluster was meticulously analyzed and expounded upon to offer a nuanced understanding of the factors there. This detailed examination aimed to shed light on the intricate dynamics at play within each category, enriching the discourse surrounding MMT adoption in affordable housing.

The classification and detailed discussion of these clusters are instrumental in synthesizing a holistic view of the critical drivers for MMT adoption, laying a robust foundation for later empirical investigations. Moreover, this structured categorization underscores the interdisciplinary nature of factors influencing MMT adoption, ranging from economic and temporal considerations to social and legislative dimensions. Incorporating insights from the literature and aligning them with empirical data collection efforts, this analysis contributes significantly to the body of knowledge on sustainable construction practices, specifically within the context of affordable housing in the United States.

3.2.2.2 Data Collection, Analysis and Categorization of the CSFs

In pursuit of setting up a hierarchical framework for the effective deployment of modular mass timber in affordable housing projects across the United States, a comprehensive data gathering effort was undertaken. This endeavor sought insights from seasoned professionals with substantial involvement in modular construction, mass timber applications, or affordable housing initiatives, or those having relevant experience across these domains. The research method incorporated a series of eleven expert interviews, recognizing the nascent and evolving nature of this field within the US context and the consequent scarcity of highly experienced professionals.

The cohort of interviewees spanned a broad spectrum of ability, including individuals with over 15 years of experience in the sector. Among the participants were CEOs and founders of leading companies specializing in mass timber and modular buildings, as well as professionals with a focus on affordable housing development through modular approaches. The geographical diversity of their project experience across the US enriched the insights gathered. The group also included individuals with a structural engineering background, offering valuable perspectives on the efficient design and installation of mass timber elements, alongside experts skilled in framing, installation, and panelized modular construction specific to mass timber projects. Additionally, the study received help from the contributions of a training coordinator and active researchers within the mass timber field, both of whom have a solid academic foundation in this area.

Figure 13 List of the foundational Critical Success Factors identified

Following a first identification of critical success factors (CSFs) through literature review, the expert interviews aimed to refine and confirm these factors based on industry ability. Notably, the foundational CSFs found included "Cost," "Time," "Quality," "Efficiency," "Demand," "Sustainability," "Social aspects," and "Legislation." Through the course of the interviews, added CSFs such as "Safety," "Logistics," "Training," "Customization," "Coordination," "Commoditization," "Standardization," and "Research" were recognized as integral to the successful adoption of modular mass timber in affordable housing. This expanded list of CSFs appeared by the sixth interview, after which no further unique factors were found, showing a saturation point in the data collection. This saturation signified a comprehensive capture of the relevant CSFs, prompting a transition towards synthesizing the expert feedback to form a consensus on the prioritized CSFs essential for guiding future modular mass timber affordable housing projects.

3.2.2.3 Research Methodology Selection

After obtaining the list of Critical Success Factors (CSFs), the immediate goal was to begin data analysis, but with the sample size obtained and the number of variables, the prediction methods offered a challenge for the accuracy and suitability of the methods for the prioritized rubric. Various Multi-Criteria Decision Making (MCDM) tools like Analytical Network Process, Decision Making Trial and Evaluation Laboratory, and Analytic Hierarchy Process were referred to as a possible method for this study. Further, experts were consulted, and Total Interpretive Structural Modelling (TISM) was suggested as a better suited method for the study. This objective explores some background for selecting TISM and how it can be performed to achieve the goals of this study.

Specific to this study, the sample size obtained was relatively small given that modular mass timber construction is relatively an innovative approach in the US construction industry. The first approach was to use multiple regression for this study, but for using multiple regression, a large dataset is needed and there should not be any collinearity among the independent factors (Frost 2017). With a handful of observations and the possibility of multicollinearity among the independent success factors, there existed a need to find a better suited approach for the development of the prioritized rubric.

The advantage of using ISM and TISM approaches over other MCDM tools such as analytic network process, decision-making trial and evaluation laboratory, and analytic hierarchy process is that they do not demand the intensity of correlation between the factors; rather, only the level of dominance is needed. This reduces bias of the experts involved in the decision-making and increases reliability of the developed model (Gardas et al. 2018b) ;(Venkatesh et al. 2015). It may be noted that the ISM approach helps solve a complicated problem in a simplified way, and guides in interpreting the entrenched aim (Kumar et al. 2018; Raut et al. 2017). Also, it helps in the transformation of the poorly and unclearly segmented rational model into a visible and well-defined model, thereby answering 'what' and 'how' in theory building (Jha et al. 2018). Additionally, it helps find the structure within the system (Chaudhuri et al. 2016; Gardas et al. 2017; Gardas Bhaskar et al. 2017). Although the ISM method has significant advantages, it also suffers from certain serious drawbacks. For instance, the interpretation of links is poor, and it does not focus on the causality of links (Patil and Warkhedkar 2016; Raut et al. 2018; Sushil 2012). Hence, to overcome these limitations of the ISM method the TISM method has been employed.

A) ISM approach

The ISM method helps analyze/evaluate the interrelationship between the shortlisted criteria. Further, it guides to present a complex system in an easy manner (Dhochak and Sharma 2016; Gardas et al. 2018a; Janssen et al. 2018). The ISM approach has been widely used for finding the mutual relationship between the criteria across several domains.

Following steps are involved in the ISM approach (Faisal and Talib 2016; Narkhede and Gardas 2018; Ravi 2015; Sagheer et al. 2009)

1. Identify factors/variables of the system. In the present study the CSFs towards the Installation of Modular Mass Timber in Affordable Housing are considered as variables.
2. Figure out the interrelationship/influence between the CSFs and tabulate the same in the structural self-interaction matrix (SSIM).
3. Transform the SSIM into a binary matrix, i.e., an Initial Reachability Matrix (IRM).
4. Transform the IRM into a final reachability matrix (FRM) by taking transitivity into account. A rule of transitivity shows that if a factor/variable 'A' influences 'B,' and 'B' influences 'C,' then 'A' can influence 'C.'
5. Partition the FRM into various levels.
6. Draw a digraph (directed graph) and remove its transitive links.
7. Finally, develop an ISM-based model by swapping nodal values with the statements of CSFs.

A) TISM Approach

In the TISM approach, the interpretive matrix is used for interpreting the undirected and directed fuzzy or binary relationships. In the case of a graphical model, the construal of links may be carried out across paired factors (both pairs and links) that were poor/partial in the ISM approach. To increase the applicability of the structural model in real life situations, the ISM approach can be extended to the TISM method.

The primary stages/steps of TISM method are briefed here under (Sushil 2012)-

1. Identify and define the factors whose interrelationship must be proved through literature or from the group of experts.
2. Establish the contextual/mutual relation between the identified factors. For example, the contextual relationship between the two attributes could be 'CSF1 influences CSF4'
3. Interpret the interrelationship between the factors.
4. Interpret the pairwise comparison logic. In the conventional ISM approach, only the direction of the relationship is interpreted. In the TISM approach, the interpretive matrix concept is employed. In a paired comparison, the i^{th} element is individually compared with all elements. the contextual relationship between the different drivers to form the adjacency matrix were denoted by letters V, A, X and O:

- V denotes that driver "i" leads or influences driver "j";
- A denotes that driver "j" leads or influences driver "i";
- X denotes that both drivers "i" and "j" lead or influence each other;
- and O denotes that both drivers "i" and "j" do not lead or influence each other.

5. (Sushil 2012) suggested that for each "i,j" pair in the matrix, the nature of the relationship can be seen; and based on the responses, the compilation of interactions and transitive links between drivers can be developed.
6. Construct a Reachability Matrix (RM) and check for transitive links. The initial RM level followed the rules of binary values 0 and 1 to replace the V, A, X and O letters. The interpretation was proved as follows based on interpretations from (Sushil 74):

- For every V in the cell, the entry (i,j) becomes 1, and entry (j,i) becomes 0.
- For every A in the cell, the entry (i,j) becomes 0, and entry (j,i) becomes 1.
- For every X in the cell, the entry (i,j) becomes 1, and entry (j,i) also becomes 1.
- For every O in the cell, both the entries (i,j) and (j,i) become 0.

7. Further, to check the transitivity rules, the power iteration analysis is necessary to develop the final RM. As the Initial RM only reflects the direct relationships between the variables, it is necessary to perform a transitivity check to explore the indirect relationships as well (Gan et al. 2018). The transitivity check (*) supports the consistency among the driver relations and was conducted using Boolean operation

of self-multiplication to reach a stable state (Wu et al. 2015), for instance, if factor CSF-1 affects CSF-2 and CSF-2 affects CSF-3, then CSF-1 also affects CSF-3 indirectly. The expression used for generating the final RM is as follows as shown in Equation:

$$R_f = R_i^k + R_i^{k+1},\ k > 1$$ (Khan et al. 2022)

8. where Rf denotes final RM and Ri denotes initial RM (Shen et al. 2016). The final RM values are reflected in Table 2. The driving power of a driver is a number being other drivers that affects the outcome. The dependence power of a driver is a number being other drivers that are affected by it.
9. The next step is to develop a level partitioning matrix based on a hierarchical structure. The partitioning of levels to form a hierarchy structure is based on forming reachability set, antecedent set and intersection set. The reachability set of a driver includes all the drivers that it may reach, the antecedent set of a driver includes all the drivers that reach it, and the intersection set of a driver includes all the common drivers from reachability and antecedent sets.
10. Partition the reachability matrix into various levels. After deriving the reachability set and antecedent set for each driver from the RM, the intersection set was developed. The determination of levels for each driver is based on the comparison of the reachability set and the intersection set. The similar nature of drivers in both sets was placed accordingly in levels based on different iterations. The repetition of iterations was calculated consecutively, which led to a four-level hierarchy from level 1 to level 4. Similar approaches were used in other studies based on principles of TISM (Gan et al. 2018; Nair and Suresh 2021).
11. Develop the diagraph by arranging elements at their elimination levels and draw the directed links accordingly. It may be noted that essential links of transitivity may be kept.
12. Formulate the interaction matrix by transforming the final diagraph into a binary matrix showing all the significant relationships. Insert '1' in the binary matrix for showing the relationship and write the interpretation statement in the interpretive matrix.

13. Develop the TISM-based model by using the final diagraph and the interaction matrix. The TISM model should highlight the interpretations of the paired comparisons along with the hierarchical structural model.

In the present research framework, the ISM approach was extended to the TISM method, which makes it a novel approach for analyzing the CSFs towards the Installation of Modular Mass Timber in Affordable Housing are considered as variables.

3.2.3 Objective 3 – Develop a prioritized rubric and an Implementation Strategies towards the adoption of MMT in the affordable housing

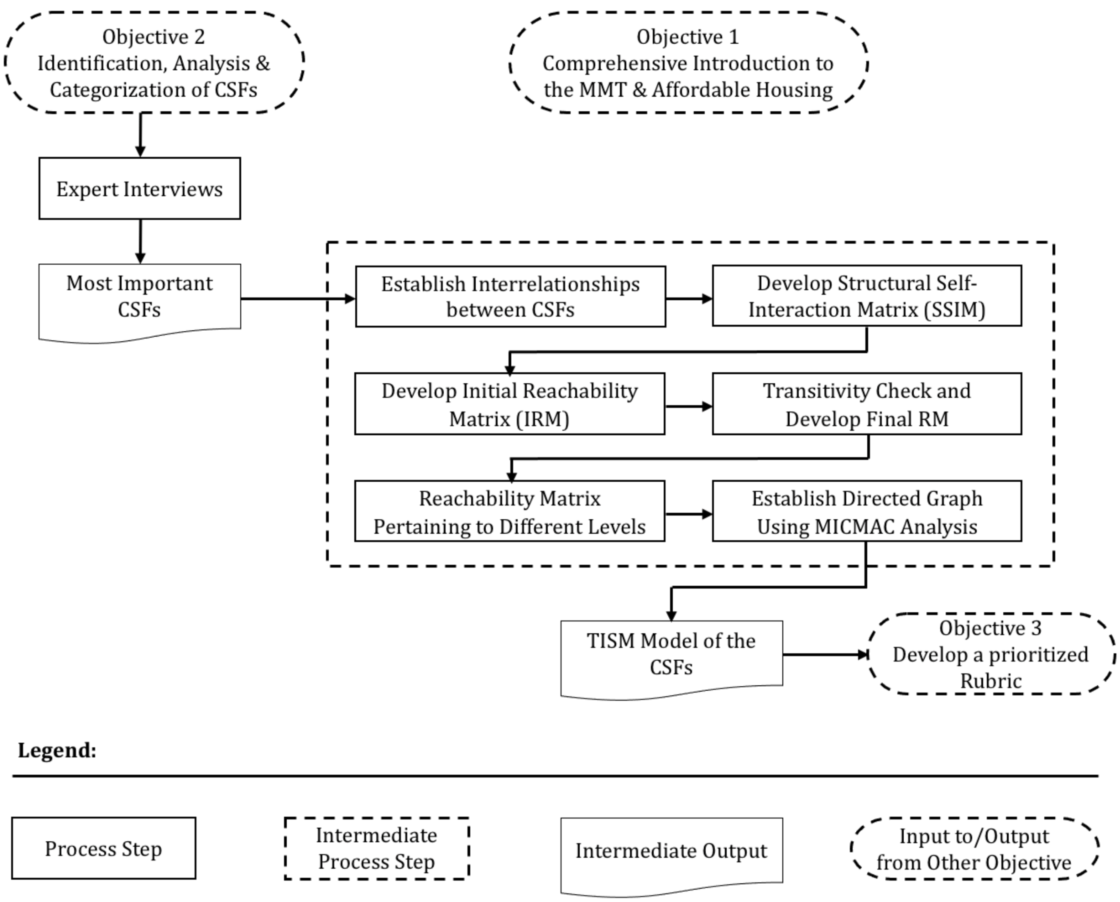

Figure 14 Research Outline: Objective 3

Objective 2 of this research ambitiously aimed to lay a solid groundwork for a structured and prioritized rubric by deciding Critical Success factors (CSFs), collecting data, and selecting method, along with implementation strategies that would underpin the successful adoption of Modular Mass Timber (MMT) in Affordable Housing projects. This aim was meticulously divided into two key sub-objectives to streamline the process: firstly, the development of the Total Interpretive Structural Modelling (TISM) model, and secondly, the crafting of the prioritized rubric alongside implementation strategies.

The TISM model, complemented by MICMAC (Matrice d'Impacts Croisés Multiplication Appliquée à un Classement) analysis, served to elucidate the intricate interconnections and hierarchical significance of the identified Critical Success Factors (CSFs). This analytical approach not only revealed the direct and indirect influences among the CSFs but also eased the identification of leverage points that could significantly enhance MMT adoption in the affordable housing sector (Zhang et al. 2021).

Building upon the insights garnered from the TISM model, this study ventured further to propose strategic recommendations aimed at amplifying the impact of these CSFs. The implementation strategies delineated here offers a comprehensive listing of CSFs, alongside the identification of key stakeholders pivotal for the strategic enhancement of these factors. Earlier literature has adeptly found various success factors; however, it often fell short of mapping the intricate relationships between these factors, delineating their relative importance, and suggesting a coherent strategy for their enhancement. This research endeavors to bridge these gaps, drawing upon a critical analysis of 40+ scholarly articles and insights from semi-structured interviews with domain experts (Pan et al. 2019; Vanclay et al. 2015; Zhang et al. 2021). This enriched perspective has enabled the formulation of targeted strategies and the identification of championing stakeholders, thereby providing a robust implementation blueprint for stakeholders to strategically bolster the adoption of MMT in affordable housing initiatives.

Implementation Strategies and prioritized rubric developed through this research signify a pivotal step towards understanding and using the CSFs for MMT adoption in affordable housing. By elucidating the dynamic interplay between these factors and finding actionable strategies for their enhancement, this study contributes a novel and pragmatic approach to accelerating sustainable construction practices within the affordable housing domain in the United States. Further investigation into these connections and strategies will continue to unfold, promising to enrich the implementation strategies and provide a more nuanced understanding of how to effectively champion the adoption of MMT in affordable housing projects.

CHAPTER 4: IMPLEMENTATION STRATEGIES DEVELOPMENT

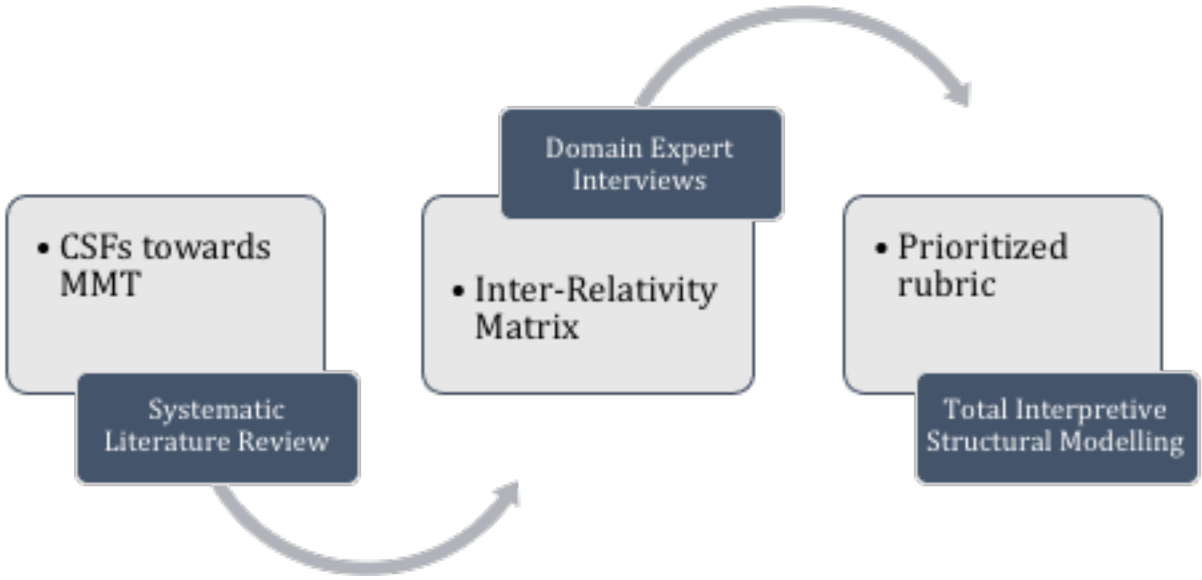

Figure 15 Three-way method of the proposed study

In this study, a comprehensive three-step approach has been used, incorporating the Total Interpretive Structural Modelling (TISM) Method and drawing on principles from relevant earlier studies. The first phase involved a thorough and systematic introduction, coupled with a literature review, to find Critical Success Factors (CSFs) related to the adoption of modular mass timber construction practices for affordable housing in the US. Following this, semi-structured interviews were conducted with domain experts to set up linkages between various CSFs and categorize them. Finally, the TISM model was constructed to develop a prioritized rubric for CSFs, easing a comprehensive understanding of the broader landscape.

4.1 Systematic Literature Review Procedure

Initiating the TISM method involves a systematic literature review to examine relevant articles for the proposed study. The article retrieval process adheres to the Preferred Reporting Items for Systematic Reviews and Meta-Analysis (PRISMA) method, a systematic data collection protocol with four distinct steps: identification, screening, eligibility, and inclusion. Widely used in the Architecture, Engineering, and Construction (AEC) field, this data extraction process is recognized and employed by researchers (Khan et al. 2022).

4.1.1 Identification

To find relevant publications, keywords for the research were found through an unconstrained search. Keywords from prior studies within a similar domain were also considered. Keywords were categorized into three domains: Mass Timber, Modular Construction, and Affordable Housing in the US. Synonymous terms for each domain were also considered. Keywords for Modular Mass Timber Construction included “modular construction,” “mass timber construction,” “modular mass timber construction,” "prefabricated,” “offsite construction,” and “prefabricated prefinished volumetric construction.” For drivers, analogous keywords like “cost-analysis,” “cost-benefits,” “advantages,” “enablers,” “merits,” and “factors” were used. For Affordable Housing, keywords included “affordable housing in the US,” “housing affordability,” and “sustainable housing.”

4.1.2 Screening

The screening process was executed based on criteria such as limiting years of publication (2010 to the present), document type (research papers, case studies, articles, and journals), and language (English).

4.1.3 Eligibility

In the eligibility phase, a thorough examination of the full abstract was conducted, leading to the exclusion of certain papers based on criteria such as lack of focus on the subject matter, addressing affordable housing, modular construction, or mass timber individually, and relevance to other sectors.

4.1.4 Inclusion

In the final phase, 40 articles focusing on the drivers were chosen for content analysis. All 40 articles underwent a critical analysis, leading to the identification of eight critical success factors: time, cost, quality, productivity, social, environmental, demand, and policy.

4.2 Domain Experts Semi-Structured Interviews

Following the analytical phase of identifying and categorizing the Critical Success Factors (CSFs) from a thorough review of the literature, this study went ahead with conducting semi-structured interviews with domain experts within the mass timber and modular construction sectors. These interviews delved into various sides of mass timber and modular projects, exploring CSFs, challenges, risks, the trajectory of technology adoption, and the prospects for its expanded use in affordable housing initiatives. Purposeful sampling was employed to select participants, ensuring they had significant knowledge and experience in mass timber and modular construction methodologies. Conducted virtually, these interviews engaged a diverse group of professionals, enriching the study with a wide array of perspectives. The sessions were meticulously recorded, transcribed verbatim, and subjected to a detailed content analysis to distil valuable insights (Liu et al. 2022).

To construct a hierarchical framework that supports the effective implementation of modular mass timber in affordable housing projects across the United States, this research engaged in an extensive data collection process. This process entailed interviewing eleven experts, a strategy that acknowledged the emerging nature of this specialization within the US and the relative scarcity of deeply experienced professionals in the field.

The interviewees stood for a broad spectrum of ability, with some professionals boasting over 15 years of experience in the sector. The participants included CEOs and founders of prominent companies in the mass timber and modular building industries, as well as experts focused on the development of affordable housing through modular methods. Their varied geographical experiences across the US contributed richly to the insights collected. The panel also featured professionals with a structural engineering background, who offered in-depth views on the efficient design and installation of mass timber elements, and specialists in framing, installation, and panelized modular construction tailored to mass timber projects. Furthermore, the research was enriched by contributions from a training coordinator and active researchers in the mass timber domain, both of whom brought a strong academic perspective to the discussions.

The aim of these expert interviews was to refine and affirm the CSFs derived from industry ability. Initially identified CSFs included "Cost," "Time," "Quality," "Efficiency," "Demand," "Sustainability," "Social aspects," and "Legislation". As the interviews progressed, added CSFs such as "Safety," "Logistics," "Training," "Customization," "Coordination," "Commoditization," "Standardization," and "Research" appeared as critical to fostering the adoption of modular mass timber in affordable housing. The expansion of CSFs stabilized by the sixth interview, showing a saturation in data collection and suggesting a comprehensive encapsulation of pertinent CSFs. This saturation marked a pivotal point in the study, signaling the readiness to synthesize expert opinions into a consensus on the prioritized CSFs vital for steering future modular mass timber projects in affordable housing. The later sections will elucidate each cluster of completed CSFs, providing a deeper understanding and highlighting the broader context of the literature surrounding each category.

4.2.1 Cost Factor

The construction sector often grapples with the issue of cost overruns, with a substantial number of projects exceeding their initially projected financial allocations (Abdul Nabi and El-adaway 2020). As per the report by the Real Estate Network, personal income as a percentage of median home listing price varies from 7.17 to 25.2 percent (Grenfell and Carpenter 2022). This phenomenon underscores the necessity for cost management strategies that can mitigate these overruns. In the context of affordable housing projects in the United States, employing Modular Mass Timber (MMT) appears as a pivotal success factor, primarily due to its cost-effectiveness. The foundation of MMT is rooted in concurrent engineering principles, aiming to curtail unnecessary cost increases during the project lifecycle. Although MMT is associated with a higher first investment, it holds the potential for significant cost savings over the entire project duration. A report by Falcon Structures highlights that 91% of general contractors perceive modular construction as beneficial for budget performance, with 48% reporting a cost reduction exceeding 10% (Becca 2023). Further, as per the 'Tall Mass Timber Toolkit' report by American Wood Council 2022, in one engineering firm's experience, mass timber buildings are roughly 25% faster to construct than concrete buildings and needed 90% less construction traffic. The factors contributing to cost reduction encompass capital expenditure, operational costs, rework, lifecycle expenses, design and construction costs, labor, and product pricing. These elements collectively advocate for the adoption of modular construction in affordable housing projects. Literature reviews and comparative analyses further reveal that mass timber projects may incur a premium of up to 15%, which could diminish to less than 2% with accrued experience (Dawson 2023). Additionally, Cross-Laminated Timber (CLT) is recognized for its cost-efficiency, thereby enhancing the cost predictability and rendering MMT a financially viable alternative to conventional construction methods. Thus, cost management is identified as a critical success factor for the implementation of MMT in affordable housing initiatives.

Further elaboration from expert interviews reinforces the significance of cost as a critical success factor. Unanimously, experts highlighted cost as a determinant of project success, linking it to project scheduling. The consensus among professionals is that standard structural designs, repetition, and a modular approach are instrumental in reducing costs.

One expert noted that cost benefits are amplified with increased material utilization and market expansion. From the perspective of developers, the economic viability of MMT is emphasized, citing its potential for expedited and profitable project completion. Other considerations affecting cost include geographical location, design simplicity, installer experience, and reduced production costs per square foot. These insights collectively underscore the multifaceted nature of cost as a critical success factor in the deployment of modular mass timber for affordable housing projects.

4.2.2 Time Factor

Amid the escalating housing crisis in the United States, highlighted by the National Low Income Housing Coalition's report on the dire shortfall of 7.3 million rental homes accessible and affordable to extremely low-income renters defined as individuals earning at or below 30% of their area median income or the federal poverty guideline—accelerating the construction process emerges as a pivotal strategy (NLIHC 2023). This staggering deficit underscores a critical demand for efficient construction methods, as the current supply chain only provides 33 affordable housing units for every 100 households in extreme financial need. The urgency to augment the delivery of affordable housing within this context of pronounced demand needs a focus on reducing construction times, thereby underscoring the significance of speed in construction practices. A 2016 McKinsey report shed light on the systemic inefficiencies plaguing the construction sector, revealing that 20% of large-scale projects face delays, with a staggering 80% exceeding their budget estimates (Agarwal et al. 2016). This analysis posits the construction industry as an ideal candidate for innovative disruption.

Compared to concrete and steel, mass timber buildings (WoodWorks 2024) are faster to build (therefore often cheaper), just as safe in fires, and create fewer CO_2 emissions. Single- and multi-family housing using mass timber components could help with the 7.3 million gaps of affordable homes (NLIHC 2023).

Broader adoption could meaningfully increase productivity and thereby reduce construction costs. A 25-story mass timber building in Milwaukee completed in 2022 took 75% less time compared to traditional construction techniques. Developers have reported cost savings of up to 35% through lower time and labor costs (Potter Brian 2024). Mass timber isn't only for small projects: Walmart is building a new 2.4-million-square-foot office campus from mass timber (Walmart 2024).

In this scenario, Modular Mass Timber (MMT) stands out as a transformative construction technique that substantially mitigates project timelines. The criticality of efficient time management in construction projects cannot be overstated, with delays and budget overruns traditionally seen as significant deterrents to the sector's success. MMT distinguishes itself through its potential to cut construction time by up to 50% compared to conventional methods, attributed to the adoption of concurrent engineering processes that streamline construction activities. The benefits of employing MMT for affordable housing are multifaceted, encompassing a rapid construction phase, diminished lead times, an accelerated return on investment, reduced design and planning phases, fewer weather-related delays, enhanced adherence to schedules, and a notable contraction in the overall project time. Research by (Si et al. 2020) underscores modular construction as an efficacious just-in-time delivery model, proposing a framework that accentuates its capability to minimize risks associated with natural disruptions. Similarly, (Chen et al. 2021) analysis on the expedited construction of an emergency pandemic hospital in Wuhan, China, via modular techniques, underscores the pivotal role of time efficiency in modular construction's appeal, particularly in responding to emergent needs.

The centrality of 'Time' as a Critical Success Factor (CSF) in the deployment of MMT for affordable housing projects has been unequivocally affirmed by domain experts. Interviews with seasoned professionals across the spectrum of mass timber and modular construction have illuminated the consensus about the substantial time savings afforded by MMT, with projections showing potential reductions in construction schedules by 20-25%. In addition, a report by McKinsey & Company states Modular construction can speed construction by as much as 50% (Bertram et al. 2019). This efficiency not only eases direct reductions in project costs but also significantly enhances overall resource use. Insights gleaned from discussions with a regional director of a Mass Timber research organization, as well as professionals from development and architectural firms, corroborate the assertion that MMT facilitates swifter construction timelines. This, in turn, allows more advanced planning and indirect savings on construction costs through improved operational efficiency. Moreover, an expert with extensive experience in the production and supply of factory built MMT units highlighted the dual benefits of safety and speed associated with this construction method, emphasizing its ability to conserve resources while ensuring rapid project completion. The unanimous acknowledgment of 'Time' as a paramount CSF by domain experts not only confirms its significance but also reinforces the imperative for its strategic consideration in future projects employing Modular Mass Timber for affordable housing, thereby aligning with the urgent need to address the housing shortage while maximizing efficiency and stakeholder value.

4.2.3 Quality Factor

Historical assessments of affordable housing projects have often highlighted concerns about the standard of quality, with findings suggesting that such projects often do not meet the living standards and expectations of their inhabitants. Research conducted by (Khan et al. 2022) has pointed out that affordable and low-cost housing projects, predominantly delivered by governmental and public organizations, typically do not prioritize quality outcomes. This situation is further compounded by the limited interest shown by private developers, attributed to the relatively narrow profit margins associated with affordable housing (Dwijendra 2013). Additionally, there exists a societal feeling that the introduction of low-cost housing within a neighborhood can lead to a depreciation in property values. (Egan 2003) has underscored that client satisfaction levels with low-cost housing are often below acceptable standards, thereby highlighting a critical need for improvement in the quality of these housing solutions.

In contrast, modular construction, along with other off-site construction techniques, presents a promising avenue for enhancing the quality of affordable housing. (Zhang et al. 2021) have underscored the potential for achieving superior quality through modular integrated construction, primarily due to the controlled factory environment in which modules are fabricated. This environment eases rigorous regulation, inspection, and testing prior to assembly, ensuring consistency, minimizing defects and damage, and significantly improving overall project quality control. Such practices not only lead to improved lifecycle performance and durability of the housing units but also contribute to a higher quality of the final product. Furthermore, the scalability of modular construction allows to produce repetitive modules on a large scale, addressing the affordability crisis in housing across various countries. The emphasis on quality as a driving factor underscores the rationale for integrating modular construction methodologies within affordable housing projects.

The benefits of modular mass timber (MMT) construction extend beyond quality enhancement, encompassing improved energy performance, reduced on-site deliveries, and minimized noise, pollution, and community disruption (Passarelli 2019). Additionally, (Bhandari et al. 2023a) have found critical performance indicators specific to modular mass timber construction, including structural stability, seismic resilience, and post-disaster recovery capabilities. These findings advocate for the establishment of Critical Success Factors (CSFs) dedicated to quality assessment within the sector.

Expert interviews further reinforce the quality advantages associated with MMT. Industry professionals with extensive experience in MMT fabrication and installation have highlighted its superior quality attributes, such as minimal rework, waste elimination, and reduced change orders. Experts from the architectural and development sectors commend MMT for its enhanced build quality and detailed manufacturing processes. Stakeholders across the supply chain, including manufacturers, structural designers, fabricators, architects, developers, and installers, contribute to the meticulous detailing of MMT projects. This collaborative approach ensures a smooth transition through the supply chain, resulting in fewer defects and a higher degree of perfection in the final product. Thus, 'Quality' appears as a pivotal Critical Success Factor in the adoption of Modular Mass Timber for affordable housing in the United States, advocating for a change in basic assumptions towards construction methods that prioritize quality without compromising affordability.

4.2.4 Efficiency Factor

The construction sector is currently confronting significant challenges in enhancing its efficiency, with an emphasis on improving quality, productivity, and sustainability. This is particularly critical as construction ranks among the leading contributors to carbon emissions globally, underlining the imperative for a more sustainable approach to construction practices (United Nations 2023). The focus on material efficiency is crucial, given its substantial impact on global warming and greenhouse gas emissions, needing a holistic perspective rather than an isolated consideration of individual components (Ruuska and Häkkinen 2014). The concept of productivity within the construction domain encapsulates the efficiency with which a project is executed, encompassing labor, equipment, construction methodologies, site management, and material use.

The construction industry's productivity is further nuanced by the potential of modular construction to enhance process and organizational efficiency. Although the benefits of modularity may not be at once clear, a deliberate pre-project evaluation of modular solutions within the specific project context can reveal significant advantages, promoting a collaborative approach to project execution (Bekdik 2024).

A notable challenge facing the construction industry is the acute shortage of skilled labor, worsened by the pandemic, with (Statista 2023) reporting a loss of approximately 975,000 construction jobs. This labor shortage, coupled with the physical demands of the industry deterring younger generations, accentuates the need for more efficient manufacturing and automation techniques. Contrary to concerns that automation could lead to job losses, the World Economic Forum (2021) predicts that automation could generate an estimated 58 million new jobs by 2025 (Cann Oliver 2018), suggesting that Modular Mass Timber Construction (MMT) could attract a broader labor force. Moreover, modular construction methods are recognized for improving worker health and safety, with 44% of contractors acknowledging their positive impact (Bibeau et al. 2020).

Affordable housing projects, reliant on cost-effective construction solutions, can benefit significantly from the integration of MMT and automation, enhancing productivity while requiring less labor. Addressing construction industry productivity entails embracing technological advancements, clear goal setting, role clarity, incentive distribution, feedback mechanisms, and motivation enhancement (Pan et al. 2020). Despite being labelled as one of the least productive sectors, the adoption of manufacturing-based business models and construction methods like MMT offers a pathway to overcoming these challenges.

MMT and other off-site construction techniques have proved a positive impact on productivity, emphasizing the importance of safety, efficiency, innovation, and the application of innovative technology, including automation and robotics, which can deliver higher output at lower costs (Le 2022). The projected growth in the modular construction market, expected to reach approximately $120.4 billion by 2027 (MarketsandMarkets 2022), underscores the potential for automation to revolutionize construction practices, potentially reducing project schedules by 30–50% and costs by 20–25%. While the first costs of automation may deter stakeholder interest, the high-volume production of modular units for affordable housing could incentivize increased adoption of automation in construction (Le 2022).

Efficiency appears as a critical success factor in the use of MMT for affordable housing, underpinned by its potential to streamline production, reduce risks, hasten installation, and perfect project outcomes. Expert interviews highlight MMT's advantages in production speed, risk mitigation, installation efficiency, and project output. The emphasis on perfecting structural solutions, engineering properties, and replicability further illustrates MMT's efficiency across trades and stakeholders, with designers noting its usability and flexibility due to standardization and repeatability. Consequently, efficiency is paramount in enhancing the adoption of MMT for affordable housing, offering a framework for assessing the sustainability and performance of modular construction against conventional practices (Bhandari et al. 2023a; Zhang et al. 2021).

4.2.5 Demand Factor

The burgeoning global population underscores a critical need for scalable housing solutions, as both developed and developing nations grapple with housing shortages. Concurrently, the construction sector faces scrutiny for its significant carbon footprint, needing sustainable practices to address the dual challenge of housing provision and environmental conservation (AIA 2023). Modular Mass Timber (MMT) construction appears as a compelling response, offering a method that aligns with the urgent demand for affordable housing while championing sustainability.

The acute housing crisis in the United States, as detailed by the National Low Income Housing Coalition, reveals a deficit of 7.3 million rental homes affordable for extremely low-income renters (NLIHC 2023). As per the report by CNBC, more than a third of US households are renters with the federal minimum wage stuck at $7.25. And, as per the data by NLIHC, a full-time worker needs to make $28.58 an hour, on average, to afford a modest two-bedroom apartment in their area (Nova Annie 2023). This scenario accentuates the demand for construction methodologies that not only hasten the building process but also adhere to affordability and sustainability criteria. MMT stands out for its potential to significantly reduce construction timelines, thereby addressing the pressing need for efficient housing delivery mechanisms. Moreover, the method's appeal extends beyond its environmental benefits, encompassing cost-effectiveness and expedited construction—qualities essential in mitigating the housing shortfall.

Demand for MMT and other offsite construction methods varies across regions, influenced by demographic and geographic factors. In Nordic and Scandinavian countries, for example, the prolonged freezing weather conditions make conventional construction methods less practical, positioning MMT as a suitable alternative. The controlled factory settings of offsite construction minimize weather-related delays, thereby enhancing the attractiveness of MMT for affordable housing projects in these climates (Wuni and Shen 2023).

The imperative for environmentally sustainable building materials has never been more pronounced, with the built environment accounting for approximately 42% of annual global CO2 emissions. Among these, building and infrastructure materials contribute to 15% of annual emissions, spotlighting mass timber as a practical solution for reducing carbon footprints (AIA 2023). The increasing global population, compounded by the economic impacts and slowed construction pace post-pandemic, amplifies the demand for housing - a situation highlighted by a report showing a 3.2 million home shortage in America (Sparbar 2023). This context sets the stage for innovative construction technologies like MMT, which promise faster and more efficient building processes.

Experts in the field universally acknowledge 'Demand' as a critical success factor for the adoption of MMT in affordable housing projects. Attributes such as mass timber's lightweight nature, its aesthetic appeal, and the unique ambiance it creates have been cited as factors driving its popularity. Additionally, the flexibility and customization options offered by MMT have been highlighted as appealing aspects, contributing to its growing demand. Positive user feedback and the potential for further research and development in this area underscore the optimistic outlook for MMT's future. The consensus among experts is that MMT's demand is influenced not only by its inherent advantages but also by the evolving preferences and satisfaction of users and owners, suggesting a bright future for MMT in addressing the affordable housing crisis while adhering to sustainability and efficiency standards.

4.2.6 Sustainability Factor

The construction sector is recognized as a significant contributor to global climate change, underscoring the imperative for energy-efficient methodologies that align with the United

Nations' Sustainable Development Goals (SDGs) (AIA 2023). Modular Mass Timber (MMT) construction emerges as a paradigmatic shift towards sustainability in the building industry, demonstrating its potential through reduced project delivery times via concurrent engineering principles (Wuni and Shen 2023), a diminution in carbon and toxic emissions (AIA 2023; Liebetanz Kai 2022), and a significant decrease in greenhouse gas emissions—by 69% (216 kgCO2e/m2) as reported by (Himes Austin 2020). Furthermore, off-site modular construction methodologies contribute to an up to 83.2% reduction in waste generation (Loizou et al. 2021). The substitution of mass timber for conventional construction materials in a substantial fraction of new urban construction could offset up to 9% of the global emissions reduction needed to achieve 2030 climate targets (Himes Austin 2020). The replacement of carbon-intensive materials such as concrete and steel with wood significantly lowers a building's embodied energy, further illustrating the sustainability benefits of MMT (Gustavsson et al. 2010).

Despite the environmental and sustainability advantages of MMT being well-documented, its application within affordable housing stays limited. The environmental credentials of MMT, including enhanced building performance, minimal waste and pollution, and improved resident comfort, position it as an attractive choice for sustainable affordable housing development (Himes Austin 2020; Pervez et al. 2021; Teng and Pan 2019). This sustainability factor is a crucial driver for the broader adoption of MMT practices in affordable housing sectors.

Sustainable design practices emphasize the use of eco-friendly materials and methods from the design phase through to construction and operation, incorporating green practices to minimize environmental impact and enhance resident well-being (Atta et al. 2021). Modular construction methods have been shown to have a significantly lower environmental impact than traditional construction methods, using approximately 20% less material and generating about 75% less wood and drywall waste (Quale John et al. 2012). Additionally, the energy efficiency of factory settings in modular construction offers a more sustainable alternative to on-site construction practices.

Mass timber is heralded not only for its material efficiency and environmental benefits but also for its role in creating dense, sustainable built environments that contribute to reducing overall building energy consumption through thermal mass effects (Mallo and Espinoza

2014). As a renewable material, Cross-Laminated Timber (CLT) exemplifies the shift towards construction materials that sequester carbon, offering an environmentally friendly alternative to conventional building materials.

In discussions with experts, the consensus appeared that 'Sustainability' stands as a paramount Critical Success Factor (CSF) for MMT projects. Experts from various domains—from manufacturing and installation to development—highlighted MMT's carbon storage capabilities, the use of local materials, renewability, and biophilic qualities. Such endorsements from professionals across the field affirm the significance of sustainability in promoting the adoption of MMT, underscoring its viability as a sustainable construction method for affordable housing. This collective viewpoint from experts reinforces the notion that sustainability is not just an environmental imperative but also a strategic advantage in the adoption of MMT for affordable housing projects.

4.2.7 Social Factor

The International Association for Impact Assessment (IAIA) characterizes the social impact of projects or technologies as the spectrum of both expected and unanticipated consequences stemming from interventions, encapsulating any resultant social changes, whether positive or negative (Vanclay et al. 2015). In the realm of construction, the social adaptability of a project is discerned through the effective engagement of clients, employees, the community, and other stakeholders, aiming to meet the needs of both present and future communities. While the primary focus of many construction endeavors is profitability, affordable housing projects command a broader vision encompassing economic, cultural, social, and environmental harmonization within communities (Sunday et al. 2021b). The assessment of social factors as a driving force behind the adoption of Modular Mass Timber (MMT) in affordable housing hinges on the evaluation of various Critical Success Factors (CSFs) linked to social performance. Research conducted by (Pan Wei et al. 2020) in the Hong Kong engineering sector found health, safety, satisfaction, and social impact as key performance indicators (KPIs) integral to quantifying the social benefits of modular construction. Their findings suggest that modular construction surpasses traditional methods in delivering quantifiable social benefits, enhancing health and safety, expediting project completion, improving the industry's image, and minimizing community disturbances.

The shift towards mass timber as an alternative to conventional concrete structures not only offers environmental advantages but also heralds economic and social benefits, including improved worker safety and potentially higher wages (UNEP 2022). Comparatively, mass timber construction presents significant social advantages, positively affecting construction workers, neighboring communities, and building occupants, by fostering a safer and more harmonious construction environment (Krone Jack 2023). The intrinsic qualities of wood, such as its natural warmth and aesthetic appeal, contribute positively to human well-being, with the material itself serving dual purposes as both structure and finish, thus cutting the need for added finishing materials (Cesnik 2022).

Diane Yentel, President and CEO of the National Low Income Housing Coalition, underscores the critical challenge of housing insecurity among the lowest income renters, worsened by systemic inequalities and inadequate federal support. Mass Timber appears as a financially practical choice over the lifecycle of a building, offering cost savings when compared to traditional building materials (Funston 2023).

During the expert interviews, diverse viewpoints were expressed about the 'Social' factor's role as a Critical Success Factor. Notably, only two of the interviewed experts specifically underscored the importance of the 'Social' factor. One expert, with a background in public relations and outreach, discussed the public's curiosity and feeling towards MMT. Meanwhile, another expert, serving as a regional manager for an affordable housing development organization, found 'Social' adaptability as a pivotal CSF. These insights highlight the nuanced understanding of 'Social' considerations within the context of MMT for affordable housing, suggesting a need for further exploration and emphasis on how MMT can foster social benefits and address the broader aims of community well-being and inclusivity. This elaboration on individual responses and considerations underscores the multifaceted nature of 'Social' as a CSF, pointing towards its critical role in achieving sustainable, inclusive, and community-oriented affordable housing solutions through MMT.

In the meticulous examination of critical success factors (CSFs) for integrating modular mass timber into affordable housing projects within the United States, the inclusion of 'Social' factors was extensively deliberated. Majority of experts consulted during this research posited that while social considerations are undeniably crucial to the broader spectrum of development projects, they do not show a unique influence on the adoption of modular mass timber in affordable housing. Given their generic applicability across several types of development endeavors, the consensus was that the 'Social' factor does not distinctly affect the specific challenges and opportunities inherent to modular mass timber projects. Consequently, to keep a focused and relevant analysis, the 'Social' factor was excluded from the final list of CSFs found in this study, aligning with the aim to spotlight factors directly affecting the practical implementation and success of modular mass timber in the affordable housing sector.

4.2.8 Legislation

The development and implementation of vigorous policies towards applying Modular Mass Timber (MMT) methods in affordable housing, and adherence to building codes is a significant critical success factor. The robust frameworks and policies made by policymakers towards increasing the use of MMT and other offsite construction methods in affordable housing are seen in many developed and developing countries around the world (Pan et al. 2019). The government's role in providing policies, guidelines, bylaws, support, incentives, schemes and regulations is a huge boost and encouragement towards the use of modular construction in affordable housing (Pan et al. 2019). Globally, governments are backing modern methods of construction, particularly modular construction and other offsite construction methods to address the pressing challenges of housing affordability in diverse ways (Khan et al. 2022). Not only could tribulations over housing affordability be addressed largely by applying MMT methods, but also endemic skill shortages in the construction industry are pushing modern methods of construction quicker than ever (Le 2022). Countries such as Sweden, Japan and Poland are pioneers in adopting offsite methods to meet their housing demands. The weather limitations and demographic restrictions of these countries are also considered by the policies of the government. For instance, in Sweden, the government had targeted a goal of 250,000 modular and sustainable homes delivery by 2020 to resolve the rising crisis of housing (The Local Sweden 2015); however, the goal was disturbed due to the pandemic, and the delivery was expected to be delayed by a year. Similarly, government schemes in developed countries such as the USA, UK, Australia and Canada are pushing the streamlined process of housing delivery amidst rising concerns of the housing shortage (Pan et al. 2019). In the USA, along with realizing modular mass timber construction as an innovative approach for housing demands, the individual capital cities of different states are taking their measures to curb the crisis in the housing sector. The 70$ million projects in New York City aim to deliver affordable housing using modular construction methods as planned by New York city's Department of Housing preservation and development (Gannon 2019). In a directive by the UK government, the mobilization of affordable housing delivery must use modular construction and other off-site construction methods by at least 25% (Oakley 2015). On contrary, the Canadian government cited the factors of labor shortage and low-skilled workers that boost the use of modular construction methods for affordable housing delivery (Builtoffsite 2020). In Australia, the grappling situation of a housing shortage which is projected to rise by 1.7 million by 2025 calls for strict measures by the government and related organizations. However, the Australian government expects that gaining traction in the housing space will only be achievable by escalating the manufacturing industry and making them the trailblazers to lead the way. Regarding this, the Cooperative Research Centre (CRC) of Australia has developed an industry-led research initiative known as Building 4.0 CRC which has an individual theme of housing and urban design focusing on affordability domains. In New Zealand, a government-led real estate development body named Kiwi Build is formulated in 2018 aiming to deliver 100,000 affordable housing using modular construction methods by 2028 (Offsite news 2018). In Asian countries, the government is (Builtoffsite 2020) playing a key role in the upliftment of offsite construction technologies in China, Hong Kong, Japan, South Korea and Malaysia, among others. For instance, in Singapore, the government launched an Industry Transformation Map (ITM) in 2017 which underpins the usage of digital technologies and offsite construction techniques in the infrastructure areas with a focus on housing (Building and Construction Authority 2017). Similarly, in Hong Kong, a Construction Innovation and Technology Fund is granted by the government to promote modular construction and other digital technologies of construction in the housing development (Pan et al. 2019). Meanwhile, in developing countries such as India, the government was underway to construct 10 million modular homes by 2022 using offsite construction methods to eradicate housing shortages in the country (Builtoffsite 2022). Often, modular construction and other offsite techniques are the last resort; however, the government needs to implement it in the first planning and business cases. Thus, legislative involvement such as robust policies and frameworks are the key factors in adopting modular construction for affordable housing.

Further, as per the 'Tall Mass Timber Toolkit' report by American Wood Council 2022 (AWC 2022), Mass timber building comes with a regulatory limitation as building codes. Individual mass timber building elements and assemblies undergo significant standardized fire testing as a mandate to confirm that the fire protection performance intended by the International Building Code is achieved. The approved code changes create three new types of construction: Types IV-A, IV-B and IV-C. Existing Type IV code requirements are unchanged by these code changes, but it will now be designated Type IV-HT in 2021 IBC. Importantly, none of these new types of construction allow use of combustible light frame construction in any manner. Further, mass timber used in the new types of construction must meet the smallest dimensions assigned in the 2018 IBC for all heavy timber construction. Notably, the primary structural frame in Type IV-A construction must have a three-hour fire resistance rating, with no reduction allowed for sprinkler protection. Types IV-B and IV-C construction must have at least a two-hour fire resistance rating for the primary structural frame.

- Non-combustible materials are needed on the exterior of all mass timber buildings, which is more restrictive than what is allowed on Type I or II (non-combustible) buildings.
- All mass timber forming concealed spaces must be protected with non-combustible materials.
- The use of lightweight wood products is not allowed for interior framing, including fire retardant treated wood.
- Type IV-A requires all mass timber to be fully protected by non-combustible material inside and outside (no exposed surfaces).
- Type IV-B allows limited exposed mass timber members on the interior, but they must be spatially separated.
- Type IV-C is limited to the same height in feet as existing HT and only allows an increased number of stories in lower hazard occupancies.
- Dual water supplies and fire pumps are needed for mass timber buildings exceeding 120 feet in height, which provides a more robust fire protection package. By comparison, this is not needed for Type I-A buildings until they exceed 420 feet in height.
- Stringent protections are needed for mass timber buildings during construction.

- Full-scale fire testing confirmed that Types IV-A and IV-B construction will withstand a complete burnout of an above average residential fuel load without the aid of sprinklers.
- Annual inspections are needed to ensure passive protection is still in place.
- Joints and penetrations must still be tested, installed and inspected as presently outlined in the IBC.

The International Code Council (ICC) adopted a comprehensive set of changes to the 2021 International Building Code (IBC) for the safe construction and use of mass timber buildings. The changes were developed through an Ad Hoc Committee of subject matter experts after years of study, peer review, full-scale fire testing at the ATF Fire Research Laboratory, and review and approval by code experts at the ICC Committee Action Hearings in 2018 and 2019 (AWC 2022).

The ICC process was undertaken recognizing that taller mass timber structures are already being approved globally and in the United States at the local level without specific support or recognition by the IBC. The approved code changes require a highly redundant and rigorous package of active and passive systems of fire protection to allow taller and larger buildings made from mass timber materials. The fire protection requirements are intended to ensure that, under any reasonable fire scenarios, life safety is provided, and in addition no structural collapse will occur despite complete burn-out of content fuels. Conservatively, the performance was dictated without consideration of the operation of automatic sprinkler systems needed for mass timber buildings. Fire testing has also proved that the charring properties of exposed mass timber elements provide a reliable and predictable measure of fire-resistive performance, even without the protection of added non-combustible materials. The result of the ICC process is that each of the new types of construction, Type IV-A, Type IV-B and Type IV-C tall mass timber buildings has fire protection requirements more robust than those needed for comparable non-combustible buildings.

Mass timber can help solve the housing shortage, yet the building material is not widely adopted because old building codes treat it like traditional lumber. The 2021 International Building Code (IBC) addressed this issue, significantly updating mass timber allowances such as increasing height limits. But mass timber use is still broadly limited because state and local building codes usually don't update automatically. The U.S. Department of Agriculture (USDA) could speed the adoption of mass timber through grants that incentivize state and local governments to adopt the latest IBC codes (Thomas 2024).

Most States Are on Older Building Codes That Inhibit Use of Mass Timber. The use of mass timber is growing. But building codes, often slow to catch up with the latest research, have limited the impact so far. Only in 2021 did amendments to the IBC enable the construction of mass timber buildings taller than six stories. Building taller increases the cost savings from building faster. State and local government adoption of building codes lags further. By 2023, only 20 states had adopted IBC 2021. Eventually builders might lobby governments to catch up, but for now there's little reason for many builders to consider mass timber when it's so restricted (Thomas 2024).

USDA Could Incentivize the Adoption of The Latest IBC. There should be a federal grant making program that implicitly requires the latest IBC codes to take part, incentivizing state and local government adoption. The USDA could house this program due to policy interest in both the timber industry (Forest Service, FS) and housing (Rural Development, RD). In fact, USDA is already making grants towards mass-timber housing, just not at a scale that directly incentivizes code changes. Since 2015, the Wood Innovations Grant Program has invested more than $93 million in projects that support the wood products economy, including multifamily buildings. USDA also recently partnered with the Softwood Lumber Board to competitively award more than $4 million to 11 mass timber projects. Most of these buildings are in states or cities that have adopted IBC 2021. For example, one winner is a 12-story multifamily building in Denver, which would be impossible without IBC 2021 (Thomas 2024).

A Simple Mechanism to Unlock the Potential of Mass Timber, a federal USDA grant program incentivizing adoption of the latest IBC amendments related to mass timber requires no new funding mechanisms and no new legislation. The structure is already available with the FS Wood Innovations Grant Program as a clear example. That program had ~$43 million in grants for FY 2023; perhaps an order of magnitude more funding would move more states to the updated IBC. This program would not drive mass timber adoption on a scale on its own, but updating building codes is a necessary first step. Because mass timber is faster to build with and results in fewer emissions, it is a crucial building material that could contribute to both housing abundance and the climate transition. (This idea of merit originated from our Housing Ideas Challenge, in partnership with Learning Collider, National Zoning Atlas, and Cornell's Legal Constructs Lab) (Thomas 2024).

Moving ahead, unanimously, most of the experts have supported Legislation as one of the most important critical success factors for successful modular mass timber adoption in affordable housing. Expert working in installation highlights, importance of up-to-date building codes in catching up and faster inspection of the installation work. Other experts having ability on academic and installation work emphasized enhanced engineering qualities by adherence to building codes. An expert working on the Mass Timber project and having background in architecture explained support of building codes in standardization of the mass timber buildings. NA expert having ability in manufacturing and development emphasized on importance and efficiency of PRG 320 certification and its adherence to efficiency and local codes adoption.

These perspectives underscore the consensus among professionals about the essential role of legislative support and regulatory frameworks in advancing the adoption of MMT in affordable housing, affirming 'Legislation' as a foundational element in promoting sustainable, efficient, and affordable construction practices.

4.2.9 Safety

In the exploration of critical success factors pivotal to the adoption of Modular Mass Timber (MMT) for affordable housing projects in the United States, safety appears as a paramount concern. The significance of safety cannot be overstated, as it directly influences the well-being of construction workers and future residents alike. This analysis integrates fire resistance, structural strength, and sustainability to illustrate the comprehensive safety profile of MMT.

During a fire resistance test of a 5-ply cross-laminated timber (CLT) panel wall at Canadian Wood Council, the panel was subjected to temperatures exceeding 1,800 Fahrenheit and lasted 3 hours and 6 minutes, far more than the two-hour rating that building codes needed. During fire exposure, mass timber chars on the outside, which forms an insulating layer protecting interior wood from damage. Additionally, when the code requires mass timber to be protected with gypsum wall board, the mass timber can achieve nearly damage-free performance during a contents-fire burnout event.

Highlighting the strength of Mass Timber, the 'Tall Mass Timber Toolkit' report by American Wood Council 2022 (AWC 2022) claims, A recent mass timber building weighs approximately 1/5th that of comparable concrete buildings, which in turn reduces the building's foundation size, inertial seismic forces and embodied energy. High strength-to-weight ratios enable mass timber to perform well during seismic activity.

Above all, Mass Timber is highly sustainable. Replacing steel with mass timber could reduce carbon dioxide emissions by between 15% and 20%. The White House Domestic Policy Council estimated that the near-term use of CLT and other emerging wood technologies in buildings 7-15 stories could have the same emissions control effect as taking more than 2 million cars off the road for one year. The fire tests confirmed that mass timber structures meet and generally exceed the fire resistance requirements in the current code. Studies have shown that buildings with wood produce fewer greenhouse gas emissions than buildings with other materials. (Oliver et al. 2014)

Further, there is currently a shortage of skilled labor in the construction industry: according to a recent analysis by Statista 2020 around 975,000 workers lost their job due to ramifications of the pandemic (Statista 2020). In addition, many workers and younger people are reluctant to pursue a career choice in the physically exhausting construction industry (Le 2022). This skills shortage issue calls for more efficient use of manufacturing and automation techniques in the construction industry. One fear among stakeholders in adopting more automation in the industry, is that it may result in increased loss of jobs; however, a recent analysis by the World Economic Forum said that the inclusion of automation techniques will also create approximately 58 million jobs by the year 2025 (Le 2022). Adopting more automation throughout the modular construction industry may offer an opportunity for a new wider labor force to enter this sector. Productivity is also a variable contingent upon the health and safety of workers, which can also be boosted by using offsite methods of construction. A McGraw Hill Smart Market report revealed that 44% of contractors think that modular construction methods have a positive impact upon health and safety of workers (Dodge Construction Network 2020b). Affordable housing is heavily reliant on low-cost construction, and via optimized coupling of modular construction techniques together with automation, each unit can be delivered and produced using less labor which makes affordable housing more palatable to the stakeholders. (Pan et al. 2020) in their other report found that modular construction enhances health and safety prospects, accelerated project delivery, improved the overall industry image and decreases the disturbances to the community.

As per the comprehensive report by Chubb, with modular and prefabricated construction, much of the work being performed occurs in a manufacturing setting, where the likelihood of fatality and severe injury is lower than in on-site construction. Incorporating modular and prefabricated components into a construction project can help to reduce the top causes of construction site injuries and fatalities.

Performing much of the work offsite allows for the reduction of risky construction site elements such as scaffolding, ladders and working at heights. With falls as the number one cause of workplace fatalities in construction, maximizing the work done at ground level can have a significant impact. According to the Center for Construction Research and Training, ladders accounted for 24% of fatal falls in construction with scaffolding involved in an added 15% of fall-related fatalities.

To the extent possible, eliminating or reducing the use of ladders can significantly reduce the risks in construction. Approximately 65% of all construction workers perform work on scaffolds, exposing workers to the risk of falls, electrocutions, and falling objects. With prefabricated or modular construction, more work is performed at the ground level, and the need for working at heights is reduced in general. Additionally, the prefabricated/modular construction process reduces the need for climbing to potentially dangerous heights to build each module. The typical height of a prefabricated modular unit ranges from 8 to 10 feet tall. This reduction in height alone can prevent a considerable number of accidents that occur due to falls.

One of the most significant differences between traditional and prefabricated/ modular construction is that the latter takes place away from the construction site in a controlled factory environment. An assembly-line-like work process is set up for the manufacturing of the building components. Team members know their work area well, understand the areas of caution, and are specialized in their tasks. Because of this well-organized workflow and process, there is a significantly reduced chance of being struck by machinery, equipment, or other objects - frequent occurrences on traditional construction sites. Manufacturing construction components away from the jobsite can reduce the amount of foot traffic occurring at the job site. This simple change means fewer workers onsite and fewer workers who can potentially be injured, killed, or otherwise involved in a caught-in/ between or struck by an object accident. The controlled environment of an indoor manufacturing setting keeps out any weather hazards that may present themselves in a traditional construction environment. When the process takes place indoors no rain delays or slippery surfaces should occur due to weather. The likelihood of slips, trips and falls is reduced inside indoor environments. Hazards such as temperature extremes and high winds can be eliminated when building components are prefabricated indoors at an off-site location.

In the exploration of critical success factors pivotal to the adoption of Modular Mass Timber (MMT) for affordable housing projects in the United States, safety appears as a paramount concern. The significance of safety cannot be overstated, as it directly influences the well-being of construction workers and future residents alike. This analysis integrates fire resistance, structural strength, and sustainability to illustrate the comprehensive safety profile of MMT.

During a rigorous examination by the Canadian Wood Council, a 5-ply cross-laminated timber (CLT) panel wall was subjected to temperatures exceeding 1,800 Fahrenheit. Remarkably, it sustained for 3 hours and 6 minutes, surpassing the two-hour rating mandated by building codes. The inherent property of mass timber to char externally forms a protective insulating layer, shielding the interior wood from damage. Further enhancing safety, building codes that need the covering of mass timber with gypsum wallboard enable it to withstand contents-fire burnout events with minimal damage.

The structural integrity of MMT also plays a critical role in safety. According to the 'Tall Mass Timber Toolkit' report by the American Wood Council (2022) (AWC 2022), mass timber buildings are significantly lighter compared to their concrete counterparts, approximately one-fifth the weight. This reduction in weight mitigates foundational stress, diminishes seismic forces, and lowers embodied energy, proving mass timber's adeptness in withstanding seismic activities.

Sustainability attributes of MMT further contribute to its safety profile. Transitioning from steel to mass timber could curtail carbon dioxide emissions by 15% to 20%. The White House Domestic Policy Council has posited that the adoption of CLT and similar wood technologies in mid-rise buildings could equate to removing over 2 million cars from the road annually in terms of emissions control. Fire resistance tests corroborate that MMT structures not only meet but generally exceed current code requirements, underscoring the environmental and safety advantages of building with wood (Oliver et al. 2014).

The comprehensive report by Chubb highlights the reduced risk of fatality and severe injury with MMT, attributed to most construction activities occurring in a controlled manufacturing setting. This methodological shift minimizes exposure to conventional construction site hazards such as falls from heights, a leading cause of workplace fatalities in the construction industry. By eliminating or minimizing the use of scaffolding and ladders, and performing more work at ground level, the risk associated with working at heights is substantially reduced. The prefabrication process itself diminishes the necessity for workers to ascend to potentially hazardous elevations, with the height of modular units typically ranging from 8 to 10 feet.

Furthermore, the indoor, controlled environment of manufacturing facilities reduces the likelihood of accidents related to weather conditions, such as slips, trips, and falls. By hastening the construction process, MMT potentially shortens the duration workers are exposed to hazardous conditions by 30% to 50%, further mitigating injury risks (The Chubb 2020).

Expert interviews conducted for this study reinforce the assertion that MMT offers a safer and more efficient construction method, particularly due to its offsite, controlled environment fabrication. These expert perspectives were carefully considered, emphasizing individual insights into the efficacy of MMT in enhancing safety standards within the affordable housing sector.

In summary, the incorporation of Modular Mass Timber into affordable housing projects is critically contingent upon its safety merits. The analysis here elucidates the multifaceted safety advantages of MMT, spanning fire resistance, structural integrity, and sustainability, corroborated by empirical evidence and expert testimony. These findings substantiate the assertion that safety, as manifested through the adoption of MMT, is a critical success factor in the realm of affordable housing development in the United States.

4.2.10 Logistics

In the realm of Modular Mass Timber (MMT) for affordable housing projects in the United States, the design process plays a foundational role. However, it is the amalgamation of offsite manufacturing, supply chain and logistics, and onsite assembly that ensures the fruition of a successful MMT project. The start of offsite manufacturing needs the creation of bespoke modules or components within a factory setting, acting as the crucial intermediary between the project's conceptual and realization phases. This phase demands not only a harmonious collaboration and communication amongst project stakeholders but also necessitates the adoption of efficient procurement strategies, resource planning, scheduling, and the implementation of just-in-time production methodologies to mitigate risks such as dimensional conflicts, design flaws, information discrepancies, variable client demands, and manufacturer constraints (Chan Tsz Wai et al. n.d.; Wuni et al. 2022; Yazdani et al. 2021).

Following the meticulous production of modules, their delivery to the construction site becomes imperative. This seemingly straightforward process is laden with potential pitfalls that could significantly impede project logistics. Challenges include navigating transportation limitations related to module size and weight, overcoming scheduling deficiencies, ensuring precise module marking and handling to prevent damage, and addressing manual handling concerns (Ibrahim Y. Wuni et al. 2019). The culmination of the modular construction process is marked by onsite assembly, where strategic crane layout planning, adequate module storage, and stability during placement are paramount. Given the susceptibility of construction sites to weather perturbations, the just-in-time delivery concept becomes instrumental in curtailing delays and mitigating risks associated with module settlement. The adoption of proactive risk management strategies alongside the integration of contemporary digital technologies throughout the offsite construction stages not only hastens the process but also amplifies its sustainability (Hussein et al. 2021).

Expert insights underscore 'Logistics' as a pivotal factor in the successful implementation of MMT for affordable housing initiatives. Interviews with seasoned professionals reveal a consensus about the expedited delivery and installation benefits of MMT. A development and affordable housing market veteran highlighted the swift delivery and installation advantages of MMT, asserting its potential to enhance the overall construction speed. This sentiment is echoed by a structural design expert who noted the reduced on-site part handling inherent to MMT, thereby streamlining installation processes. Furthermore, an expert in supply and logistics advocated for the adoption of electric trucks to bolster sustainability and recommended using larger mills for shipping and delivery to foster regional market expansion.

These expert testimonies not only affirm the significance of logistics in the adoption of MMT for affordable housing but also reflect a collective recognition of the method's inherent advantages in terms of speed, efficiency, and sustainability. The concerted effort to navigate logistical challenges through strategic planning, technological integration, and sustainable practices delineates a comprehensive approach towards realizing the full potential of MMT in contributing to the affordable housing sector.

4.2.11 Training

In the exploration of critical success factors essential for the installation of modular mass timber in affordable housing projects within the United States, the imperative role of comprehensive training and skill development emerges prominently. Stakeholders, including architects, designers, engineers, and manufacturers, play a pivotal role in enhancing the efficiency and implementation of this construction methodology. A seamless supply chain management coupled with advanced training for both offsite and onsite labor force is indispensable for elevating the overall project success. This insight draws upon the perspectives shared by experts in market analysis and hands-on experience in installation and labor training programs, underscoring the necessity of fostering learning environments and skill enhancement to optimize productivity in mass timber projects (Blismas and Wakefield 2009; Wuni and Shen 2023).

The evolution of the timber production chain, encompassing processes from harvesting to assembling, signifies a transition towards a more industrialized approach, transforming the traditional carpenter's role. This shift incorporates a spectrum of technologies ranging from heavy machinery and computer-aided design to manual tools, creating a structured hierarchy of specialized tasks within the wood industry. The emerging requirements pivot away from manual labor towards proficiency in automated methodologies, thereby expanding inclusivity across various demographics by mitigating physical exertion and emphasizing the need for high-skilled labor (Carvalho et al. 2020a). Innovative training approaches, such as game engine platforms, have been identified as effective means to enhance coordination among construction teams and improve workers' skills, further substantiating the value of advanced learning tools in the construction sector (Ezzeddine and Soto 2021).

Moreover, the quality of modular construction, particularly in the context of mass timber, benefits significantly from a controlled factory environment, allowing builders access to necessary tools and equipment, thus ensuring superior built asset structures and quality standards. Nonetheless, challenges such as limitations in manufacturing capabilities, a lack of advanced automation techniques, and a scarcity of research hinder the potential for quality enhancement when compared to conventional construction methods. Addressing these challenges requires breakthroughs in technology and manufacturing processes, including the application of robotics and automation to refine the production quality of modular units (Le 2022; Pan Wei et al. 2019).

In recognition of these challenges and opportunities, organizations like WoodWorks have taken initiatives to develop training programs and manuals specifically tailored for mass timber construction. The U.S. Mass Timber Construction Manual serves as a comprehensive guide, offering insights into planning, procurement, and project management tailored for contractors and installers new to mass timber. This resource facilitates the adaptation of traditional construction experiences to mass timber, highlighting the unique aspects of this material that contribute to cost-effectiveness. Funded primarily by the U.S. Endowment for Forestry and Rural Communities and developed in collaboration with mass timber manufacturers, the manual is an invaluable tool for all members involved in a mass timber project (WoodWorks 2024).

The significance of training for enhancing efficiency in modular mass timber construction is further emphasized through expert interviews. Experts with experience in manufacturing and installation underscore the necessity for contractors to be well-versed in pre-installation processes, component handling, production scheduling, and sequencing. These competencies are crucial for ensuring a smooth assembly and high-quality installation on-site, illustrating the direct impact of skilled labor on project success. The emphasis on individual responses and the collective wisdom derived from these interactions highlight the criticality of training as a foundational element for the successful adoption of modular mass timber in affordable housing projects across the U.S.

In conclusion, the concerted effort of stakeholders, innovative training methodologies, and the strategic implementation of technology and automation are central to overcoming the current limitations and unlocking the full potential of modular mass timber construction. As this research delves into the critical success factors for the adoption of this promising construction methodology, it becomes evident that training and skill development stand as pivotal pillars, ensuring project efficiency, quality, and overall success in the realm of affordable housing.

4.2.12 Customization

In the comprehensive analysis of the pivotal elements crucial for the effective deployment of modular mass timber within the framework of affordable housing projects across the United States, the factor of design customization emerges as a fundamental cornerstone. This thesis chapter delves into the nuanced role that customization plays in the broader context of modular mass timber's application, particularly emphasizing its significance in facilitating affordable and emergency housing solutions. The growing ethical consciousness around human rights and climate change underscores the urgency for adaptable construction methodologies like modular mass timber, renowned for its quick delivery times and ability to uphold the dignity of large refugee communities through quality housing.

Design customization transcends mere aesthetic appeal, serving as a vital component that significantly influences the demand for, adaptability of, and ultimate success in modular mass timber projects. The intrinsic characteristics of mass timber—highlighted by its structural robustness, lightweight nature, and ecological benefits—present unparalleled opportunities for architectural ingenuity and customization (Fernandes Carvalho et al. 2020a; Khan et al. 2022). Such versatility paves the way for design solutions tailored to the unique requirements of specific sites, client aspirations, and sustainability goals, broadening the scope for mass timber's application in diverse affordable housing endeavors.

Beyond the construction phase, the aspect of design flexibility bears long-term implications for the sustainability and maintenance of affordable housing units. Insights from experts with an architectural lens on mass timber installation projects reveal that bespoke design solutions can adeptly navigate environmental challenges, conform to local building regulations, and resonate with community needs, ensuring project compliance alongside resilience and sustainability over time. Innovations in modular connections and geometries, as exemplified by the BUILDFROMFOREST I&TD Project, illustrate the potential for enhancing transport efficiency through non-traditional room module systems beyond the conventional rectangular cuboid forms (Carvalho et al. 2020b).

Experts emphasize the criticality of incorporating customization during the design phase, enabling project developers to maximize the efficiency of prefabricated mass timber components. This strategic optimization not only aligns with environmental sustainability by curtailing material wastage but also bolsters project affordability through cost-effective material procurement and streamlined construction processes.

The collaborative ethos underpinning the customization of design in modular mass timber projects necessitates early and continuous engagement among architects, engineers, and various stakeholders. Such collaboration is instrumental in harnessing the structural and environmental merits of mass timber, intertwining design flexibility with innovative solutions tailored to meet the nuanced demands of affordable housing projects. This holistic approach fosters the creation of spaces that are not only sustainable and cost-efficient but also aesthetically inviting and conducive to resident well-being (Fernandes Carvalho et al. 2020a; Khan et al. 2022).

Furthermore, the integration of digital tools and technologies is pivotal in actualizing design customization within modular mass timber projects. Cutting-edge software like 4D Building Information Modelling (BIM) empowers project stakeholders with detailed design visualization and scheduling capabilities, streamlining the construction workflow. This technological facilitation ensures the precision in fabricating modular mass timber components, effectively translating bespoke designs into tangible structures while minimizing construction errors and delays (Mayouf et al. 2024).

Discussions with experts yielded a consensus on the advantages of providing customization options in mass timber projects. While some experts highlighted the demand-driven flexibility of modular mass timber as a significant benefit, others pointed out the potential cost implications of customization, noting its capacity to distinguish projects competitively yet potentially escalate costs from both developers' and consumers' perspectives.

In essence, ‘customization’ stands as a critical success factor for the installation of modular mass timber in affordable housing projects within the U.S. This factor leverages mass timber's inherent advantages, addresses project-specific necessities, and significantly contributes to the sustainability, affordability, and efficacy of housing solutions. The successful execution of customized design strategies requires a comprehensive, integrated approach, emphasizing stakeholder collaboration, digital technology integration, and a commitment to innovation and flexibility. As the construction sector continues to explore modular mass timber's potential, the tailored customization of design will persist as a crucial determinant of its widespread adoption in affordable housing initiatives.

4.2.13 Coordination

Within the ambit of critical success factors pivotal for the deployment of modular mass timber in affordable housing projects across the United States, the dimension of 'coordination' amongst project stakeholders stands out as a fundamental prerequisite. This thesis chapter delves into the essence of coordination as an integral component of construction management, highlighting its role in managing the interplay between project participants including the project owner, contractors, subcontractors, suppliers, and regulatory bodies. The overarching aim of coordination within construction management realms is to foster an environment where all stakeholders collaboratively work towards the attainment of project goals, ensuring timely delivery, budget adherence, and conformance to stipulated quality standards (The Eden Group 2023).

The advent of modular mass timber as a construction material introduces unique complexities and opportunities, necessitating a synchronized effort from all entities involved in the project—from the preliminary planning phase through to construction and eventual occupancy. This harmonious synergy is essential among developers, architects, engineers, contractors, local government entities, and the community at large. The factory-based manufacturing environment inherent in modular construction facilitates superior coordination, enabling streamlined repetitive tasks and heightened automation levels. Such advancements can significantly reduce project schedules by 30–50% and costs by 20–25%, thereby augmenting project productivity (Le 2022). Compliance with local codes and standards is paramount since modular construction lacks specific universal standards, often requiring the engagement of multiple stakeholders including clients, contractors, suppliers, and fabricators at this juncture (Wuni et al. 2022). Collaboration, information exchange, and effective communication stand as the pillars for attaining success in modular construction endeavors (Li et al. 2018).

Insights from expert interviews have underscored the critical nature of stakeholder engagement in construction projects, pinpointing early involvement and consistent communication as key to aligning expectations and achieving shared objectives.

Moreover, the integration of digital tools and platforms emerges as a vital enabler for enhancing stakeholder coordination. The application of Building Information Modeling (BIM) alongside other project management software fosters real-time communication, coordination, and information sharing, equipping stakeholders with the ability to visualize project progress, pre-empt potential hurdles, and make well-informed decisions. Alongside innovations in timber-based materials, BIM technology serves as a conduit for testing and coordinating diverse actors and project phases. Additionally, modern methods of construction (MMCs) like computer numerical control (CNC) cutting, 3D printing, and radiofrequency monitoring of constructive components throughout their lifespan present novel opportunities to merge features and trades with minimized ecological footprint (Hannah and Hunter 2018).

The integrated project delivery (IPD) principle is particularly resonant with the requisite for adept stakeholder coordination in modular mass timber projects. IPD amalgamates the people, business structures, systems, and practices into a cohesive methodology that synergizes the talents and visions of all participants, aiming to elevate project outcomes, enhance client value, and minimize waste across all building processes (design, fabrication, construction) (Abdul Hamid et al. 2018; Alinezhad et al. 2020). This approach is deemed especially beneficial for complex projects that incorporate innovative technologies like mass timber, where conventional project delivery methodologies may fall short in addressing inherent challenges effectively.

Feedback from structural experts highlights that upfront coordination is instrumental in sequencing and the efficient installation of modular mass timber projects. A distinction is made between manufacturing coordination and job site coordination, both of which are crucial for project success. Experiences shared by experts affiliated with developers and manufacturers reveal that early project involvement coupled with advanced coordination can significantly reduce change orders, thereby facilitating expedited project completion.

In summary, stakeholder coordination emerges as an indispensable critical success factor for the implementation of modular mass timber in affordable housing initiatives within the U.S. This comprehensive approach encompasses regulatory adherence, effective knowledge dissemination, digital tool integration, and the adoption of collaborative project delivery methodologies. Proficient coordination amongst stakeholders not only boosts project efficiency but also drives innovation, contributing significantly to the successful assimilation of modular mass timber into the affordable housing landscape. As the construction sector continues to evolve, the strategic importance of stakeholder coordination in harnessing the benefits of emerging materials and technological advancements becomes increasingly paramount.

4.2.14 Commoditization

The transition of modular mass timber from a specialized construction material to a standardized option within the affordable housing sector underscores its role as a critical success factor (CSF) for projects across the United States. This chapter delves into the commoditization of modular mass timber, a process pivotal to enhancing its accessibility, affordability, and scalability for affordable housing developments. This narrative is built upon an analysis that incorporates existing literature and expert insights, focusing on the multifaceted impact of commoditization on the adoption of modular mass timber.

Affordable housing, as defined by (Hamid et al. 2018), hinges on a delicate balance between income, expenditure, and a myriad of other considerations such as finance cost structures, availability, demographic occupation needs, distribution processes, and government policies. (Leishman et al. 2012) further refine this concept by emphasizing the significance of location and housing quality in defining affordability. In recent times, the methods employed in designing and constructing affordable housing have lagged, unable to keep pace with the burgeoning demand, which accentuates the crisis within the sector. (Khan et al. 2022) argue for a transformation in construction practices towards methods that are not only financially viable but also environmentally sustainable, pointing towards modular mass timber as a beacon of hope in this context.

The process of commoditization plays a crucial role in demystifying modular mass timber and fostering its acceptance among key stakeholders ranging from developers and policymakers to builders and end-users. As experts in the mass timber industry suggest, the growing commoditization of this material underscores its environmental, efficiency, and aesthetic benefits, which are increasingly recognized across the construction sector. Such recognition is indispensable for cultivating a supportive regulatory landscape and propelling demand, thereby accelerating mass timber's integration into affordable housing projects.

Delving deeper into expert perspectives reveals the nuanced advantages of mass timber commoditization. Industry professionals highlight the potential for optimized production processes and reduced costs as mass timber demand escalates, positioning it as a formidable competitor to traditional materials like steel and concrete. Reduced production costs directly lower construction expenses, significantly impacting housing affordability. Experts with architectural expertise emphasize that the standardization of mass timber components, an intrinsic aspect of its commoditization, simplifies design processes, boosts construction efficiency, and curtails project timelines—elements that are vital within the ambit of affordable housing. From a marketing viewpoint, professionals specializing in training and development underscore the importance of effective advertisement and education in achieving societal acceptance of modular mass timber.

The criticality of establishing standards and certifications for modular mass timber cannot be overstated within the commoditization framework. Such measures reassure developers and consumers about the quality, safety, and sustainability of mass timber products, fostering trust and smoothing its assimilation into mainstream construction practices.

In sum, the commoditization of modular mass timber emerges as a foundational CSF in its adoption for affordable housing projects within the United States. The industry's journey towards the widespread acceptance and standardization of mass timber heralds a new era of construction, promising affordable, sustainable, and high-quality housing solutions. Stakeholders are urged to adopt a collaborative approach, embracing regulatory advocacy, education, innovation, and standardization, to navigate existing obstacles and unlock modular mass timber's transformative potential in the affordable housing sector. This analysis, enriched by expert testimonies, underscores the collective endeavor required to realize the benefits of modular mass timber commoditization fully.

4.2.15 Standardization

The adoption of modular mass timber for affordable housing in the United States stands at the nexus of innovation and sustainability, offering a promising solution to the nation's housing affordability crisis. This critical analysis delves into the imperative role of standardization as a critical success factor (CSF) for the seamless integration and widespread acceptance of modular mass timber within the affordable housing sector. Standardization, in this context, is elucidated as the harmonization of design, production, and assembly processes that underpin the modular mass timber construction methodology. This section meticulously explores the multifaceted implications of standardization, emphasizing its significance in augmenting scalability, enhancing cost-efficiency, and ensuring compliance with regulatory frameworks.

In the face of challenges such as the scarcity of skilled labor and the need for rapid construction methodologies, the modular mass timber approach, underscored by standardization, emerges as a strategic response. The concept of serial standardization, which champions the replication of identical products in substantial volumes, addresses the dire necessity for swift reconstruction and mass relocation (Carvalho et al., 2020). The ethos of standardization embodies the optimization of the modular construction model, where the uniformity of offsite-assembled units equipped with essential services significantly bolsters economic viability through mass production. Such an approach is particularly advantageous in the context of housing programs where repeatability and efficiency are paramount (Carvalho et al. 2020b).

The standardization of modular mass timber transcends the operational efficiency, striking at the heart of cost, quality, and accessibility challenges inherent in the affordable housing domain (Hamid et al. 2018). By fostering a streamlined design phase and enhancing predictability in cost and scheduling, standardization directly contributes to the delivery of superior housing solutions at a fraction of the cost and time associated with traditional construction methods. Furthermore, the alignment of mass timber projects with prevailing building codes and standards emerges as a critical factor for regulatory acceptance and adoption (Leishman et al. 2012). The uniformity brought about by standardization simplifies the regulatory review process, enabling a smoother pathway for mass timber constructions across varied jurisdictions in the United States.

Expert engagements illuminate the multifaceted benefits of standardization within the modular mass timber landscape. Insights from industry veterans underscore the optimization of production processes, design efficiency, and the marketing appeal of standardized mass timber products. These perspectives highlight the pivotal role of standardization in reducing production costs, streamlining the construction process, and enhancing the market competitiveness of mass timber solutions. Moreover, the manufacturing environment of modular construction, characterized by heightened coordination and automation, offers substantial reductions in project timelines and costs, thereby elevating overall project productivity (Khan et al. 2022).

In advancing the standardization of modular mass timber, the establishment of clear standards and certifications is indispensable. Such frameworks not only assure stakeholders of the material's quality, safety, and environmental sustainability but also play a crucial role in fostering trust among consumers, developers, and regulatory bodies. The collective efforts of industry associations, regulatory agencies, and educational institutions are paramount in propelling the standardization agenda forward, addressing potential adoption barriers, and elucidating the myriad benefits of modular mass timber construction.

In conclusion, the standardization of modular mass timber is identified as a cornerstone CSF for its adoption in affordable housing projects across the United States. By embracing uniform standards and practices, the construction industry is poised to unlock the transformative potential of this innovative material, promising affordable, sustainable, and high-quality housing solutions. The journey toward standardization necessitates a collaborative and holistic approach, encompassing regulatory advocacy, continuous education, innovation, and strategic partnerships. This endeavor exemplifies a progressive construction paradigm that adeptly navigates economic, environmental, and societal objectives, heralding a new era in affordable housing development.

4.2.16 Research

The dynamic evolution of modular mass timber as a cornerstone for affordable housing in the United States underscores the indispensable role of research as a critical success factor (CSF). This section methodically explores the expansive influence of research in accelerating the adoption and effective implementation of modular mass timber technologies. It critically examines how research bridges innovation with material science and sustainable building practices, thereby acting as a pivotal force in dismantling existing obstacles and cultivating new opportunities within the construction landscape.

The application of modular mass timber in construction offers a controlled and safe work environment, conducive to the creation of structurally sound and quality-enhanced buildings (Khan et al. 2022). Despite these advantages, the modular construction sector grapples with challenges such as underdeveloped manufacturing capabilities, a deficiency in automation techniques, and a significant gap in targeted research efforts. These limitations often cast modular construction in a light not dissimilar to traditional construction methodologies. Advancements in technology and an expansion in the scope of manufacturing production, catalyzed by research, are imperative for elevating quality standards in modular construction (Pan et al. 2019). The integration of robotics and automation within production settings promises to refine module quality, while the implementation of skilled technical training ensures the maintenance of this quality post-delivery on construction sites (Le 2021).

Expert opinions emphasize that research in the realm of modular mass timber for affordable housing transcends theoretical exploration, constituting a practical and multi-dimensional necessity within the construction process. This encompasses everything from the enhancement of mass timber's performance and sustainability through material science, to the innovation of construction methodologies and the streamlining of manufacturing processes. The visibility of key performance indicators through market reports and scholarly research is instrumental in propelling the modular construction model forward within affordable housing initiatives.

Research significantly influences the adoption of modular mass timber in affordable housing by spearheading advancements in material science. As reported by the American Wood Council in their "Tall Mass Timber Toolkit" (AWC 2022), innovation in wood product treatment and engineering markedly bolsters mass timber's structural integrity, fire resistance, and environmental sustainability. Such advancements render mass timber an increasingly viable option for affordable housing projects. Moreover, investigations into the lifecycle of mass timber products underscore the environmental benefits of carbon sequestration and reduced greenhouse gas emissions, in comparison with conventional building materials (Atta et al. 2021; Mao et al. 2013).

The modular construction methodology benefits from a fusion of Design for Manufacture (DfM) and Design for Assembly (DfA) principles, streamlining the fabrication process to expedite assembly, reduce costs, and enhance productivity. Concurrent engineering principles further allow for simultaneous site development and factory fabrication, distinguishing modular construction from traditional building methods (Wuni et al. 2019).

Research is pivotal in refining the manufacturing processes for modular mass timber components. Through timber-based material innovations and the utilization of Building Information Modeling (BIM), alongside Computer Numerical Control (CNC) cutting, 3D printing, and radiofrequency identification technologies, the construction sector is poised to reap the benefits of modern methods of construction (MMCs). These methods promise a reduced ecological footprint while maximizing the integration of various construction elements (Hannah and Hunter 2018).

Interviews with experts highlight the criticality of research for the wider adoption and adaptation of modular mass timber in affordable housing. Training program experts underline the necessity of research for the expansion of modular mass timber, particularly focusing on affordability and ease of installation. Another expert posits that active research facilitates community engagement and education regarding this technology, thereby enhancing performance evaluation and implementation strategies.

In summation, research stands as a foundational CSF in the adoption and integration of modular mass timber within the United States' affordable housing sector. By fostering material science innovations, refining construction techniques, and optimizing manufacturing processes, research empowers the construction industry to navigate challenges and fully leverage the potential of modular mass timber as a sustainable, efficient, and economically viable building material. The continued synergy between academic research, industry innovation, and policy development is essential in realizing the transformative impact of modular mass timber in mitigating the affordable housing crisis.

4.3 TISM Model and MICMAC Analysis for CSFs of Modular Mass Timber Adoption towards Affordable Housing

In this study, the Total Interpretive Structural Modelling (TISM) methodology was employed to develop a conceptual framework outlining the factors driving the adoption of Modular Mass Timber Construction in Affordable Housing. TISM is an extension of Interpretive Structural Modelling (ISM), introduced by Warfield in 1974, which assesses the interrelationships among variables within a specific problem based on expert judgments (Attri et al. 2013). While ISM is useful for recognizing relationships between variables, it lacks clarity on how these links operate. In response, TISM has emerged as an enhanced version, providing a clear hierarchical structure of variables with explicit interactions and interdependencies (Sushil 2012, 2018). TISM uses directed graphs to construct the framework, mapping interactions and links between variables in the system. Given the complex and multidimensional nature of factors influencing Modular Mass Timber adoption in Affordable Housing, where system dynamics rely on connections between different factors, TISM offers more profound insights into implementation relations.

While TISM is widely applied across various fields, it has found particular use among Architecture, Engineering, and Construction (AEC) researchers in diverse domains. Examples include its application in assessing the "barriers to lean construction implementation" (Chaple et al. 2021), exploring the "challenges faced by the construction industry in the COVID-19 era" (Nair and Suresh 2021), and investigating the "drivers toward adopting Modular Integrated Construction for Affordable Sustainable Housing" (Khan et al. 2022).

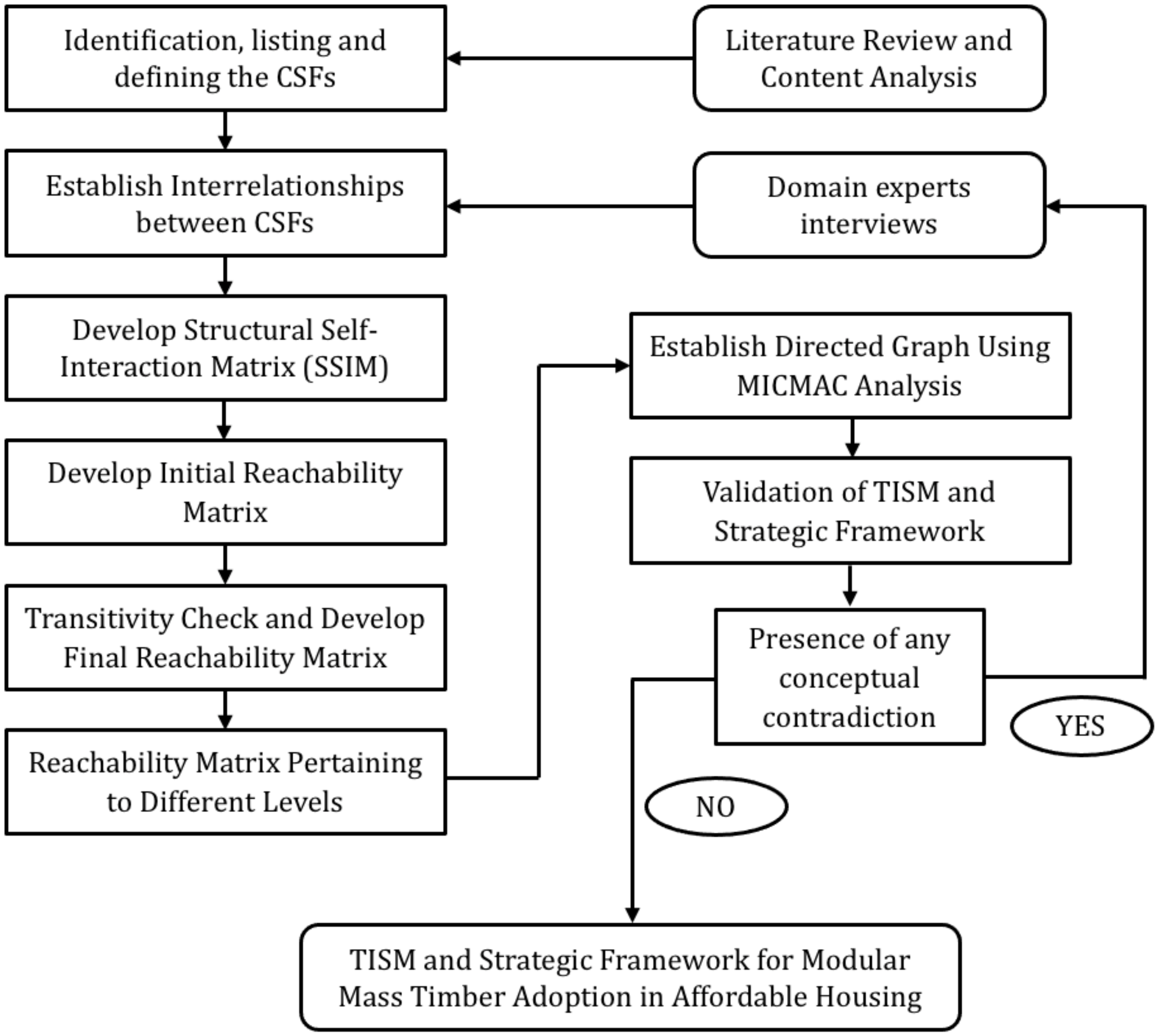

Figure 16 Steps in TISM approach (Khan et al. 2022)

The procedural steps for developing the TISM model, as outlined by (Nair and Suresh 2021) and (Khan et al. 2022), involve the following:

4.3.1 Factors Identification

Identification of critical success factors (CSFs) involves a two-step process. Initially, a comprehensive literature review is conducted, followed by experts' opinions to compile, list, and define these CSFs. The first step in developing the TISM is to identify, list and define the critical success factors. In this study, the CSFs for Modular Mass Timber adoption in affordable housing were identified following the systematic literature review process, as outlined and described in the previous section. Following is a list of the critical success factors identified, namely cost, time, quality, Efficiency, Demand, Sustainability, Legislation, Safety, Logistics, Training, Customization, Coordination, Commoditization, Standardization, and Research. Unlike the other studies as (Khan et al. 2022), (Blismas and Wakefield 2009), factors were not categorized into the clusters to recognize the individual unique importance and linkage to other factors.

1. **Establish Interrelationships between Factors**

   The second step is to establish a pairwise and contextual relationship between different variables to develop a structural self-interaction matrix (SSIM) of the variables. The pair-wise relation is also known as the adjacency matrix, which was developed analyzing the semi-structured expert interviews. The paired matrix between the fifteen CSFs was developed initially followed by a cross exploration of factors to identify the influence.

   Interpret the pairwise comparison logic. In the conventional ISM approach, only the direction of the relationship is interpreted. In the TISM approach, the interpretive matrix concept is employed. In a paired comparison, the i^{th} element is individually compared with all elements. the contextual relationship between the different drivers to form the adjacency matrix were denoted by letters V, A, X and O:

- V denotes that driver “i” leads or influences driver “j”;
- A denotes that driver “j” leads or influences driver “i”;
- X denotes that both drivers “i” and “j” lead or influence each other;
- and O denotes that both drivers “i” and “j” do not lead or influence each other.

   (Sushil 2012) suggested that for each “i,j” pair in the matrix, the nature of the relationship can be observed; and based on the responses, the compilation of interactions and transitive links between drivers can be developed.

Table 7 SSIM of the Critical Success Factors

X / Y		Research	Standardisation	Commoditisation	Coordination	Customisation	Trained Labor	Logistics	Safety	Legislation	Sustainability	Demand	Efficiency	Quality	Time	Cost
		CSF15	CSF14	CSF13	CSF12	CSF11	CSF10	CSF9	CSF8	CSF7	CSF6	CSF5	CSF4	CSF3	CSF2	CSF1
Cost	CSF1	**A, X, X, V, O**	**V, A,A, A, X, X, X, X, X**	**V, V, O, X, X, A, A**	**V, A, A, A, A, A, X, X, X**	**V, A, A, A, A, X, X, X**	**A, A, A, A, X, O, V, V**	**A, A, A, A, X, X**	**V, A, A, A, O, O, O, O, X, X**	**V, A, A, A, A, A, O, O, O, O, O, X**	**A, A, A, O, O, O, X, V, V, V**	**V, V, V, V, V, A, V, X, A, A, X, X**	**V, V, O, O, A, A, X, X**	**O, A, A, X, X, X, V, V, V, V**	**O, O, A, A, A, A, A, X, X, X, X, X**	
Time	CSF2	**O, O, O, A, A**	**A, A, A, X, X, X, X, X**	**A, A, O, O, O, X**	**A, A, V, X, X, X, X, X, X**	**A, O, A, X, X, X, X**	**O,A, A, A, A, X, X, X**	**A, A, A, A, X**	**V,A, A, O, O, O, O, X, X, X**	**V, V, O, O, O, O, A, A, A, A, X, X**	**A, X, V, V, O, O, O, O, O, O**	**V, V, V, A, A, A, O, O, O, X, X, X**	**A, A, A, X, X, X, X, X**	**O, O, V, V, V, V, V, A, X, X, X**		
Quality	CSF3	**V, A, A, A, A**	**O, V, V, A, A, X, X**	**O, O, O, X, V**	**A, O, X, X, X, X, X, X**	**O, O, A, V, X, X, X**	**V, A, A, A, A, X**	**A, O, O, O, X, X**	**A, O, O, O, V, V, X, X, X**	**A, A, A, V, V, O, O, O, O, X, X**	**A, A, A, A, X, X, O, O, O, O**	**A, A, A, A, V, V, V, V, X, X, X**	**O, A, V, X, X, X, X, X**			
Efficiency	CSF4	**A, A, A, X**	**A, A, V, X**	**O, O, A**	**A, X, X, V, V**	**A, A, V, X**	**X, A, A, A**	**O, A, X**	**X, X, X, O, O, V**	**X, A, A, O, O, O, O, O**	**V, V, V, O, O, O, O, O**	**X, V, V, V, V, X, O, O**				
Demand	CSF5	**O, V, V, X, X**	**O, A, A, V, V, X, X**	**X, X, X, O, V, A**	**O, O, O, A, X, X, X, X, X**	**A, A, A, V, V, X, X, X**	**V, A, A, X, X, O, O, O**	**A, O, O, O, X, X**	**A, X, V, V, O, O, O, O, O, O**	**A, A, V, V, V, V, O, O, O, O, X, X**	**O, X, X, V, V, A, A, A, A, A**					
Sustainability	CSF6	**V, X, X, X, X**	**V, X, O, O, O, O**	**A, O, V, V**	**A, O, O, O, O, X, X**	**A, O, O, O, X, X**	**O, O, O, O, V, A**	**O, O, X, X, A**	**A, V, O, O, O, O, O O**	**A, A, A, O, O, O, X, X, X, X**						
Legislation	CSF7	**O, X, X, X, X**	**A, A, A, V, V, V, X, X**	**A, V, V, X, X, X**	**V, A, A, O, O, O, O, X, X**	**A, A, V, V, V, O, X, X**	**V, O, O, O, X, X, X, X**	**V, X, O, O, O, O**	**A, O, O, O, O, X, X, X, V, V**							
Safety	CSF8	**A, A, X, X, X**	**A, V, V, O, O, O, X, X**	**X, O, O, O, O, O**	**A, A, O, O, O, X, X, X, X**	**V, A, X, X, O, O, O, O**	**V, A, A, A, X, X, X, X**	**A, O, O, X, X, X**								
Logistics	CSF9	**X, O, O**	**X, X, X, A**	**O, V, V**	**X, X, X, O, V**	**X, A, O, O**	**X, X, O, O, O**									
Trained Labor	CSF10	**A, A, A, A**	**V, O, A, A, X, X**	**V, V, O, A, A, X**	**A, A, V, O, X, X, X**	**V, O, A, A, A, X**										
Customisation	CSF11	**V, X, X, X**	**X, X, V, V, A, A,**	**X, V, V, A, A, A**	**A, X, X, X, X, O, V, V**											
Coordination	CSF12	**O, X, X, X, X**	**X, X, X, X, X, A, A, V**	**A, X, V, O, O, O**												
Commoditisation	CSF13	**X, X**	**X, X, X, V, A**													
Standardisation	CSF14	**A, A, A, X, X**														
Research	CSF15															

As can be seen in Table 7, mixed nature of interactions between critical success factors are developed following the literature and expert interview process. To preserve the distinctiveness of each expert's viewpoint and to meticulously account for the individual preferences regarding the Critical Success Factors (CSFs), the responses from twelve experts were comprehensively documented. This meticulous documentation culminated in the creation of a structural self-interaction matrix (SSIM), providing a detailed representation of all expert opinions. This matrix served as a foundational tool for valuing each unique perspective, subsequently facilitating the development of a consensus through the application of a binary iteration method. This approach ensures a holistic and nuanced understanding of the CSFs as perceived by the collective wisdom of the participating experts, thereby enriching the research thesis with diverse, expert insights.

4.3.2 Develop an Initial Reachability Matrix

The third phase of the analysis involves the construction of the Reachability Matrix (RM), which stands in contrast to the adjacency matrix. While the adjacency matrix solely delineates the direct relationships or connections among the critical success factors, the RM extends this by elucidating both direct and indirect interrelations among the factors. Utilizing the principles of Interpretive Logic Knowledge Base, the initial formulation of the RM was undertaken to facilitate a comparative analysis of the factors in pairs. Drawing upon the framework established by the adjacency matrix, the development process for the RM was segmented into initial and final stages. The preliminary stage of the RM was characterized by the adoption of binary values 0 and 1 to substitute for the symbols V, A, X, and O, as per the guidelines delineated by (Sushil 2012). This binary coding serves to simplify and clarify the matrix, making it easier to discern the nuanced network of relationships among the success factors.

- For every V in the cell, the entry (i,j) becomes 1, and entry (j,i) becomes 0.
- For every A in the cell, the entry (i,j) becomes 0, and entry (j,i) becomes 1.
- For every X in the cell, the entry (i,j) becomes 1, and entry (j,i) also becomes 1.
- For every O in the cell, both the entries (i,j) and (j,i) become 0.

Subsequently, to validate the transitivity rules, conducting a power iteration analysis becomes essential for the refinement of the Reachability Matrix (RM) into its final form. The preliminary RM captures solely the direct interactions among the variables, necessitating a transitivity examination to uncover the indirect linkages as well (Gan et al. 2018). This examination, guided by the principles of transitivity, serves as a pivotal tool for establishing a definitive relational framework, especially in instances where consensus remains elusive from expert consultations. The procedure for ensuring relational consistency among the factors involves the application of a Boolean operation of self-multiplication until a stable configuration is attained (Wu et al. 2015). This operation is predicated on the logic that if a critical success factor CSF-1 influences CSF-2, and in turn, CSF-2 influences CSF-3, it implies an indirect influence of CSF-1 on CSF-3. The methodology employed to generate the final RM is encapsulated in the following equation (Khan et al. 2022):

$$R_f = {R_i}^k + R^{k+1}, k > 1 \text{ (Khan et al. 2022)}$$

within the framework of this analysis, R_f signifies the developed final Reachability Matrix, while Ri represents the initial Reachability Matrix, as delineated by (Shen et al. 2016). The derived values constituting the final RM are systematically catalogued in Table 8. The term 'Driving Power' associated with a Critical Success Factor (CSF) refers to the quantity of other CSFs that it impacts, thus influencing the project's outcome. Conversely, the 'Dependence Power' of a CSF indicates the count of other CSFs that are impacted by it, showcasing the interconnected nature of these factors. Analysis of Table 8 highlights the presence of several transitive connections among the CSFs, ensuring the preservation of consistency within the model as it progresses through the iteration stages.

Table 8 Reachability Matrix (RM) for Critical Success Factors.

X \ Y		Cost	Time	Quality	Efficiency	Demand	Sustainability	Legislation	Safety	Logistics	Training	Customisation	Coordination	Commoditisation	Standardisation	Research	Driving Power
		CSF1	CSF2	CSF3	CSF4	CSF5	CSF6	CSF7	CSF8	CSF9	CSF10	CSF11	CSF12	CSF13	CSF14	CSF15	
Cost	CSF1	1	1*	1	1	1	1	1*	1	1*	1*	1*	1*	1	1	1	15
Time	CSF2	1	1	1	1	1*	0	1*	1*	1*	1*	1	1	1*	1	1*	14
Quality	CSF3	1*	1*	1	1	1	0	1*	1	1*	1*	1	1	1*	1	1*	14
Efficiency	CSF4	1*	1	1	1	1	0	1*	1	1*	1*	1*	1	1*	1*	1*	14
Demand	CSF5	1*	1*	1	1*	1	1*	1*	1*	1*	1*	1	1	1	1	1	15
Sustainability	CSF6	1*	1*	1	1	1	1	1	1*	0	1	1*	1*	1	1*	1	14
Legislation	CSF7	1*	1*	1	1	1*	1	1	1*	1	1	1	1*	1	1	1	15
Safety	CSF8	1*	1	1*	1	1	1	1	1	1	1	1	1	1	1*	1	15
Logistics	CSF9	1	1	1*	1	1	1	1	1	1	1	1*	1	1	1	1*	15
Trained Labor	CSF10	1	1	1	1	1*	1*	1	1	1*	1	1*	1	1*	1*	1*	15
Customisation	CSF11	1	1	1	1	1	1*	1	1*	1*	1	1	1	1*	1	1	15
Coordination	CSF12	1	1	1	1	1	1	1	1	1	1	1	1	1*	1	1	15
Commoditisation	CSF13	1	1*	1*	1*	1	1*	1	1*	1*	1*	1	1*	1	1	1	15
Standardisation	CSF14	1	1	1	1	1	1*	1	1*	1	1	1	1	1	1	1*	15
Research	CSF15	1	1	1	1	1*	1	1	1	1*	1	1	1	1	1	1	15
Dependency Power		15	15	15	15	15	12	15	15	14	15	15	15	15	15	15	221 / 221

Note: (*) denotes the transitivity relation check.

4.3.3 Develop a Level Partitioning Matrix

The fourth phase involves constructing a Level Partitioning Matrix, structured according to a hierarchical framework. This process entails organizing the levels into a hierarchical format, which is accomplished by establishing a Reachability set, an Antecedent set, and an Intersection set for each Critical Success Factors (CSFs). Specifically, the Reachability set for a CSF encompasses all other CSFs it can potentially influence, the Antecedent set comprises all CSFs that can influence it, and the Intersection set includes all CSFs common to both the Reachability and Antecedent sets.

Following the extraction of the Reachability and Antecedent sets from the Reachability Matrix, the Intersection sets were formulated. The assignment of levels to each CSF is contingent upon the analysis of the Reachability set against the Intersection set. CSFs displaying congruence across both sets were systematically categorized into levels through a series of iterative processes. This iterative methodology resulted in the articulation of a three-tiered hierarchical structure, ranging from level I to level III. This methodological approach aligns with the principles of Total Interpretive Structural Modelling (TISM) and mirrors methodologies applied in similar scholarly inquiries, as indicated in references (Gan et al. 2018; Nair and Suresh 2021). The details of the iterative level partitioning process, underpinned by the hierarchical structure, are presented in Table 9.

As detailed in Table 9, the initial level (Level I) comprises of thirteen specific CSFs except CSF9 (Logistics) and CSF6 (Sustainability) in level II and level III respectively. In the hierarchical structure, CSFs positioned at lower levels are situated higher within the hierarchy, indicating that they are influenced by those positioned lower in the hierarchical order. Conversely, CSFs located at the highest level (Level III) appear at the bottom of the hierarchy table, exerting significant influence on those above them within the structure. CSFs placed within the intermediary levels function as both influencers of those above and as entities influenced by those below them in the hierarchical arrangement.

Table 9 Level partitioning matrix based on hierarchy structure.

Factors	Reachability Set	Antecedent Set	Intersection Set	Level
CSF1	1, 2, 3, 4, 5, 6, 7, 8, 9, 10, 11, 12, 13, 14, 15	1, 2, 3, 4, 5, 6, 7, 8, 9, 10, 11, 12, 13, 14, 15	1, 2, 3, 4, 5, 6, 7, 8, 9, 10, 11, 12, 13, 14, 15	**I**
CSF2	1, 2, 3, 4, 5, 7, 8, 9, 10, 11, 12, 13, 14, 15	1, 2, 3, 4, 5, 6, 7, 8, 9, 10, 11, 12, 13, 14, 15	1, 2, 3, 4, 5, 7, 8, 9, 10, 11, 12, 13, 14, 15	**I**
CSF3	1, 2, 3, 4, 5, 7, 8, 9, 10, 11, 12, 13, 14, 15	1, 2, 3, 4, 5, 6, 7, 8, 9, 10, 11, 12, 13, 14, 15	1, 2, 3, 4, 5, 7, 8, 9, 10, 11, 12, 13, 14, 15	**I**
CSF4	1, 2, 3, 4, 5, 7, 8, 9, 10, 11, 12, 13, 14, 15	1, 2, 3, 4, 5, 6, 7, 8, 9, 10, 11, 12, 13, 14, 15	1, 2, 3, 4, 5, 7, 8, 9, 10, 11, 12, 13, 14, 15	**I**
CSF5	1, 2, 3, 4, 5, 6, 7, 8, 9, 10, 11, 12, 13, 14, 15	1, 2, 3, 4, 5, 6, 7, 8, 9, 10, 11, 12, 13, 14, 15	1, 2, 3, 4, 5, 6, 7, 8, 9, 10, 11, 12, 13, 14, 15	**I**
CSF6	1, 2, 3, 4, 5, 6, 7, 8, 10, 11, 12, 13, 14, 15	1, 5, 6, 7, 8, 9, 10, 11, 12, 13, 14, 15	1, 5, 6, 7, 8, 10, 11,12, 13, 14, 15	**III**
CSF7	1, 2, 3, 4, 5, 6, 7, 8, 9, 10, 11, 12, 13, 14, 15	1, 2, 3, 4, 5, 6, 7, 8, 9, 10, 11, 12, 13, 14, 15	1, 2, 3, 4, 5, 6, 7, 8, 9, 10, 11, 12, 13, 14, 15	**I**
CSF8	1, 2, 3, 4, 5, 6, 7, 8, 9, 10, 11, 12, 13, 14, 15	1, 2, 3, 4, 5, 6, 7, 8, 9, 10, 11, 12, 13, 14, 15	1, 2, 3, 4, 5, 6, 7, 8, 9, 10, 11, 12, 13, 14, 15	**I**
CSF9	1, 2, 3, 4, 5, 6, 7, 8, 9, 10, 11, 12, 13, 14, 15	1, 2, 3, 4, 5, 7, 8, 9, 10, 11, 12, 13, 14, 15	1, 2, 3, 4, 5, 7, 8, 9, 10, 11, 12, 13, 14, 15	**II**
CSF10	1, 2, 3, 4, 5, 6, 7, 8, 9, 10, 11, 12, 13, 14, 15	1, 2, 3, 4, 5, 6, 7, 8, 9, 10, 11, 12, 13, 14, 15	1, 2, 3, 4, 5, 6, 7, 8, 9, 10, 11, 12, 13, 14, 15	**I**
CSF11	1, 2, 3, 4, 5, 6, 7, 8, 9, 10, 11, 12, 13, 14, 15	1, 2, 3, 4, 5, 6, 7, 8, 9, 10, 11, 12, 13, 14, 15	1, 2, 3, 4, 5, 6, 7, 8, 9, 10, 11, 12, 13, 14, 15	**I**
CSF12	1, 2, 3, 4, 5, 6, 7, 8, 9, 10, 11, 12, 13, 14, 15	1, 2, 3, 4, 5, 6, 7, 8, 9, 10, 11, 12, 13, 14, 15	1, 2, 3, 4, 5, 6, 7, 8, 9, 10, 11, 12, 13, 14, 15	**I**
CSF13	1, 2, 3, 4, 5, 6, 7, 8, 9, 10, 11, 12, 13, 14, 15	1, 2, 3, 4, 5, 6, 7, 8, 9, 10, 11, 12, 13, 14, 15	1, 2, 3, 4, 5, 6, 7, 8, 9, 10, 11, 12, 13, 14, 15	**I**
CSF14	1, 2, 3, 4, 5, 6, 7, 8, 9, 10, 11, 12, 13, 14, 15	1, 2, 3, 4, 5, 6, 7, 8, 9, 10, 11, 12, 13, 14, 15	1, 2, 3, 4, 5, 6, 7, 8, 9, 10, 11, 12, 13, 14, 15	**I**
CSF15	1, 2, 3, 4, 5, 6, 7, 8, 9, 10, 11, 12, 13, 14, 15	1, 2, 3, 4, 5, 6, 7, 8, 9, 10, 11, 12, 13, 14, 15	1, 2, 3, 4, 5, 6, 7, 8, 9, 10, 11, 12, 13, 14, 15	**I**

4.3.4 MICMAC analysis of the Critical Success Factors

This phase entails conducting a MICMAC (Matrice d'Impacts Croisés-Multiplication Appliquée à un Classement) analysis, utilizing the hierarchical levels depicted in Table 9 This analytical method focuses on assessing the influence distribution of various variables by pinpointing their Driving and Dependence Powers. Table 8 elaborates on the Driving and Dependence Powers calculated for each Critical Success Factor. Through MICMAC analysis, factors within the Modular Mass Timber Construction for Affordable Housing framework are categorized into four distinct groups: 'Dependent' (characterized by low Driving Power and high Dependence Power), 'Driving or Independent' (marked by high Driving Power and low Dependence Power), 'Autonomous' (noted for low Driving and Dependence Power), and 'Linkage' (defined by high Driving and Dependence Power). This categorization aids in analyzing the dynamics among CSFs in terms of their influence and susceptibility, as previously outlined in the fourth step. Figure 17 graphically represents the positioning of the Critical Success Factors across four quadrants, determined using a scale-centric approach as recommended by (Sushil 2018) and (Warfield and Member 1974). This positioning is predicated on their identified Driving and Dependence Powers within the Reachability Matrix, underscored by cross-impact matrix multiplication.

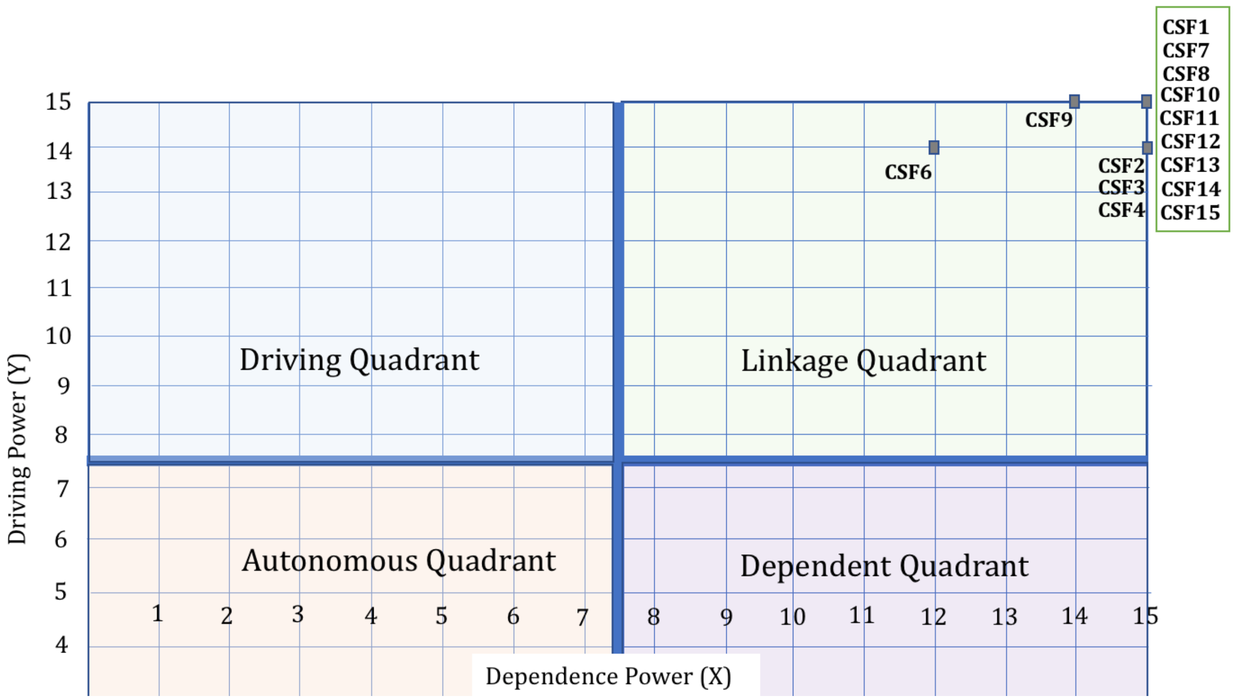

Figure 17 MICMAC Analysis of the CSFs

According to the insights derived from Figure 17, all the fifteen critical success factors are identified within the linkage quadrant, evidencing both substantial driving and dependence powers: CSF1 (Cost), CSF2 (Time), CSF3 (Quality), CSF4 (Efficiency), CSF5 (Demand), CSF6 (Sustainability), CSF7 (Legislation), CSF8 (Safety), CSF9 (Logistics), CSF10 (Training), CSF11 (Customization), CSF12 (Coordination), CSF13 (Commoditization), CSF14 (Standardization) and CSF15 (Research). Their positioning in the linkage quadrant underscores their critical role in both influencing and being influenced by the MMT adoption process, highlighting the necessity for a balanced and integrated approach to address these factors simultaneously.

Notably, the absence of any CSFs in the driving, autonomous and dependent quadrants indicate a focused concentration of influence among the identified factors. The lack of autonomous factors suggests there are no CSFs that operate in isolation or with minimal connections to others, emphasizing the interconnected nature of the project's success elements. Similarly, the absence of dependent factors signifies that none of the identified CSFs are overly susceptible to influence without possessing some degree of driving power themselves, highlighting the proactive role each plays in facilitating MMT adoption for affordable housing.

The detailed examination of elements such as Sustainability, Logistics, and the trio of Time, Quality, and Efficiency underscores their pivotal roles and the intricate dynamics between their influence and reliance. The pronounced influencing capacity of Logistics and the even-handed impact and reliance of other Critical Success Factors (CSFs) highlight the imperative for thoughtful strategic planning and cohesive project management methodologies to adeptly manage these interconnections.

To sum up, for developers and architects to effectively execute modular mass timber initiatives for affordable housing, a comprehensive strategy that acknowledges the mutual dependencies among all CSFs is essential. Focused consideration on logistics, sustainability, time management, quality assurance, and operational efficiency is key. Exploiting the synergies among these factors can elevate project performance, foster the growth and ecological sustainability of modular mass timber solutions, and thereby support their increased integration into the affordable housing market.

In conclusion, the MICMAC analysis offers valuable insights into the dynamics and interrelationships of the CSFs critical to the adoption of modular mass timber in affordable housing. Understanding the substantial driving and dependence powers of the majority of CSFs, alongside the pivotal role of logistics and sustainability, provides implementation strategies for stakeholders to prioritize and address these factors comprehensively. This analytical approach not only aids in recognizing the key areas of focus but also facilitates the development of targeted strategies to enhance the adoption process, ensuring a more efficient, sustainable, and successful implementation of modular mass timber in affordable housing projects.

4.3.5 Develop the transitive links between different factors and build a TISM model

The culmination of the analysis involves the establishment of transitive relationships among various Critical Success Factors (CSFs) and the construction of a Total Interpretive Structural Modelling (TISM) framework. Drawing on the foundational work of developing the Reachability Matrix and conducting MICMAC analysis, transitive relationships are delineated to elucidate the interconnections among the critical success factors (Sushil 2012). Leveraging the principles of systems thinking and interpretive logic, the TISM framework was formulated. Prioritized rubric illustrates the transitive relationships among the Critical Success Factors, shedding light on their dynamic interactions as depicted in Figure 18. The

TISM framework depicted in Figure 18 maps out the intricate web of fifteen Critical Success Factors central to the adoption of Modular Mass Timber Construction towards Affordable Housing in the US.

It becomes apparent through the TISM framework that the Sustainability factor (CSF6) emerges as a paramount element, characterized by its pronounced influence and minimal dependency. This factor acts as a cornerstone, with all other critical success factors being influenced by the sustainability domain, as evidenced by the transitive relationships highlighted in Figure 18 For example, efficiency is profoundly influenced by sustainability considerations, necessitating a deep comprehension of sustainability dynamics. All the experts remarked on the significance of sustainability features, particularly those for end-users as well as researchers, as crucial for facilitating successful outcomes, suggesting that without external pressure for change, significant progress remains elusive.

The dominant positioning of Sustainability and Logistics factors exerts influence over those situated in the linkage quadrant such as Cost, Time, Quality, Efficiency, Demand, Legislation, Safety, Training, Customization, Coordination, Commoditization, Standardization, and Research. Specifically, the Cost, Demand, Legislation, Safety, Logistics, Training, Customization, Coordination, Commoditization, Standardization, and Research, affect the Time, Quality, and Efficiency factors through transitive relationships, such as improved scheduling, building codes adherence, and higher production. The Level I critical success factors, also play a pivotal role in Modular Mass Timber adoption towards the Affordable Housing, yet their effectiveness is contingent upon the advancement of other critical success factors such as Sustainability and Logistics at lower levels. Insights from Figure 18 indicate that Sustainability aspects like biophilia and low embodied carbon drive demand, while affordability, safety or customization bolster it. Several experts suggested that the integration of circular economy principles into modular mass timber could broaden its application and amplify its environmental benefits. One of the experts working in manufacturing of modular homes and having experience of working on installation process, projected a significant surge in the circular economy following MMT success. Research by (Brissi et al. 2021; Sunday Festus et al. 2021a) corroborated the influential role of sustainable, social, environmental and economic factors in shaping affordability, demand, highlighting consumer attitudes, perceptions, and financial constraints as key determinants.

An expert working on affordable housing development projects stressed the critical housing shortage and its root causes—cost, timing, and logistical challenges—as central barriers to addressing demand.

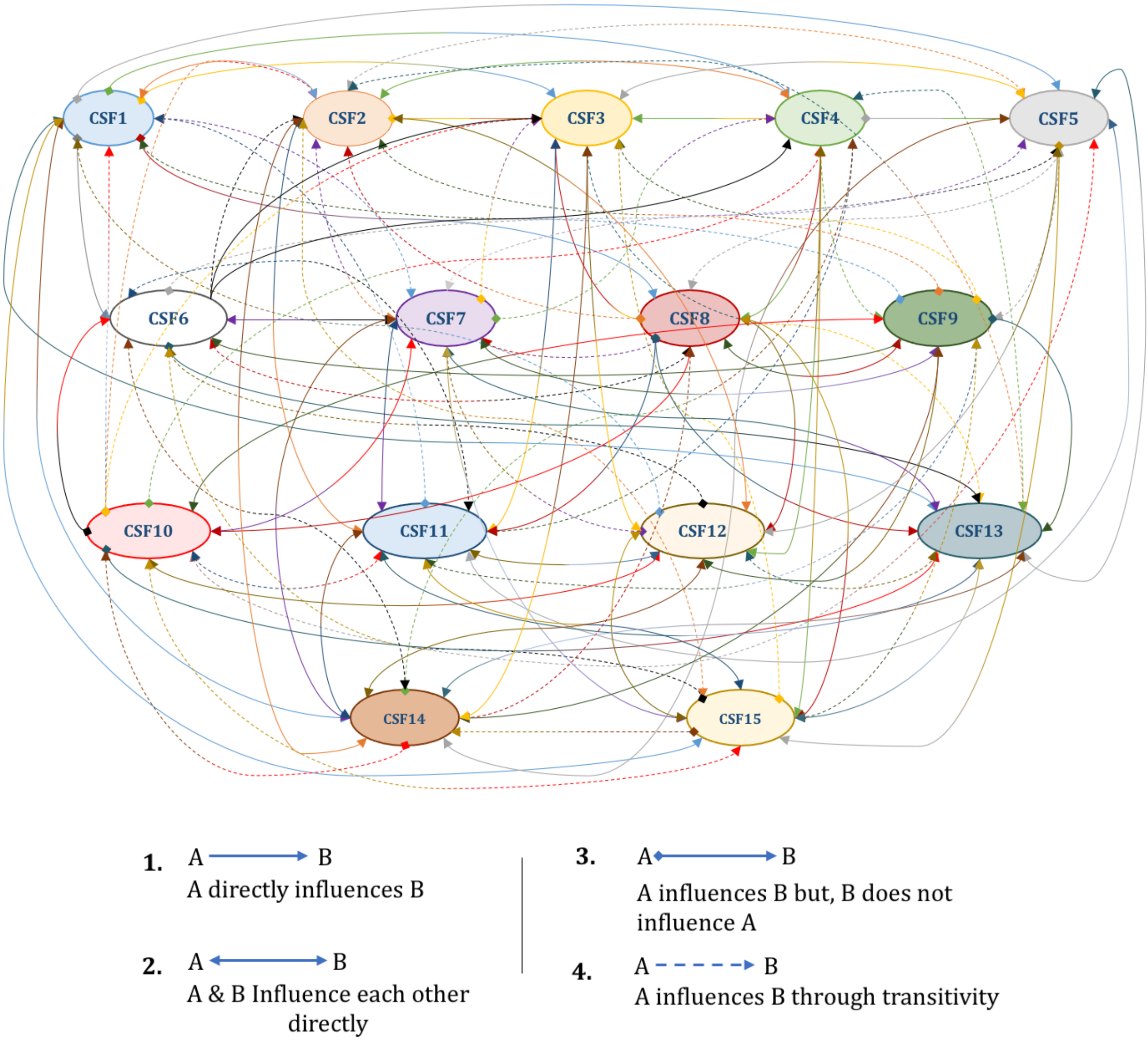

Figure 18 Prioritized rubric - TISM model of the CSFs

The figure 18 provides a detailed overview of how the Critical Success Factors (CSFs) are interrelated and depend on each other. An arrow pointing in one direction indicates a direct influence from one factor to another. Arrows pointing in both directions signify mutual direct influence between two factors. A symbol with a diamond at one end and an arrow at the other represents a relationship where one factor directly influences the other, while the latter only has an indirect influence in return. Lastly, a symbol with diamonds on both ends indicates that both factors influence each other indirectly.

This underscores the importance of prioritizing the critical success factors in Levels II and III to enhance the performance of those in Level I. Although some critical success factors may not be directly connected, their mutual influence is palpable. For instance, the Quality factor's association with Demand is influenced by consumer expectations and the quest for superior products. In summary, the TISM framework offers a comprehensive overview of critical success factors and their interconnectedness, illuminating their significance in the adoption of Modular Mass Timber towards the Affordable Housing.

4.4 Implementation Strategies

In this chapter, a detailed exploration of the strategies applied throughout this study is provided, highlighting a methodical process that emphasizes the importance of each Critical Success Factor (CSF). The foundation of these strategies stems primarily from insights gathered through expert interviews and comprehensive literature reviews. The chapter explores how these factors are interconnected, offering clarity on how the study's findings can be pragmatically applied within the construction industry. This deliberate methodology promotes a deep understanding of each CSF, aiding in the crafting of precise and impactful interventions. Figure 19 illustrates the relationships between critical factors in a color-coded matrix, where 'indirect influence' represents the connections among CSFs identified through the transitivity rule, and 'direct influences' reflect relationships established based on the consensus from interviews with industry experts.

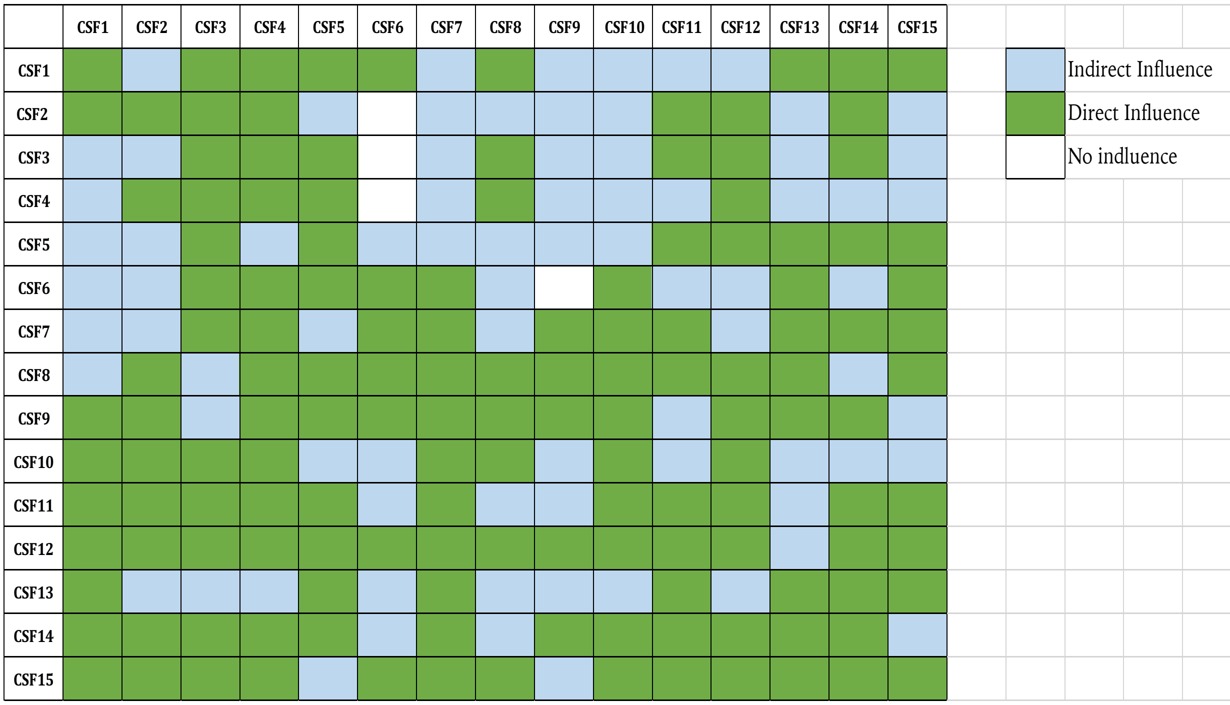

Figure 19 Color-coded Influence Diagram

Following section will describe the implementation strategies of the individual Critical Success Factors (CSF) using the inter-relativity and implications,

4.4.1 CSF1: Cost

a. Inter-relativity of the CSFs

- **Cost directly influences –** Quality, Efficiency, Demand, Sustainability, Legislation, Safety, Commoditization, Standardization and research.
- **Cost indirectly influences –** Time, Legislation, Logistics, Training, Customization and Coordination.
- **Cost gets directly influenced by –** Time, Efficiency, Logistics, Training, Customization, Coordination, Commoditization, Standardization and Research.
- **Cost gets indirectly influenced by –** Quality, Efficiency, Demand, Sustainability, Legislation and Safety.

b. Implications

Cost is a crucial factor in Modular Mass Timber (MMT) construction for affordable housing, impacting and being shaped by various aspects of project management. It influences project complexity, quality control, efficiency, and sustainability, while also being affected by time, demand, legislative requirements, and more. This interplay underscores the necessity for strategic cost management to accommodate for customization, while pushing for standardization and efficiency in design and construction processes.

Practically, understanding cost dynamics allows developers and installers to optimize resources and strategies, ensuring affordable housing projects are financially viable yet do not compromise on essential values. This approach facilitates the development of sustainable, efficient, and cost-effective housing solutions, making cost a pivotal element in the successful deployment of MMT in affordable housing initiatives.

4.4.2 CSF2: Time

a. Inter-relativity of the CSFs

- **Time directly influences –** Cost, Quality, Efficiency, Customization, Coordination and Standardization.
- **Time indirectly influences –** Demand, Legislation, Safety, Logistics, Training, Commoditization and Research.
- **Time gets directly influenced by –** Efficiency, Safety, Logistics, Training, Customization, Coordination, Standardization and Research.
- **Time gets indirectly influenced by –** Cost, Quality, Demand, Sustainability, Legislation and Commoditization.

b. Implications

Time significantly influences Modular Mass Timber (MMT) construction for affordable housing, impacting project design, safety, environmental footprint, and attractiveness to investors. By dictating project efficiency and timeline, it directly affects the resolution of the housing crisis and enhances project coordination and standardization. Conversely, project facets like prefabrication, regulatory compliance, and workforce efficiency shape the timeline, emphasizing streamlined processes for quality and sustainability.

In practice, managing time efficiently is key to successful MMT projects, enabling rapid, sustainable, and cost-effective housing solutions. This approach highlights the importance of time as a critical factor in achieving the goals of affordable housing projects, ensuring timely delivery without compromising on standards.

4.4.3 CSF3: Quality

a. Inter-relativity of the CSFs

- **Quality directly influences –** Efficiency, Demand, Safety, Customization, Coordination and Standardization.
- **Quality indirectly influences –** Cost, Time, Legislation, Safety, Logistics, Training, Commoditization and Research.
- **Quality gets directly influenced by –** Cost, Time, Efficiency, Demand, Sustainability, Legislation, Training, Customization, Coordination, Standardization and Research.
- **Quality gets indirectly influenced by –** Safety, Logistics and Commoditization.

b. Implications

Quality stands at the forefront of Modular Mass Timber (MMT) construction for affordable housing, impacting everything from costs and durability to regulatory compliance and market acceptance. Ensuring high quality across all facets, including prefabrication, lifecycle costs, and building practices, directly influences the project's sustainability, safety, and efficiency. Quality's pivotal role is also reinforced by rigorous quality control, design precision, and sustainable resource management, which together drive innovation and meet high consumer and regulatory standards. In essence, prioritizing quality in MMT projects ensures the delivery of durable, sustainable, and cost-effective housing, fostering market scalability and aligning with the industry's goals of excellence and sustainability.

4.4.4 CSF4: Efficiency

a. Inter-relativity of the CSFs

- **Efficiency directly influences –** Time, Quality, Demand, Safety, and Coordination.
- **Efficiency indirectly influences –** Cost, Legislation, Logistics, Training, Customization, Commoditization, Standardization and Research.
- **Efficiency gets directly influenced by –** Cost, Time, Quality, Sustainability, Legislation, Safety, Logistics, Training, Customization, Coordination, Standardization and Research.
- **Efficiency gets indirectly influenced by –** Demand and Commoditization.

b. Implications

Efficiency is pivotal in Modular Mass Timber (MMT) construction for affordable housing, influencing project dynamics by reducing labor, time, and material waste, and streamlining assembly and logistics. This focus on efficiency leads to cost reductions, supports regulatory compliance, and enhances project sustainability. Although it may limit customization due to prefabrication, the emphasis on efficient practices promotes economic viability and fosters innovation. In practical terms, efficiency in MMT projects means sustainable, cost-effective housing solutions are delivered faster, aligning with environmental goals and meeting the urgent need for affordable housing through optimized resource use and innovative construction methods.

4.4.5 CSF5: Demand

a. Inter-relativity of the CSFs

- **Demand directly influences –** Quality, Customization, Coordination, Commoditization, Standardization and Research.
- **Demand indirectly influences –** Time, Cost, Efficiency, Sustainability, Legislation, Safety, Logistics and Training.
- **Demand gets directly influenced by –** Cost, Quality, Efficiency, Sustainability, Safety, logistics, Customization, Coordination, Commoditization and Standardization.
- **Demand gets indirectly influenced by –** Time, Legislation, Training and Research.

b. Implications

Demand serves as a key driving force in the Modular Mass Timber (MMT) construction sector, especially within affordable housing projects. It influences a broad spectrum of Critical Success Factors (CSFs), from encouraging cost reductions through efficient production to necessitating variations in design to meet urgency and consumer expectations. Demand shapes production scales, spurs innovation and investment, and prompts regulatory bodies to adapt and endorse MMT technology. It also underlines the importance of material sourcing strategies, supply chain efficiency, and the cultivation of skilled professionals. Moreover, demand fosters the development of adaptable and scalable designs, ensures early stakeholder involvement, and emphasizes the need for consistent quality and interoperability, thereby distinguishing MMT projects in the competitive market.

In practical applications, demand not only directs the focus towards efficient and sustainable building practices but also accelerates the adoption of innovative solutions to meet housing needs. Demand drives the industry towards creating distinguishable, quality, and scalable housing solutions, ensuring that projects align with consumer expectations and regulatory standards. Consequently, understanding and responding to demand within the MMT sector is crucial for developers and installers aiming to leverage this technology for affordable housing, guiding strategic decisions that align with market needs and sustainability goals.

4.4.6 CSF6: Sustainability

a. Inter-relativity of the CSFs

- **Sustainability directly influences –** Quality, Efficiency, Demand, Legislation, Training, Commoditization and Research.
- **Sustainability indirectly influences –**Cost, Time, Safety, Customization, Coordination and Standardization.
- **Sustainability gets directly influenced by –** Cost, Legislation, Safety, logistics, Coordination and Research.
- **Sustainability gets indirectly influenced by –** Demand, Training, Customization, Commoditization and Standardization.

b. Implications

Sustainability stands as a critical driving force in Modular Mass Timber (MMT) construction, particularly within the affordable housing sector. It intricately influences various aspects of construction projects, from the initial investment in eco-friendly materials to the adoption of practices that enhance environmental performance and reduce waste. While embracing sustainability may entail higher upfront costs, the long-term value it generates—through energy efficiency, reduced carbon footprint, and adherence to green building standards—cannot be overstated. Sustainability not only responds to growing environmental concerns but also encourages the industry towards innovation, the use of renewable materials, and the implementation of environmentally responsible construction techniques.

In practical terms, integrating sustainability into MMT projects for affordable housing has profound implications. It guides the selection of materials, influences design decisions to meet sustainability goals, and promotes the adoption of integrated project delivery and lean construction methods. This approach not only increases the market demand for sustainable housing solutions but also paves the way for standardization in green building practices and certifications.

4.4.7 CSF7: Legislation

a. Inter-relativity of the CSFs

- **Legislation directly influences –** Quality, Efficiency, Sustainability, Logistics, Training, Customization, Commoditization, Standardization and Research.
- **Legislation indirectly influences –**Cost, Time, Demand, Safety and Coordination.
- **Legislation gets directly influenced by –** Sustainability, Safety, Logistics, Training, Customization, Coordination, Commoditization, Standardization and Research.
- **Legislation gets indirectly influenced by –** Cost, Time, Quality, Efficiency and demand.

b. Implications

Regulatory requirements, from permitting processes, building codes, zoning and compliance standards, directly influence development costs, construction practices, and material selection. Legislation not only mandates adherence to specific standards for sustainability and safety but also impacts design flexibility and material choices through building codes and policies. By providing incentives or imposing restrictions, legislation encourages the construction sector to comply with standards, thus incentivizing the adoption of MMT and integrating it into the market.

In practical applications, compliance with regulatory frameworks ensures project viability, aligning construction practices with legal standards and fostering market acceptance. Legislation encourages the construction industry to innovate within defined boundaries, promoting the use of sustainable materials and practices. For developers and installers, staying alongside of legislative changes and incentives is key to optimizing project outcomes, ensuring that MMT constructions not only meet current standards but are also positioned for future regulatory evolutions, driving the broader adoption of sustainable, affordable housing solutions.

4.4.8 CSF8: Safety

a. Inter-relativity of the CSFs

- **Safety directly influences –** Time, Efficiency, Demand, Sustainability, Legislation, Logistics, Training, Customization, Coordination, Commoditization, and Research.
- **Safety indirectly influences –**Cost, Quality and Standardization.

- **Safety gets directly influenced by –** Cost, Quality, Efficiency, Logistics, Training, Coordination and Research.
- **Safety gets indirectly influenced by –** Time, Demand, Sustainability, legislation, Customization, Commoditization and Standardization.

b. Implications

Safety measures directly impact project timelines, insurance costs, and stakeholder confidence, while also shaping building codes and regulations. However, prioritizing safety can sometimes limit design and construction flexibility. In return, factors like cost-effective design, coordination, and adherence to regulatory standards bolster safety by reducing accidents, enhancing structural integrity, and fostering a safer work environment.

In practical applications, emphasizing safety within MMT projects leads to improved market appeal, adoption rates, and ensures worker and structural safety. It necessitates research into fire-resistance and structural enhancements, driving innovation within the sector. For developers and installers, integrating safety measures from the design phase through to construction ensures compliance with regulations, minimizes risks, and enhances overall project viability.

4.4.9 CSF9: Logistics

a. Inter-relativity of the CSFs

- **Logistics directly influences –** Cost, Time, Efficiency, Demand, Sustainability, Legislation, Safety, Training, Coordination, Commoditization and Standardization.
- **Logistics indirectly influences –**Quality, Customization and Research.
- **Logistics gets directly influenced by –** Legislation, Safety, Coordination and Standardization.
- **Logistics gets indirectly influenced by –** Cost, Time, Quality, Efficiency, Demand, Training, Customization, Commoditization and Research.

b. Implications

Logistics, as a Critical Success Factor (CSF) plays a vital role in ensuring the efficient movement, handling, and storage of materials. It directly influences the project's coordination, timely delivery, and cost-effectiveness by streamlining the supply chain and reducing transportation costs. The adoption of environmentally friendly practices, such as the use of electric trucks, not only mitigates environmental impact but also aligns with policies on urban development and building codes.

In practical applications, effective logistics management facilitates the availability and accessibility of materials, contributing to the affordability of projects and reducing the overall carbon footprint. By optimizing transportation and material handling processes, logistics plays a critical role in maintaining high standards of efficiency and sustainability. For developers and installers, focusing on logistics from the planning phase through execution can significantly enhance project outcomes, making MMT a more attractive option for sustainable, affordable housing solutions.

4.4.10 CSF10: Training

a. Inter-relativity of the CSFs

- **Training directly influences –** Cost, Time, Quality, Efficiency, Legislation, Safety and Coordination.
- **Training indirectly influences –**Demand, Sustainability, Logistics, Customization, Commoditization, Standardization and Research.
- **Training gets directly influenced by –** Sustainability, Legislation, Safety, Logistics, Customization, Coordination, Standardization and Research.
- **Training gets indirectly influenced by –** Cost, Time, Quality, Efficiency, Demand and Commoditization.

b. Implications

Training emerges as a critical factor in enhancing the Modular Mass Timber (MMT) construction process for affordable housing, fundamentally reducing errors, boosting workforce efficiency, and fostering better construction practices. Through focused training programs, the workforce gains enhanced craftsmanship skills, leading to higher quality outcomes that in turn stimulate demand. It supports efficient transportation and assembly processes, and plays a vital role in standardizing construction practices, ensuring consistent quality, and adhering to building codes.

In the practical realm of MMT projects, training not only facilitates the adoption of sustainable construction techniques but also ensures the project's adherence to environmental responsibilities and safety standards. For developers and installers, investing in training means ensuring that all stakeholders understand the process thoroughly, which is crucial for meeting the diverse needs of affordable housing.

4.4.11 CSF11: Customization

a. Inter-relativity of the CSFs

- **Customization directly influences –** Cost, Time, Quality, Efficiency, Demand, Legislation, Training, Coordination, Standardization and Research.
- **Customization indirectly influences –** Sustainability, Safety, Logistics and Commoditization.
- **Customization gets directly influenced by –** Time, Quality, Efficiency, Demand, Legislation, Training, Coordination, Standardization and Research.
- **Customization gets indirectly influenced by –** Cost, Efficiency, Sustainability, Logistics and Training.

b. Implications

Customization influences and is influenced by other CSFs, leading to tailored solutions that meet specific requirements, optimized material use, and reduced waste. However, it also introduces challenges such as increased planning, design, and manufacturing complexity, coordination difficulties, and potential cost increases.

In practical applications at MMT's installation and development projects, this data can guide the creation of adaptable and scalable designs that meet unique preferences and sustainability goals. It can also help in understanding the limitations imposed by standardization and prefabrication, and in developing strategies to allow flexible design adaptations within established parameters. This understanding can contribute to the feasibility and cost-effectiveness of tailored designs, ultimately leading to the delivery of diverse and specific affordable housing solutions.

4.4.12 CSF12: Coordination

a. Inter-relativity of the CSFs

- **Coordination directly influences –** Cost, Time, Quality, Efficiency, Demand, Sustainability, Legislation, Safety, Logistics, Training, Customization, Standardization and Research.
- **Coordination indirectly influences –** Commoditization.

- **Coordination gets directly influenced by –** Time, Quality, Demand, Safety, Training, Customization, Coordination, Standardization and Research.
- **Coordination gets indirectly influenced by –** Cost, Sustainability, Legislation, Commoditization.

b. Implications

Coordination as a Critical Success Factor (CSF) plays a pivotal role in affordable housing projects. It not only reduces costs by streamlining processes and minimizing waste but also enhances project execution and resource allocation. However, it requires efficient knowledge transfer, risk management, and stakeholder alignment.

In the context of MMT's installation and development projects, this data can be instrumental in improving stakeholder understanding, facilitating problem-solving, and simplifying project management tasks. It can also aid in streamlining supply chains, enhancing communication across the construction process chain, and fostering innovation. This understanding can contribute to the feasibility and cost-effectiveness of tailored designs, ultimately leading to the delivery of diverse and specific affordable housing solutions.

4.4.13 CSF13: Commoditization

a. Inter-relativity of the CSFs

- **Commoditization directly influences –** Cost, Demand, Legislation, Customization, Standardization and Research.
- **Commoditization indirectly influences –** Time, Quality, Efficiency, Sustainability, Safety, Logistics, Training and Coordination.
- **Commoditization gets directly influenced by –** Cost, Demand, Sustainability, Legislation, Safety, Logistics, Standardization and Research.
- **Commoditization gets indirectly influenced by –** Time, Quality, Efficiency, Training, Customization and Coordination.

b. Implications

Commoditization, influences affordable housing projects by reducing costs and timelines through standardization of components and processes. It enhances quality, efficiency, and marketability, while also driving innovation. However, it may limit customization and necessitate unique material handling processes.

In the context of MMT's installation and development projects, this data can be leveraged to determine economic viability, promote standardization and scalability, and enhance market appeal. It can also aid in fostering innovation, facilitating mass production, and increasing affordability and accessibility in the market. This understanding can contribute to the delivery of diverse and specific affordable housing solutions.

4.4.14 CSF14: Standardization

a. Inter-relativity of the CSFs

- **Standardization directly influences –** Cost, Time, Quality, Efficiency, Demand, Legislation, Logistics, Training, Customization, Coordination and Commoditization.
- **Standardization indirectly influences –** Sustainability, Safety and Research.
- **Standardization gets directly influenced by –** Cost, Time, Quality, Demand, Legislation, Logistics, Customization, Coordination, Commoditization and Research.
- **Standardization gets indirectly influenced by –** Efficiency, Sustainability, Safety and Training.

b. Implications

Standardization, as a Critical Success Factor (CSF), has a profound impact on affordable housing projects. It streamlines production, minimizes waste, shortens timelines, and enhances quality by ensuring consistent high-quality materials and practices. It also promotes efficiency, feasibility, and attractiveness to developers. However, it also presents challenges such as the need for flexible design adaptations within established parameters and the need for enhanced communication across the construction process chain.

In the context of MMT's installation and development projects, this data can be utilized to reduce expenses, ensure uniformity and safety, streamline production, and reduce variability. It can also aid in promoting standardization leading to efficiency gains and cost reduction, and advancing material efficiency and construction techniques to ensure efficiency. This understanding can contribute to the delivery of diverse and specific affordable housing solutions.

4.4.15 CSF15: Research

a. Inter-relativity of the CSFs

- **Research directly influences –** Cost, Time, Quality, Efficiency, Sustainability, Legislation, Safety, Training, Customization, Coordination, Commoditization and Standardization.
- **Research indirectly influences –** Demand and Logistics.
- **Research gets directly influenced by –** Cost, Demand, Sustainability, Legislation, Safety, Customization, Coordination and Commoditization.
- **Research gets indirectly influenced by –** Time, Quality, Efficiency, Logistics, Training and Standardization.

b. Implications

Research, as a Critical Success Factor (CSF), significantly influences affordable housing projects. It lowers costs by finding more efficient processes, reduces duration by optimizing design and installation, and enhances quality through innovation. It also drives demand by making affordable living an attractive option and enhances sustainability by promoting renewable material usage.

In the context of MMT's installation and development projects, this data can be utilized to study available resources and technological innovations, determine feasibility, sustainability and cost-effectiveness, and drive the need for innovation. It can also aid in reducing carbon footprint, determining regulatory policies, and fostering innovation to ensure compatibility and scalability. This understanding can contribute to the delivery of diverse and specific affordable housing solutions.

CHAPTER 5: CONCLUSION AND FUTURE RESEARCH

5.1 Summary of outputs

The challenge of escalating housing shortages presents a significant hurdle for the United States, complicating the delivery of Affordable Housing (AH). Concurrently, the construction sector has been traditionally slow in adopting innovative construction methodologies that promise enhanced cost-efficiency and effectiveness. Recent advancements in Offsite Construction techniques, particularly Modular Mass Timber (MMT) Construction, represent a progressive stride towards resolving these issues. Despite MMT's potential across various construction projects, its advantages have yet to be fully realized within the affordable housing sector. Literature indicates that MMT could address numerous affordable housing challenges through its superior speed, cost-efficiency, sustainability, and quality. This study, therefore, employs a multifaceted approach comprising systematic literature reviews, semi-structured expert interviews, and Total Interpretive Structural Modelling (TISM) to explore the Critical Success Factors (CSFs) influencing MMT adoption in affordable housing. From the literature and expert interviews, multiple factors were identified and categorized into fifteen clusters: cost, time, quality, efficiency, demand, sustainability, legislation, safety, Logistics, training, customization, coordination, commoditization, standardization and research, leading to the creation of a level partitioning matrix with a three-level hierarchy. This matrix was further elucidated through a MICMAC analysis and a TISM Model. The analysis reveals:

Sustainability (CSF6), positioned with coordinates (12,14), displays a notable influence with considerable dependency, ranking it at Level 3 within the level partitioning. This placement suggests that while sustainability is shaped by various project elements, it concurrently holds significant sway over the project's long-term success and environmental compatibility. In practice, embedding sustainability into the project's core strategy is crucial, ensuring it both influences and aligns with other critical factors for enduring project outcomes.

Logistics (CSF9), marked at (14, 15), is categorized under Level 2, indicating its critical role as both a dependent and a driving force within the project. This duality highlights logistics as a keystone factor that, while being affected by project dynamics, significantly dictates the efficiency and flow of project operations. Operationally, emphasizing a cohesive logistics strategy is paramount, optimizing the movement of resources and information to bolster project execution

Time, Quality, Efficiency, each noted at (15, 14), alongside other CSFs at (15,15), are identified at Level 1. These factors are foundational, exerting substantial influence on the project with minimal external impact on them. The operational takeaway here is the imperative of prioritizing these factors from the project's inception. Effective management of time, adherence to quality standards, and operational efficiency are non-negotiable for catalyzing the success of interconnected project elements, ensuring smooth and effective project progression.

The specific insights into factors such as Sustainability, Logistics, and Time, Quality, Efficiency highlight their critical roles and the nuanced interplay between driving and dependency powers. The low dependence power and comparatively significant driving power for CSF Sustainability, the high driving power of Logistics and the balanced influence and dependence of the remaining CSFs underscore the need for strategic planning and integrated project management practices that can navigate the complexities of these interrelations. Implementation strategies to enhance MMT adoption in affordable housing was proposed, addressing the key stakeholders and strategies for boosting the success of MMT adoption in affordable housing with respect to the Critical Success Factors (CSFs), their significance, and strategies for adoption enhancement.

The study's contributions are manifold, spanning theoretical innovations and practical implications. Theoretically, it presents a comprehensive understanding and novel integration of CSFs towards the Installation of MMT in affordable housing, this extends classification of critical success factors into fifteen clusters for a deeper understanding, develops a transparent TISM-based framework illustrating interactions among these factors, and contributes implementation strategies for fostering MMT adoption in affordable housing. Practically, it outlines critical success factors and key domains for MMT adoption in affordable housing, facilitating empirical research into the inter-relativity, hierarchies and distribution of impact of these factors, enhances stakeholders' resource allocation strategies at the installation, and informs policy development for affordable housing promotion.

Despite these contributions, the study acknowledges limitations such as the need for further empirical validation of the TISM model and suggests future research directions including wider stakeholder surveys and additional individual factor analyses to refine the understanding of critical success factor relationships in MMT adoption towards the affordable housing. This research lays a foundation for leveraging modern construction methods like MMT to foster inclusive and cohesive communities, addressing the pressing need for affordable housing in the US.

This research thesis has delved deeply into the nexus of Modular Mass Timber (MMT) adoption for affordable housing in the U.S., with a particular focus on identifying and analyzing the Critical Success Factors (CSFs). By employing a robust methodological framework that included a comprehensive literature review, expert interviews, case study analysis, MICMAC Analysis, and TISM research method, this study has provided a granular understanding of the challenges and opportunities associated with MMT. This culminated in the development of a TISM Model of Critical Success Factors, and implementation strategies aimed at facilitating the broader adoption of MMT in the affordable housing sector.

5.2 Body of knowledge contributions – CSF6

To demonstrate one of the applications of this study, this section offers an in-depth examination of the role of sustainability - one of the Critical Success Factors (CSFs) in the application of Modular Mass Timber (MMT) for affordable housing projects. It synthesizes theoretical foundations from extensive literature reviews with practical insights from industry leaders, serving as a pivotal guide for future installers, construction practitioners, and researchers. This part of the study specifically focuses on understanding how sustainability, as a critical success factor, influences and is influenced by other factors in the project ecosystem. It provides a structured approach to identifying strategies that enhance sustainability's impact on project success, involving key stakeholders in the process to ensure the realization of affordable housing goals through MMT.

As per the comprehensive literature review, the construction sector is acknowledged as a significant contributor to global climate change, underscoring the imperative for adopting energy-efficient construction methodologies that align with the United Nations' Sustainable Development Goals (SDGs). Within this context, MMT stands out as a transformative approach towards more sustainable building practices. As demonstrated in the literature, MMT offers several environmental benefits, including the reduction of project delivery times through concurrent engineering principles (Wuni and Shen 2023), a decrease in carbon and toxic emissions (AIA 2023; Liebetanz Kai 2022), and a significant cut in greenhouse gas emissions by 69% (216 kgCO2e/m2), as highlighted by (Himes Austin 2020). Furthermore, the adoption of off-site modular construction methods contributes to an up to 83.2% reduction in waste generation (Loizou et al. 2021). The potential for mass timber to replace conventional, carbon-intensive construction materials in a considerable portion of new urban construction projects could offset up to 9% of the global emissions reduction required to meet the 2030 climate targets (Himes Austin 2020), underscoring the pivotal role of sustainability in the adoption of MMT.

Through the lens of the MICMAC analysis and the TISM Model, sustainability emerges as a factor with notable influence and dependency, positioned at Level 3 within the analysis. This strategic placement suggests that while sustainability is influenced by various elements of a project, it also exerts significant influence over the project's long-term success and its alignment with environmental objectives. The analysis underlines the importance of embedding sustainability at the core of the project's strategy, thereby ensuring it acts as both an influencer and an outcome in harmony with other critical factors for lasting project achievements.

This detailed focus on sustainability not only showcases its integral role in the broader context of MMT in affordable housing but also illustrates the systematic strategies that can be employed to enhance its positive impact. By prioritizing sustainability, this thesis outlines a roadmap for leveraging MMT in a way that not only addresses housing affordability but also contributes to global sustainability efforts, aligning construction practices with pressing environmental goals.

5.3 Conclusion

The study meticulously identified and analyzed fifteen CSFs essential for the successful installation of MMT in affordable housing projects. These factors were analyzed for their interdependencies and influence on project outcomes concerning cost, time, quality, sustainability, and regulatory compliance, among others. The TISM Model depicts the inter-dependency and implementation strategies developed offers actionable insights and a systematic approach for enhancing MMT adoption, positioning it as a pivotal resource for developers, industry practitioners, policy makers and academic researchers.

The conclusions drawn from this research underscore the multifaceted nature of MMT adoption in affordable housing. It elucidates that while MMT presents a promising avenue for sustainable construction and housing affordability, its success is contingent upon a holistic approach that addresses technical, economic, regulatory, and social dimensions. Implementation strategies proposed not only aids in navigating these complexities but also underscores the criticality of collaborative efforts among various stakeholders for the successful integration of MMT into mainstream construction practices.

5.4 Research Contributions

This thesis makes several significant contributions to the field:

- It provides a comprehensive understanding and analysis of the Critical Success Factors (CSFs) towards the Modular Mass Timber adoption in Affordable Housing, grounded in empirical evidence and rigorous analysis. These CSFs represents an element that is necessary to accomplish a successful affordable housing project using MMT.
- The MICMAC analysis alongside the TISM (Total Interpretive Structural Modeling) Model provides a comprehensive understanding of how the 15 identified Critical Success Factors (CSFs) are interlinked and influence each other. This network of relationships acts as an invaluable tool for future project implementers and developers, offering a strategic guide for effective resource allocation and project planning. By highlighting the complex interdependencies and varying levels of influence among these factors, the analysis facilitates the development of a methodical strategy. This strategy involves engaging key stakeholders and adopting tailored approaches to enhance project outcomes in relation to each specific factor. The insights gained from this interconnected framework enable a more nuanced and effective approach to project management, ensuring a higher likelihood of success in the implementation of initiatives.
- This research melds theoretical insights derived from comprehensive literature reviews with practical knowledge shared by industry veterans, effectively closing a

significant divide. It lays down a solid groundwork that fosters both academic discourse and real-world application in the realms of sustainable and cost-effective housing solutions. This approach not only enriches the academic field with nuanced, real-world perspectives but also equips practitioners with evidence-based strategies to tackle housing challenges effectively, marking a step forward in developing accessible housing.

5.5 Future Research Areas

Building upon the findings of this thesis, future research could explore several promising avenues:

- An empirical validation of the implementation strategies through pilot projects or longitudinal studies to assess its impact on MMT adoption rates. There are a few limitations of the study, firstly the validity of the TISM model will be further improved once more empirical information can be included through case studies or pilot projects. In future studies, survey will be conducted via wider relevant stakeholders. In addition, further analysis, such as fuzzy and sensitivity analysis (Khan et al. 2022), shall be conducted to further examine the relationship between the drivers.
- This research advocates for a thorough exploration of the socio-economic impacts that Modular Manufacturing Technology (MMT) brings to affordable housing projects. It focuses on understanding how MMT influences community well-being and ensures the sustainability of housing affordability over time. Looking ahead, the study proposes an extensive examination of MMT's deployment in multifamily housing settings. This future research will assess potential cost reductions and the technology's flexibility in adapting to diverse architectural designs. It will also consider the efficiency of transportation logistics, the implementation of optimal management practices, and the role of specialized research and training initiatives. By undertaking this multifaceted analysis, the aim is to uncover deeper insights into how MMT can be effectively integrated into affordable housing strategies, thereby contributing to both economic savings and enhanced living standards.
- Examination of the role of digital technologies [e.g., Building Information and Modelling (BIM), Artificial Intelligence (AI)] in enhancing the design, production, and

assembly processes of MMT, potentially unlocking new efficiencies and innovations. the integration of digital tools and platforms emerges as a vital enabler for enhancing stakeholder coordination. The application of Building Information Modeling (BIM) alongside other project management software fosters real-time communication, coordination, and information sharing, equipping stakeholders with the ability to visualize project progress, pre-empt potential hurdles, and make well-informed decisions. Alongside innovations in timber-based materials, BIM technology serves as a conduit for testing and coordinating diverse actors and project phases. Additionally, modern methods of construction (MMCs) like computer numerical control (CNC) cutting, 3D printing, and radiofrequency monitoring of constructive components throughout their lifespan present novel opportunities to merge features and trades with minimized ecological footprint (Hannah and Hunter 2018). Further, the role of Artificial Intelligence (AI) in construction engineering and management has become the current research focus. AI's main benefits includes modelling and pattern detection, prediction, and optimization (Pan and Zhang 2021). In conclusion, this research paves the way for in-depth exploration into how digital technologies, such as Building Information and Modelling (BIM) and Artificial Intelligence (AI), can significantly improve the design, production, and assembly processes in MMT. By leveraging these advancements, there is a promising potential to achieve new levels of efficiency and innovation.

- This study offers a comprehensive examination of the critical success factors (CSFs) relevant to the implementation of Modular Manufacturing Technology (MMT) within the affordable housing sector. As a contribution to the future scope, it proposes the development of tailored implementation strategies for each CSF. By delving deeper into these factors and identifying their sub - key performance indicators, the research aims to establish a structured hierarchy of impact. This approach will intend to prioritize these factors, creating a rubric that outlines effective strategies for individual factor. Such strategies are designed to enhance project efficiency significantly by utilizing the strengths of each identified success factor. This methodology will not only clarify the pathway towards leveraging MMT for affordable housing projects but also open avenues for further detailed investigations into optimizing and capitalizing on these critical success factors for improved outcomes.

5.6 Discussion on the Research Impact

The impact of this research is manifold. It not only contributes to advancing academic knowledge in the field of sustainable construction and affordable housing but also serves as a catalyst for effective installation and project management. By providing a clear and actionable implementation strategies, it encourages a more coherent and unified approach towards the Installation of MMT, potentially leading to significant sustainability, economic, and social benefits. Moreover, the emphasis on stakeholder collaboration and research underscores the potential for MMT to act as a linchpin in the transition towards more sustainable and equitable housing development.

Through the diligent endeavors and significant results of this study, I envisage a future where sustainable and accessible housing solutions address the critical demand for shelter while making a meaningful contribution to the Sustainable Development Goals. This vision underscores the paramount importance of my collective commitment to advancing housing accessibility and environmental stewardship for a more equitable and sustainable world.

5.7 Summary

In essence, this thesis presents a thorough investigation into the critical success factors influencing the adoption of Modular Mass Timber in affordable housing, underscored by a implementation strategies aimed at bolstering MMT's integration into the housing market. The insights gleaned from this research offer valuable guidelines for stakeholders across the construction ecosystem, setting the stage for future inquiries and practical endeavors aimed at realizing the full potential of MMT in addressing the pressing challenges of sustainability and affordability in housing. This work stands as a testament to the complex yet rewarding journey towards sustainable and affordable housing development, heralding a new era of construction that is both innovative and inclusive.

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APPENDIX A: INTERVIEW SCRIPT

Introducing myself, I am Kaustubh Thakare, a second-year graduate student pursuing a master's degree in construction management at Michigan State University. My research focus centers on the utilization of Modular Mass Timber technology for affordable housing in the United States. The aim of my thesis is to gather insights from industry experts like yourself to develop a structured rubric and establish key performance indicators essential for the successful execution of affordable building projects employing Modular Mass Timber technology.

To begin our interview, first I would like to ask a few questions regarding the subject's involvement in this industry and his/her background,

- What are your qualifications or job title or professional involvement in the construction industry related to modular/mass timber/ both projects?
- How many Modular/Mass Timber/Both construction projects have you been involved in throughout your career?
- What geographic scope or region falls under your professional responsibilities or expertise?

Interview Questions in General

1. Reflecting on the past successful Modular/Mass Timber projects you have undertaken, what were the Critical Success Factors that contributed significantly to the overall success of those initiatives?
2. What construction process considerations, including challenges and opportunities, are specific to the affordable housing projects when utilizing modular/mass timber?
3. Could you discuss the usual difficulties faced and specific adaptations required in context of the production and installation of modular/mass timber components for housing projects?
4. Have you identified particular strategies or practices that could potentially enhance the efficiency of construction and assembly when utilizing modular/mass timber?
5. In general, how can the project team navigate local building codes and regulations related to modular construction and mass timber?

6. Looking ahead, what do you see as the future prospects and challenges for the adoption of modular/mass timber in addressing affordable housing needs in the USA?
7. What are your perspectives on the interrelated dynamics among different Critical Success Factors in projects, such as Cost, Time, Quality, Efficiency, Demand, Sustainability, Social aspects, and Legislation?

Thank you for your insights. Your responses will contribute to a better understanding of the modular mass timber construction industry and its potential to address the affordable housing demand. If you have any additional comments or recommendations, please feel free to share them.

APPENDIX B: IRB APPROVAL

MICHIGAN STATE UNIVERSITY

EXEMPT DETERMINATION
Revised Common Rule

October 27, 2023

To: George H Berghorn

Re: **MSU Study ID:** STUDY00009830
Principal Investigator: George H Berghorn
Category: Exempt 2(ii)
Exempt Determination Date: 10/27/2023
Limited IRB Review: Not Required.

Title: Critical Success Factors for Modular Mass Timber Projects for Affordable Housing Development

Funding Source: National Housing Endowment
Funding Title: 2018 HELP- MSU Construction Management Program
Funding Status: Funded

This study has been determined to be exempt under 45 CFR 46.104(d) 2(ii).

Principal Investigator (PI) Responsibilities: The PI assumes the responsibilities for the protection of human subjects in this study as outlined in Human Research Protection Program (HRPP) Manual Section 8-1, Exemptions.

Continuing Review: Exempt studies do not need to be renewed.

Modifications: In general, investigators are not required to submit changes to the Michigan State University (MSU) Institutional Review Board (IRB) once a research study is designated as exempt as long as those changes do not affect the exempt category or criteria for exempt determination (changing from exempt status to expedited or full review, changing exempt category) or that may substantially change the focus of the research study such as a change in hypothesis or study design. See HRPP Manual Section 8-1, Exemptions, for examples. If the study is modified to add additional sites for the research, please note that you may not begin the research at those sites until you receive the appropriate approvals/permissions from the sites.

Please contact the HRPP office if you have any questions about whether a change must be submitted for IRB review and approval.

New Funding: If new external funding is obtained for an active study that had been determined exempt, a new initial IRB submission will be required, with limited exceptions. If you are unsure if a new initial IRB submission is required, contact the HRPP office. IRB review of the new submission must be completed before new

Office of Regulatory Affairs
Human Research Protection Program

4000 Collins Road
Suite 136
Lansing, MI 48910

517-355-2180
Fax: 517-432-4503
Email: irb@msu.edu
www.hrpp.msu.edu

funds can be spent on human research activities, as the new funding source may have additional or different requirements.

Reportable Events: If issues should arise during the conduct of the research, such as unanticipated problems that may involve risks to subjects or others, or any problem that may increase the risk to the human subjects and change the category of review, notify the IRB office promptly. Any complaints from participants that may change the level of review from exempt to expedited or full review must be reported to the IRB. Please report new information through the study's workspace and contact the IRB office with any urgent events. Please visit the Human Research Protection Program (HRPP) website to obtain more information, including reporting timelines.

Personnel Changes: After determination of the exempt status, the PI is responsible for maintaining records of personnel changes and appropriate training. The PI is not required to notify the IRB of personnel changes on exempt research. However, he or she may wish to submit personnel changes to the IRB for recordkeeping purposes (e.g. communication with the Graduate School) and may submit such requests by submitting a Modification request. If there is a change in PI, the new PI must confirm acceptance of the PI Assurance form and the previous PI must submit the Supplemental Form to Change the Principal Investigator with the Modification request (available at hrpp.msu.edu).

Closure: Investigators are not required to notify the IRB when the research study can be closed. However, the PI can choose to notify the IRB when the study can be closed and is especially recommended when the PI leaves the university. Closure indicates that research activities with human subjects are no longer ongoing, have stopped, and are complete. Human research activities are complete when investigators are no longer obtaining information or biospecimens about a living person through interaction or intervention with the individual, obtaining identifiable private information or identifiable biospecimens about a living person, and/or using, studying, analyzing, or generating identifiable private information or identifiable biospecimens about a living person.

For More Information: See HRPP Manual, including Section 8-1, Exemptions (available at hrpp.msu.edu).

Contact Information: If we can be of further assistance or if you have questions, please contact us at 517-355-2180 or via email at IRB@msu.edu. Please visit hrpp.msu.edu to access the HRPP Manual, templates, etc.

Exemption Category. The full regulatory text from 45 CFR 46.104(d) for the exempt research categories is included below. [1234]

Exempt 1. Research, conducted in established or commonly accepted educational settings, that specifically involves normal educational practices that are not likely to adversely impact students' opportunity to learn required educational content or the assessment of educators who provide instruction. This includes most research on regular and special education instructional strategies, and research on the effectiveness of or the comparison among instructional techniques, curricula, or classroom management methods.

Exempt 2. Research that only includes interactions involving educational tests (cognitive, diagnostic, aptitude, achievement), survey procedures, interview procedures, or observation of public behavior (including visual or auditory recording) if at least one of the following criteria is met:

(i) The information obtained is recorded by the investigator in such a manner that the identity of the human subjects cannot readily be ascertained, directly or through identifiers linked to the subjects;

(ii) Any disclosure of the human subjects' responses outside the research would not reasonably place the subjects at risk of criminal or civil liability or be damaging to the subjects' financial standing, employability, educational advancement, or reputation; or

(iii) The information obtained is recorded by the investigator in such a manner that the identity of the human subjects can readily be ascertained, directly or through identifiers linked to the subjects, and an IRB conducts a limited IRB review to make the determination required by 45 CFR 46.111(a)(7).

Exempt 3. (i) Research involving benign behavioral interventions in conjunction with the collection of information from an adult subject through verbal or written responses (including data entry) or audiovisual recording if the subject prospectively agrees to the intervention and information collection and at least one of the following criteria is met:

(A) The information obtained is recorded by the investigator in such a manner that the identity of the human subjects cannot readily be ascertained, directly or through identifiers linked to the subjects;

(B) Any disclosure of the human subjects' responses outside the research would not reasonably place the subjects at risk of criminal or civil liability or be damaging to the subjects' financial standing, employability, educational advancement, or reputation; or

(C) The information obtained is recorded by the investigator in such a manner that the identity of the human subjects can readily be ascertained, directly or through identifiers linked to the subjects, and an IRB conducts a limited IRB review to make the determination required by 45 CFR 46.111(a)(7).

(ii) For the purpose of this provision, benign behavioral interventions are brief in duration, harmless, painless, not physically invasive, not likely to have a significant adverse lasting impact on the subjects, and the investigator has no reason to think the subjects will find the interventions offensive or embarrassing. Provided all such criteria are met, examples of such benign behavioral interventions would include having the subjects play an online game, having them solve puzzles under various noise conditions, or having them decide how to allocate a nominal amount of received cash between themselves and someone else.

(iii) If the research involves deceiving the subjects regarding the nature or purposes of the research, this exemption is not applicable unless the subject authorizes the deception through a prospective agreement to participate in research in circumstances in which the subject is informed that he or she will be unaware of or misled regarding the nature or purposes of the research.

Exempt 4. Secondary research for which consent is not required: Secondary research uses of identifiable private information or identifiable biospecimens, if at least one of the following criteria is met:

(i) The identifiable private information or identifiable biospecimens are publicly available;

(ii) Information, which may include information about biospecimens, is recorded by the investigator in such a manner that the identity of the human subjects cannot readily be ascertained directly or through identifiers linked to the subjects, the investigator does not contact the subjects, and the investigator will not re-identify subjects;

(iii) The research involves only information collection and analysis involving the investigator's use of identifiable health information when that use is regulated under 45 CFR parts 160 and 164, subparts A and E, for the purposes of ``health care operations'' or ``research'' as those terms are defined at 45 CFR 164.501 or for ``public health activities and purposes'' as described under 45 CFR 164.512(b); or

(iv) The research is conducted by, or on behalf of, a Federal department or agency using government-generated or government-collected information obtained for nonresearch activities, if the research generates identifiable private information that is or will be maintained on information technology that is subject to and in compliance with section 208(b) of the E-Government Act of 2002, 44 U.S.C. 3501 note, if all of the identifiable private information collected, used, or generated as part of the activity will be maintained in systems of records subject to the Privacy Act of 1974, 5 U.S.C. 552a, and, if applicable, the information used in the research was collected subject to the Paperwork Reduction Act of 1995, 44 U.S.C. 3501 et seq.

Exempt 5. Research and demonstration projects that are conducted or supported by a Federal department or agency, or otherwise subject to the approval of department or agency heads (or the approval of the heads of bureaus or other subordinate agencies that have been delegated authority to conduct the research and demonstration projects), and that are designed to study, evaluate, improve, or otherwise examine public benefit or service programs, including procedures for obtaining benefits or services under those programs, possible changes in or alternatives to those programs or procedures, or possible changes in methods or levels of payment for benefits or services under those programs. Such projects include, but are not limited to, internal studies by Federal employees, and studies under contracts or consulting arrangements, cooperative agreements, or grants. Exempt projects also include waivers of otherwise mandatory requirements using authorities such as sections 1115 and 1115A of the Social Security Act, as amended. (i) Each Federal department or agency conducting or supporting the research and demonstration projects must establish, on a publicly accessible Federal Web site or in such other manner as the department or agency head may determine, a list of the research and demonstration projects that the Federal department or agency conducts or supports under this provision. The research or demonstration project must be published on this list prior to commencing the research involving human subjects.

Exempt 6. Taste and food quality evaluation and consumer acceptance studies: (i) If wholesome foods without additives are consumed, or (ii) If a food is consumed that contains a food ingredient at or below the level and for a use found to be safe, or agricultural chemical or environmental contaminant at or below the level found to be safe, by the Food and Drug Administration or approved by the Environmental Protection Agency or the Food Safety and Inspection Service of the U.S. Department of Agriculture.

Exempt 7. Storage or maintenance for secondary research for which broad consent is required: Storage or maintenance of identifiable private information or identifiable biospecimens for potential secondary research use if an IRB conducts a limited IRB review and makes the determinations required by 45 CFR 46.111(a)(8).

Exempt 8. Secondary research for which broad consent is required: Research involving the use of identifiable private information or identifiable biospecimens for secondary research use, if the following criteria are met:

(i) Broad consent for the storage, maintenance, and secondary research use of the identifiable private information or identifiable biospecimens was obtained in accordance with 45 CFR 46.116(a)(1) through (4), (a)(6), and (d);

(ii) Documentation of informed consent or waiver of documentation of consent was obtained in accordance with 45 CFR 46.117;

(iii) An IRB conducts a limited IRB review and makes the determination required by 45 CFR 46.111(a)(7) and makes the determination that the research to be conducted is within the scope of the broad consent referenced in paragraph (d)(8)(i) of this section; and

(iv) The investigator does not include returning individual research results to subjects as part of the study plan. This provision does not prevent an investigator from abiding by any legal requirements to return individual research results.

[1]Exempt categories (1), (2), (3), (4), (5), (7), and (8) cannot be applied to activities that are FDA-regulated.

[2] Each of the exemptions at this section may be applied to research subject to subpart B (Additional Protections for Pregnant Women, Human Fetuses and Neonates Involved in Research) if the conditions of the exemption are met.

[3] The exemptions at this section do not apply to research subject to subpart C (Additional Protections for Research Involving Prisoners), except for research aimed at involving a broader subject population that only incidentally includes prisoners.

[4] Exemptions (1), (4), (5), (6), (7), and (8) of this section may be applied to research subject to subpart D (Additional Protections for Children Involved as Subjects in Research) if the conditions of the exemption are met. Exempt (2)(i) and (ii) only may apply to research subject to subpart D involving educational tests or the observation of public behavior when the investigator(s) do not participate in the activities being observed. Exempt (2)(iii) may not be applied to research subject to subpart D.

APPENDIX C: DATA COLLECTION SURVEY FORM

Inter-Relativity Matrix

'**Critical Success Factors (CSFs) in Adoption of Modular Mass Timber Installation**'.

thakaustubh@gmail.com Switch accounts

Not shared

COST

Please select how the COST Factor is related to the following Factors

	Influences	Get Influenced by	No Influence	Mutual Influence
Research	☐	☐	☐	☐
Standardisation	☐	☐	☐	☐
Coordination	☐	☐	☐	☐
Training	☐	☐	☐	☐
Logistics	☐	☐	☐	☐
Safety	☐	☐	☐	☐
Building Codes	☐	☐	☐	☐
Sustainability	☐	☐	☐	☐
Demand	☐	☐	☐	☐
Quality	☐	☐	☐	☐
Time	☐	☐	☐	☐

TIME

Please select how the TIME Factor is related to the following Factors

	Influences	Get Influenced by	No Influence	Mutual Influence
Research	☐	☐	☐	☐
Standardisation	☐	☐	☐	☐
Coordination	☐	☐	☐	☐
Training	☐	☐	☐	☐
Logistics	☐	☐	☐	☐
Safety	☐	☐	☐	☐
Building Codes	☐	☐	☐	☐
Sustainability	☐	☐	☐	☐
Demand	☐	☐	☐	☐
Quality	☐	☐	☐	☐

QUALITY

Please select how the QUALITY Factor is related to the following Factors

	Influences	Get Influenced by	No Influence	Mutual Influence
Research	☐	☐	☐	☐
Standardisation	☐	☐	☐	☐
Coordination	☐	☐	☐	☐
Training	☐	☐	☐	☐
Logistics	☐	☐	☐	☐
Safety	☐	☐	☐	☐
Building Codes	☐	☐	☐	☐
Sustainability	☐	☐	☐	☐
Demand	☐	☐	☐	☐

DEMAND

Please select how the DEMAND Factor is related to the following Factors

	Influences	Get Influenced by	No Influence	Mutual Influence
Research	☐	☐	☐	☐
Standardisation	☐	☐	☐	☐
Coordination	☐	☐	☐	☐
Training	☐	☐	☐	☐
Logistics	☐	☐	☐	☐
Safety	☐	☐	☐	☐
Building Codes	☐	☐	☐	☐
Sustainability	☐	☐	☐	☐

SUSTAINABILITY

Please select how the SUSTAINABILITY Factor is related to the following Factors

	Influences	Get Influenced by	No Influence	Mutual Influence
Research	☐	☐	☐	☐
Standardisation	☐	☐	☐	☐
Coordination	☐	☐	☐	☐
Training	☐	☐	☐	☐
Logistics	☐	☐	☐	☐
Safety	☐	☐	☐	☐
Building Codes	☐	☐	☐	☐

LEGISLATION - Building Codes

Please select how the LEGISLATION Factor is related to the following Factors

	Influences	Get Influenced by	No Influence	Mutual Influence
Research	☐	☐	☐	☐
Standardisation	☐	☐	☐	☐
Coordination	☐	☐	☐	☐
Training	☐	☐	☐	☐
Logistics	☐	☐	☐	☐
Safety	☐	☐	☐	☐

SAFETY

Please select how the SAFETY Factor is related to the following Factors

	Influences	Get Influenced by	No Influence	Mutual Influence
Research	☐	☐	☐	☐
Standardisation	☐	☐	☐	☐
Coordination	☐	☐	☐	☐
Training	☐	☐	☐	☐
Logistics	☐	☐	☐	☐

LOGISTICS

Please select how the LOGISTICS Factor is related to the following Factors

	Influences	Get Influenced by	No Influence	Mutual Influence
Research	☐	☐	☐	☐
Standardisation	☐	☐	☐	☐
Coordination	☐	☐	☐	☐
Training	☐	☐	☐	☐

TRAINING

Please select how the TRAINING Factor is related to the following Factors

	Influences	Get Influenced by	No Influence	Mutual Influence
Research	☐	☐	☐	☐
Standardisation	☐	☐	☐	☐
Coordination	☐	☐	☐	☐

COORDINATION

Please select how the COORDINATION Factor is related to the following Factors

	Influences	Get Influenced by	No Influence	Mutual Influence
Research	☐	☐	☐	☐
Standardisation	☐	☐	☐	☐

STANDARDISATION

Please select how the COORDINATION Factor is related to the following Factors

	Influences	Get Influenced by	No Influence	Mutual Influence
Research	☐	☐	☐	☐

Any comment/feedback for improvisation?

Your answer

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