IDENTIFICATION OF CRITICAL SUCCESS FACTORS FOR MANUFACTURING OF MODULAR MASS TIMBER FOR AFFORDABLE HOUSING IN THE US

By

Shreya Rajendra Ghodekar

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ABSTRACT

This thesis explores the affordability of housing through the lens of modular mass timber technology, specifically Cross Laminated Timber (CLT). The study is grounded in an investment perspective of affordable housing, considering profitability, marketability, and favorable financing focused on multifamily housing.

The study employs robust methodology, including data collection procedures, semi-structured interviews, and a systematic literature review. Sophisticated statistical methods such as Spearman's Rank Correlation Coefficient and Decision-Making Trial and Evaluation Laboratory (DEMATEL) are utilized to delve into the strength of interrelationships among the identified Critical Success Factors (CSFs) and to investigate cause-effect relationships.

The findings offer valuable insights into common themes, effective project management strategies, the role of standardization, and the critical importance of coordination and collaboration in the industry. These insights inform the creation of a prioritized rubric to guide strategic decisions in the industry.

This thesis presents a systematic examination of the critical success factors influencing the successful manufacturing of modular CLT for affordable housing in the US. It contributes significantly to the field and lays a solid foundation for future research into mass timber modular manufacturing, technological advancements, and construction methods. The research serves as a valuable guide for decision-making and strategy formulation in CLT modular manufacturing.

For Mom and Dad, who always reminded me that words have the power to change the world.

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Go Green! Go White!

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CHAPTER I INTRODUCTION

1.1 Background

1.1.1 Residential Construction in the US

The home building industry is booming in the US and with this exponential growth comes a re-evaluation of what new homebuyers want. Residential construction involves building individual and multi-family housing, which may include single-units, manufactured housing, such as mobile homes and pre-built houses, duplexes, quadplexes, apartment buildings and condominiums. In this $610 billion (about $1,900 per person in the US) industry of residential construction, on average, single-family construction is estimated to account for more than 80% of total permanent site residential structures, with multifamily housing comprising the remainder. Single-family housing construction has decreased as a percentage of total residential construction since it peaked in 2010 ("US Insider Monthly December 2022" 2022). National Association of Home Builders report states that housing's combined contribution to GDP averages from 15-18% involving residential investments in the form of construction of new single family and multi-family structures, residential remodeling, production of manufactured homes, and broker's fees and consumption spending on housing services ranging from 12-13% of GDP("Housing's Contribution to Gross Domestic Product" n.d.). United States Department of Housing and Urban Development announced new residential construction statistics in February 2023 (*US Census Beureau* 2023), where we can compare the annual rate of permitted, newly started, and completed residential project till date.

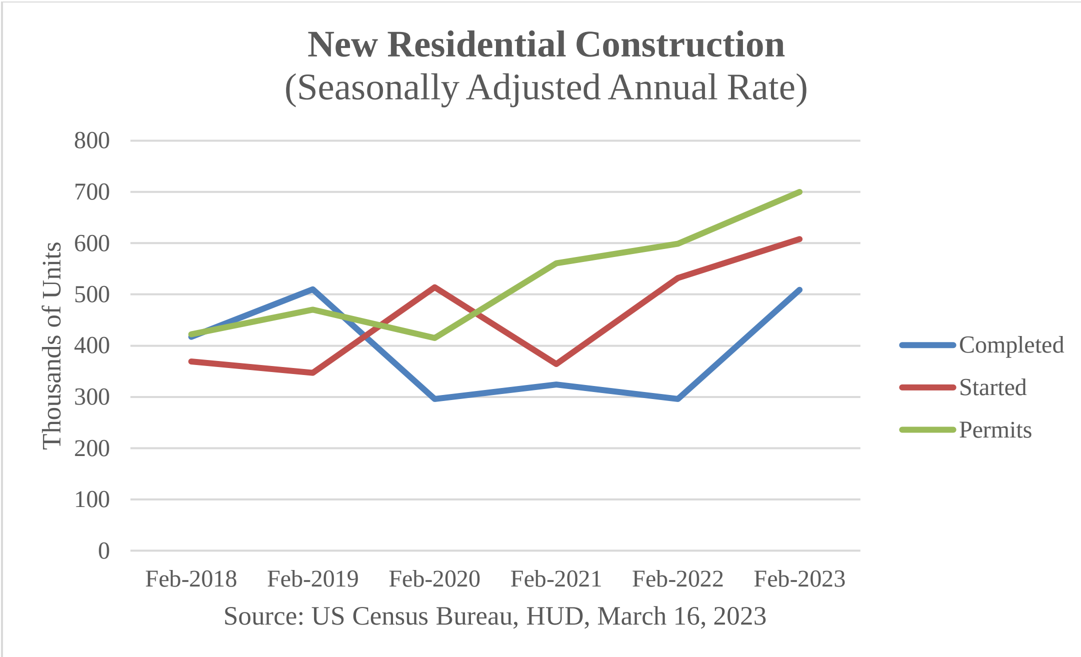

*Figure 1 New Residential Construction in the US (*US Census Beureau *2023)*

According to Forbes, even though housing prices have come down at a reasonable rate in past couple of years, high interest rates coupled with appreciated home values still make it difficult for many prospective buyers to access affordable housing (Millsap 2023).

1.1.2 Aspects of Housing Studies

Housing studies encompass wide range of research topics which typically include housing policies and planning, affordability studies, housing quality and safety, housing and health studies, housing and environment, housing finance and economics, and several other aspects. The affordability of housing aspect examines how housing costs and income are related, the impact of housing costs on households, and strategies to make housing more affordable. In terms of housing affordability, there is a wide variety of data available, which makes it much easier to conduct research and analysis on this topic. As a rule of thumb, data on housing affordability is collected through surveys and administrative records, and it is often made public by the municipalities involved. The concept of affordability varies regionwide. For improving affordability across different countries, new strategies need to be developed in different regions depending on the driving factors in that region. Housing affordability policies being an important public issue, ways need to be found by authorities to inform policy decisions and evaluate the effectiveness of policy interventions. With that said, housing affordability is a critical issue as many households struggle with it due to spending a sizable portion of their household income for housing costs. Because of these factors housing affordability is a popular area of research within the broader field of housing studies.

1.1.3 Affordable Housing and current scenarios in the US

The development of affordable housing has been a major part of the growth. The demand for affordable housing all over the US which would meet the needs of housing crisis has reached its highest peak. Housing affordability is a complex issue that varies greatly across the United States. It's influenced by a variety of factors, including income levels, housing costs, and regional economic conditions. Multifamily housing refers to residential buildings that contain more than one housing unit, such as apartments or condominiums. These types of housing can often be more affordable due to economies of scale in construction and operation, and efficient use of land (Walter and Bruen 2022). According to the US department of Housing & Urban Development, affordable housing is defined as housing on which the occupant is paying no more than 30 percent of gross income for housing costs, including utilities ("Defining Housing Affordability" 2017). This can be interpreted as the "income-based affordability" definition. This standard applies to both rental and owner-occupied housing. Housing programs in the United States have long measured housing affordability in terms of percentage of income. "In the 1940s, the maximum affordable rent for federally subsidized housing was set at 20 percent of income, which rose to 25 percent of income in 1969 and 30 percent of income in 1981. Over time, 30 percent threshold also became the standard for owner-occupied housing, and it remains the indicator of affordability for housing in the United States" ("Defining Housing Affordability" 2017). By developing quality housing and infrastructure, we can enhance people's life expectancy and quality of life. This improvement in living standards can attract investments, which in turn can stimulate economic growth. The nation-wide status of median income ranging from 2015-2019 can be analyzed in the US map of figure 2.

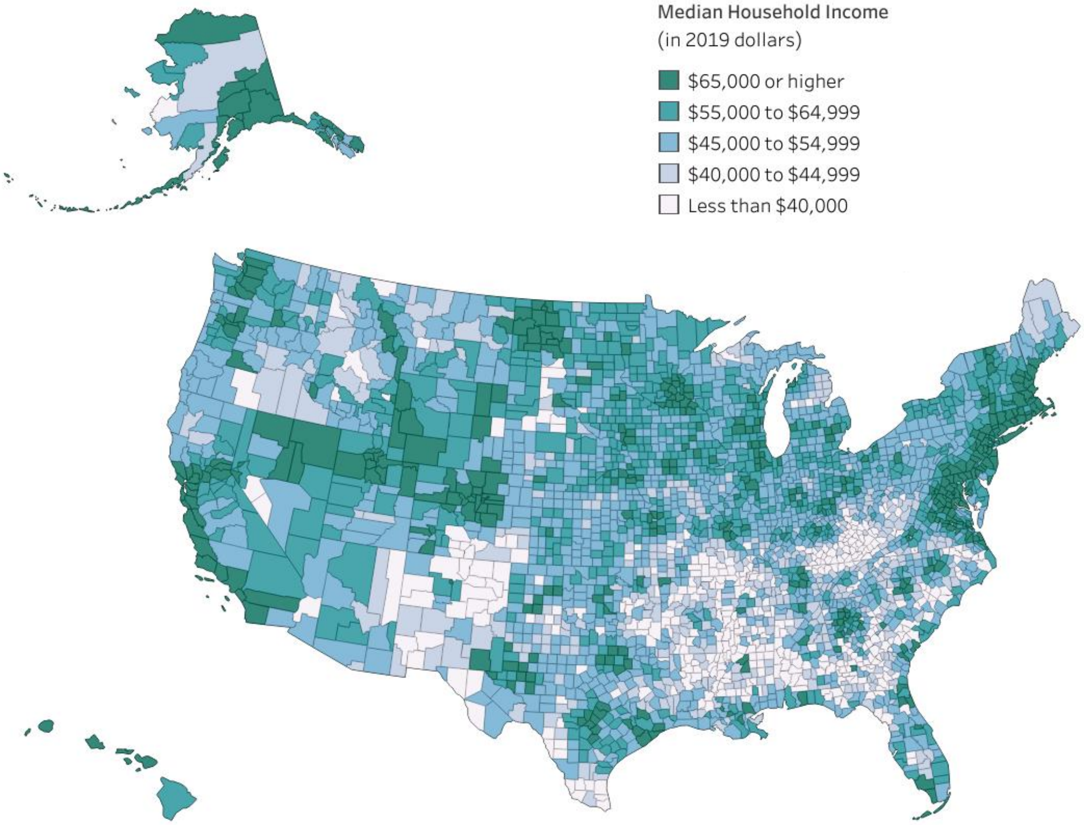

Figure 2 Median Household Income: 2015-2019 ("ACS 5-Year Median Household Income" n.d.)

The two main reasons of government intervention for providing affordable housing is millions of Americans at risk without housings and nonchalant developers due to insufficient returns and complex financing processes ("The Problem" n.d.). The Department of Housing and Urban Development's initiatives such as the Section 8 program, housing vouchers and tax reliefs are not enough considering the projected population growth and needs (Kingsley 2017). Addressing the affordability crisis will require policy solutions that encourage the construction of affordable, multifamily housing. This could include financial incentives for developers, regulatory reforms, and direct investment in affordable housing (Dunn 2022; Walter and Bruen 2022). This shortfall creating unfavorable conditions in the market affects low-income households, the cost of construction, and unavailability of labor. Also resulting in investment challenges as Developers often face financial challenges that disincentivize investment in affordable housing. These can include high land and construction costs, regulatory barriers, and insufficient returns on investment.

Post pandemic years, housing preferences have changed & worsened the housing supply scenarios (McCue 2022). The housing prices increased by 7 to 19 percent year over year though the stock of rental homes & home-for-sale is declining (Bernstein et al. 2021). Most masses were burdened severely nationwide. Figure 3 highlights the regions where there is maximum need for affordable housing. What's considered affordable can vary greatly from one region to another. For example, housing prices in California are typically much higher than in Michigan. Therefore, the income needed to afford housing will also vary across regions.

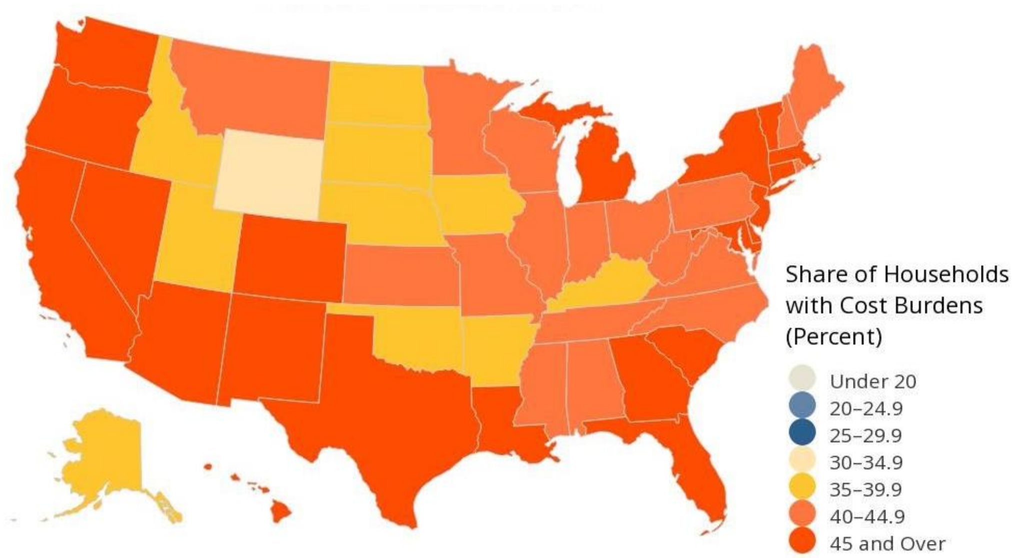

Figure 3 Burdened Renter Households Post Pandemic("Joint Center for Housing Studies" 2023)

Fig.4 & Fig. 5 give us an idea about the supply shortage and increased price pressure in the housing market. The number of affordable units (those with rents less than $1,000 per month) declined by 4.7 million from 2015 to 2020 (Dunn 2022; Walter and Bruen 2022). This loss of affordable housing contributes to the overall affordability crisis The current shortage of close to 6.8 million houses is the reason behind the low pace of housing supply against the population growth ("The Problem" n.d.). This shortage is contributing to the affordability crisis, as high demand and low supply drive up housing prices. The factors such as availability of land parcel, zoning criteria, monetary crisis, racial wealth gap, homeownership market, labor shortage, and hike in cost of building material address the issue of housing demand-supply conflict & the need to build affordable housing(Bernstein et al. 2021).

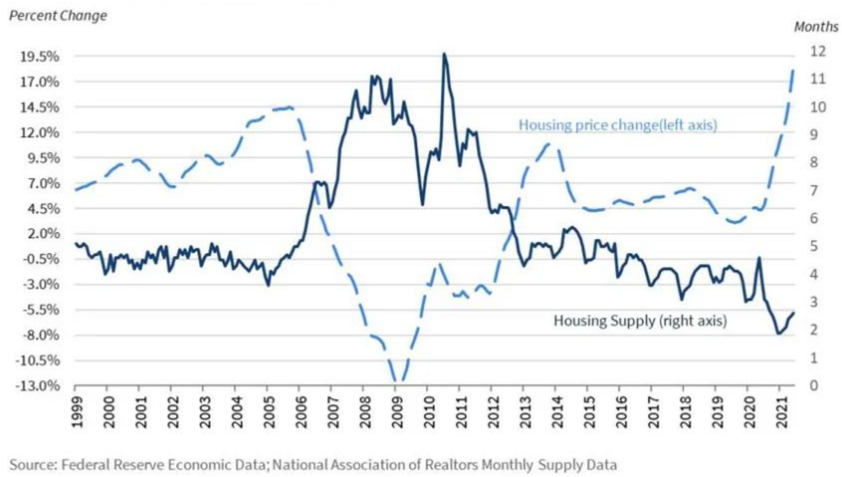

Figure 4 Housing Supply and Prices (Bernstein et al. 2021)

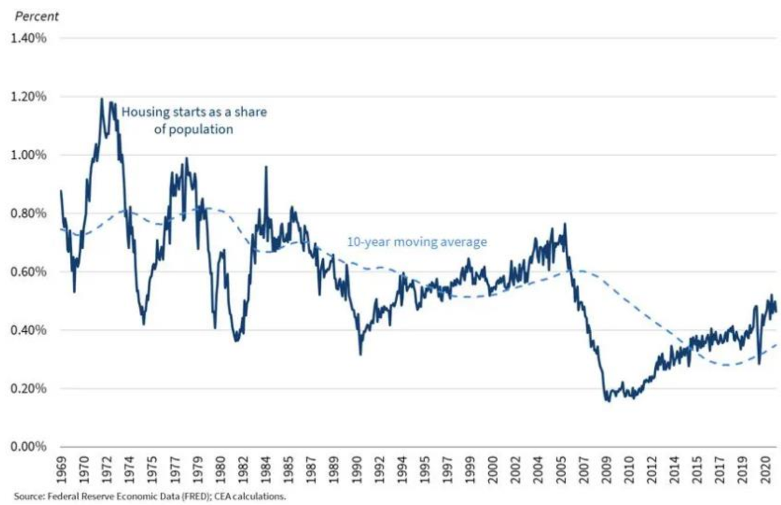

Figure 5 Housing Production and Population Growth (Bernstein et al. 2021)

The study by Thompson J. (2020), suggests that only government initiatives are not enough to solve this nation-wide problem of affordable housing. Modular construction offers a solution to the affordable housing crisis. With expectations of cost and time savings, many developers are now looking forward to the modular construction industry. Innovations and technological developments in modular construction can help developers capitalize in the US affordable housing market (Edmonds et al. 2018).

1.1.4 Modular Construction

Nowadays modular construction practices are used in the construction industry as an alternative to conventional on-site construction for residential homes where building units or modules are mass produced off site in a manufacturing facility (Edmonds et al. 2018). This global modular construction market worth $91 billion as of 2022 is expected to reach $120 billion by 2027("Modular Construction Market Dynamics" 2022). Detailed planned and integrated coordination in the logistic and assembly aspect can offer faster and safer manufacturing, better predictability to completion time, superior quality, less workers on site, less resource wastage, and a more environmentally friendly solution than conventional process (Ferdous et al. 2019). Fig. 6 summarizes the categorization of modular construction market.

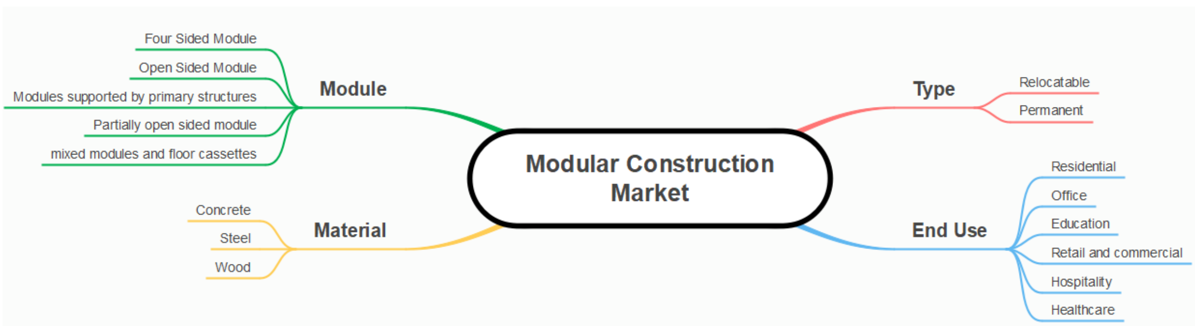

Figure 6 Modular construction market (adapted from ("Modular Construction Market Dynamics" 2022))

To understand modular construction, we first need to understand the production systems for residential industry (refer Table 1). Depending upon the process choice different type of production system with varied capabilities can be chosen (Jonsson and Rudberg 2017).

Table 1 Production System categories (Jonsson and Rudberg 2015)

Component Manufacture and Sub-assembly (CM&SA)	Traditional approach of on-site production of residential building with value adding activities carried out on-site.
Prefabrication and Sub-assembly (PF&SA)	Approach with high prefabrication off-site divided in sub-assemblies and most on-site assembly activities.
Prefabrication and Pre-assembly (PF&PA)	Approach with high degree of prefabrication off-site including some part of off-site pre-assembly.
Modular Building (MB)	High degree of off-site production and assembly of volumetric modules with prominent level of completion off-site.

Depending on degree of standardization ranging from pure customization to pure standardization a matrix was developed by Jonsson and Rudberg (2015) using above forms of production system. Figure 7 represents the matrix to measure performance of production system and suggests that modular building with pure standardization creates an ideal situation with high productivity.

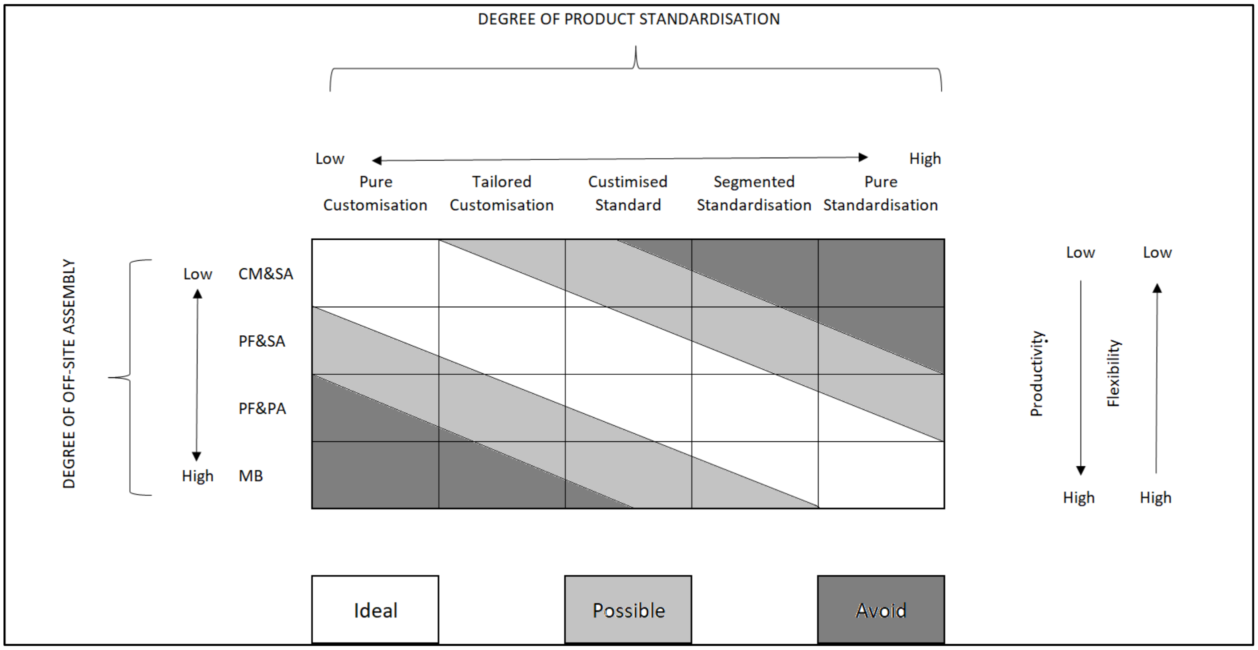

Figure 7 Matrix of production system (adapted from (Jonsson and Rudberg 2017))

Recent studies in modular construction trend leaves both immediate and long-term consequences with primary positive impacts derived from two main characteristics: a) standardization and b) off-site fabrication. Having indistinguishable final design product compared with stereotypes modular construction has limitless design opportunities. Completing 60-90% of work in factory allows to avoid delays in project caused by weather risks (Ortiz 2019).

Modular construction is often undervalued because of the perception among the masses as "manufactured housing" is a low-quality product. Despite various advantages, the usage of actual modular construction is insufficient. Varied interest of organizations within the construction industry differs in process of modular construction adoption (Shin et al, 2022). A few of the reasons behind this lack of adoption are the barriers such as constraints to mass production, front loaded designs, and complicated approval processes. For a modular approach to scale, it requires uniform and repetitive products. Naturally, building types like apartments and hotels with standardized units are candidates for this process. Advancements in technology trying to create distinct and non-repetitive modules are the potential constraints for adapting modular approach.

1.1.5 Mass Timber Construction

The construction sector faces one of its biggest challenges when it comes to building affordable housing. We need fresh solutions that are scalable, durable, energy-efficient, and promote well-being. It is time for us to focus on the next best way to build affordable housing in the quantities needed to provide decent housing and to create a foundation for all other opportunities. Historically timber has been considered as a promising building material due to its structural rigidity, environmental sustainability, and renewability nature. To ensure efficient material utilization and address the wide range of variety of wood products, engineered mass timber products were developed. These products are manufactured to achieve several engineering properties such as strength, durability, and consistency (Ahmed and Arocho 2020). Recently, the modern timber construction industry has evolved in technical terms, especially due to constant growth, nationally and internationally. Timber construction has evolved from an infancy to a well-established market system that can be used for most large-scale buildings, and which is significantly different from the conventional, centuries-old method (Koppelhuber et al. 2017). Buildings have the potential to act as climate change solutions, and mass timber could serve as an economic, social, and environmental solution. Figure 8 explains the rising trend of mass timber projects all over the US. Mass timber is most popularly used on the West Coast of the United States, with moderate popularity observed in the Southwest, Midwest, and Eastern regions. Its usage is least prevalent in the central parts of the country.

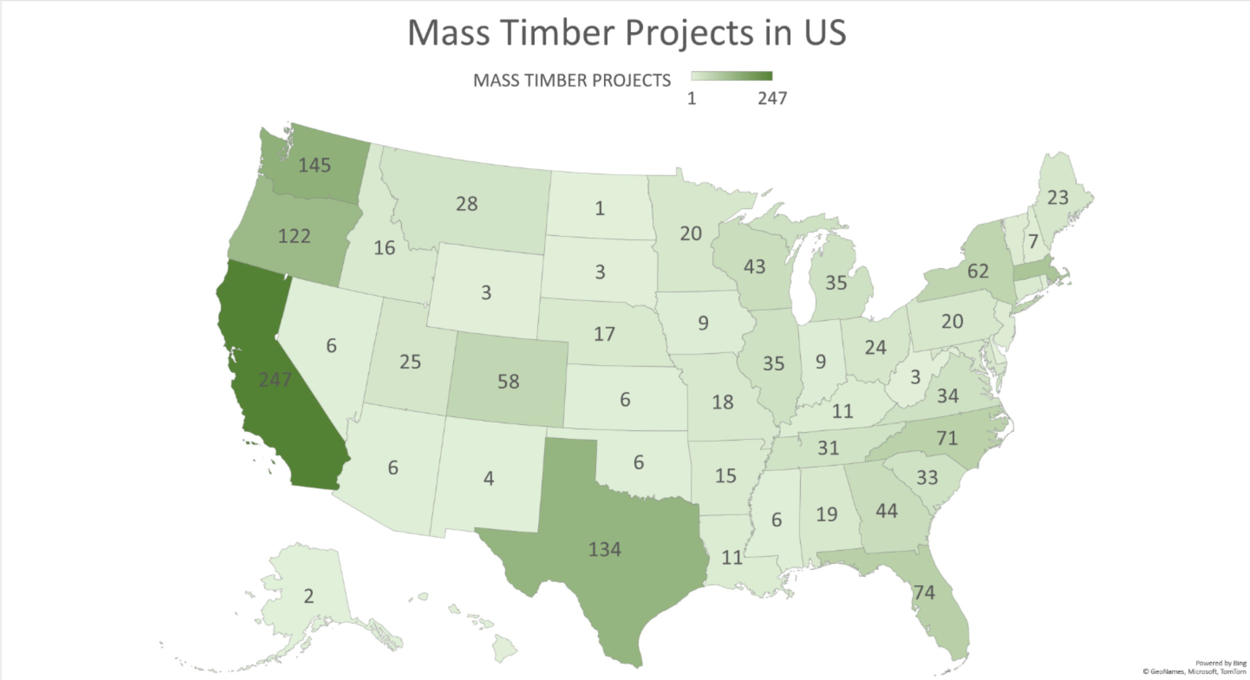

Figure 8 Mass Timber projects in the US (“WoodWorks Innovation Network” n.d.)

With time there have been great improvements and several types of mass timber product developed to date. Apart from the widely popular Cross-laminated Timber (CLT) products, there are various other products available on the market and used for different purposes. Glulam, Nail-laminated Timber (NLT), Dowel-laminated Timber (DLT), Mass Plywood Panel (MPP), Heavy Timber Decking & Joined Timber are some of the other product varieties in Mass Timber.

Figure 9 Cross Laminated Timber (CLT)

Figure 10 Nail Laminated Timber (NLT)

Figure 11 Dowel Laminated Timber (DLT)

Figure 12 Mass Plywood Panel (MPP)

Figure 13 Glulam

Figure 14 Timber Decking

All Images Source: (Anderson et al. 2021)

1.1.5.1 Cross Laminated Timber (CLT)

"CLT is a panelized structural engineered wood product that can be used in all major building components such as floors, interior and exterior walls, and roofs" (2021 International Mass Timber Report, 2021, p.3). CLT are typically made up of three or more layers of pre-selected lumber, each layer laid perpendicular to each other, pressed with special adhesive for exceptional strength. Figure 15 below illustrates the difference between CLT and Glulam product.

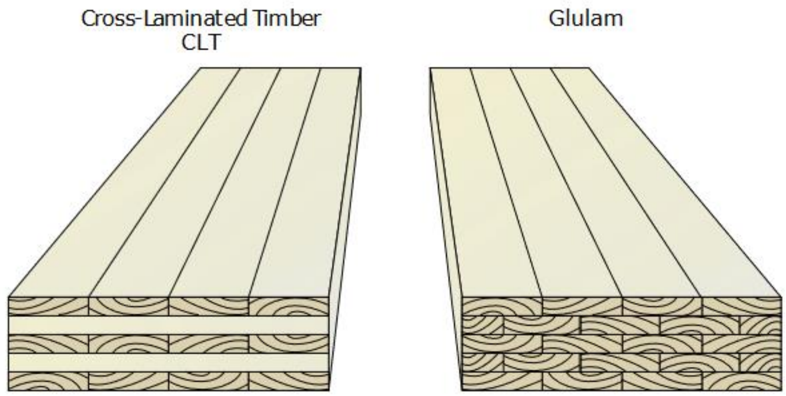

Figure 15 CLT vs Glulam (Pilgrim et al. 2022)

CLT panel sizes limited by press size and trucking regulations are ranged between 4 feet to 12 feet in width, up to 60 feet in length and 3.5 inches to 9 inches in thickness (2021 International Mass Timber Report, 2021). CLT panels are commonly made from solid sawn softwood lumber, including spruce-pine-fir (SPF), Douglas fir (DF) and Southern Yellow Pine (SYP) and can be sourced from numerous manufacturers in the U.S., Canada, and Europe. It can also be made with laminated veneer lumber (LVL), laminated strand lumber (LSL) and other structure composite lumber (SCL) products. CLT can be used in any type of construction allowing wood structural system and are typically suited for Type IV buildings as per IBC 2015. As per new explicit recognition of CLT in IBC 2021, 18 storied buildings are allowed for construction (US Mass Timber Construction Manual, 2022). It is convenient transport and assembly, as well as its cross-membered wood construction, have made CLT the most popular mass timber product (Ortiz 2019).

1.1.5.2 CLT Manufacturing Process

As we transition to the manufacturing process in detail, for a CLT manufacturing certain steps must be followed. The CLT Handbook published by ThinkWood describes nine basic steps of CLT Manufacturing as follows-

1)Primary lumber selection,

2)lumber grouping

3)Lumber planning

4)Lumber or layers cutting to length

5)Adhesive application

6)CLT panel lay-up

7)Assembly pressing,

8) CLT on-line quality control, machining and cutting,

9)Product marking, surface matching, packaging, and shipping.

Figure 16 explains in detail the step-by-step process of CLT manufacturing.

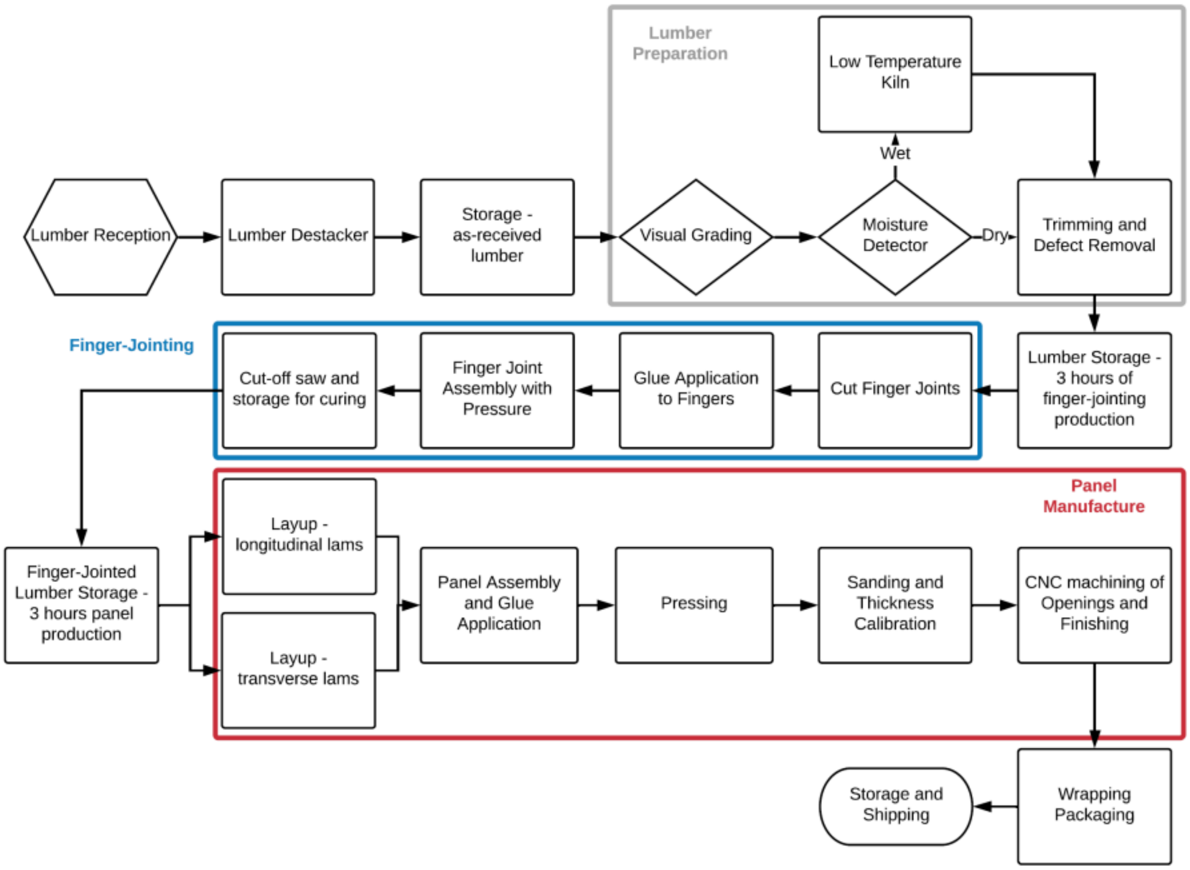

Figure 16 CLT Panel Manufacturing Process (Adapted from (Zhang and Lan 2022))

Industrial scale production of CLT along with the advanced technologies involves steps such as material receiving and preparation by sorting grade, species, dimensions and checking moisture content. Next step is to finger-join the laminations using machines. This continuous piece of lumber by finger-jointing is then cut lengthwise. After the cutting process comes the process of surfacing where a small layer from the lamination is planed off to get a piece of lumber with uniform dimensions. These surfaced laminations are then layered on one another in alternating axis in three or more layers and pressed with a special adhesive. This varies as per adhesives used and pressing technology affecting time and energy consumption in the process. One of the final steps in this manufacturing process includes cutting irregular edges by CNC machines for uniform trim. Packaging and shipping complete the whole manufacturing process wherein metal hardware called as pick points are placed into the panels, then sequentially assembled to directly move into place rather than unloading and storing on construction site (2021 International Mass Timber Report, 2021, pp. 66-68).

1.2 Research Need

During the pandemic, the price of goods used in residential construction has increased, squeezing already-tight project budgets, and delaying completions ("The White House" 2022). It is observed that there is a limited adoption of potentially cost-saving, off-site building techniques used widely in other countries. Rethinking construction processes to be leaner, faster, affordable, and relatable to the manufacturing industry can solve the housing shortage in developing countries. With gaining momentum of timber products in the US, Cross Laminated Timber (CLT) has been developed as a worldwide well-known and versatile building material (Brandner 2013). Until now modular construction and CLT have been studied and executed in isolation, but the combination is rare. However, construction practitioners are still reluctant to consider mass timber as a mainstream building material (Ahmed and Arocho 2020). While mass timber technology has potential to address the affordable housing crisis in the US, there are still several areas that need to be researched.

Standardization reflects the uniformity in manufacturing by avoiding rework, speeding up the production system, and maintaining high quality. It is establishing the benchmark for manufacturing. Mass production also reduces the overall cost with the repetitive production process. Standardization used in mass-production results in time and cost cutting. In CLT production, every manufacturer has their own standardized elements. Mass timber is treated as a collaborative service and not as a commodity like other materials because of minor differences between each mass timber manufacturer's capabilities (FPI Innovation 2013). There is a need to develop standardized testing protocols for quality control and testing modular mass timber components for maintaining consistency in manufacturing. In addition, will these key set of standards meet performance requirements needs to be researched. Also, there is a need to find ways to commodify mass timber products.

Implementation of a fully collaborative design process including manufacturing and assembly requirements right from the design stage, helping designers for continuous improvement and product development is the main aim of DFMA method (Yuan et al. 2018). As per DFMA guidelines, use of standardized and off-the-shelf products will lower the purchasing lead time and eventually reduce the cost (Lu et al. 2021). For improving assembly efficiency, quality and security design should be considered with mechanized or automated assembly. This leads us to research whether DFMA technique can be used for mass timber production and what will be its impact on scaling the production.

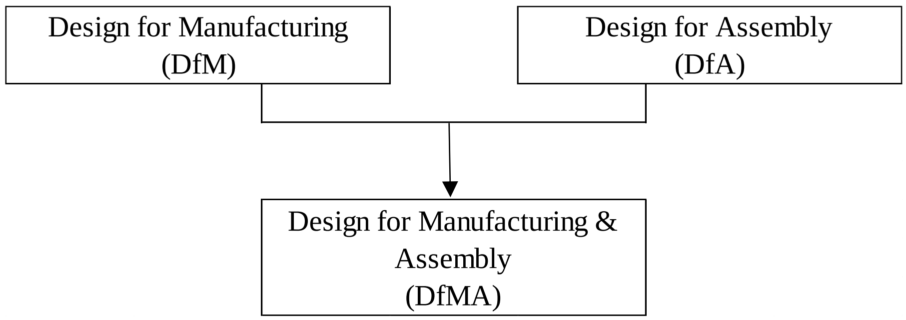

Figure 17 Concept of DfMA

To scale the production of an item, manufacturing process efficiency plays a key role. "Efficient production is achieved when a product is created at its lowest average total cost; production efficiency measures whether the economy is producing as much as possible without wasting precious resources" ("MOSIMTEC" 2018). This efficiency is dependent on several factors such as production planning and control (PPC), number of production steps (Mousavi et al. 2016), production lines, bottlenecks in the process ("MOSIMTEC" 2018). The research is needed to optimize the manufacturing process of modular mass timber components, including improving the efficiency of production lines, reducing material waste, and optimizing the use of automation and robotics. Further there is a need to research on optimizing the supply chain for modular mass timber components, including identifying potential bottlenecks in the supply chain and developing strategies to improve coordination and transportation efficiency.

1.3 Goals & Objective

A Housing Supply Action Plan to ease the burden of housing costs over time, by boosting the supply of quality housing in every community is a necessity of today("The White House" 2022). So far modular construction techniques have helped achieving satisfactory results with quicker construction time, minimal on-site construction activities, flexibility, high quality of construction with the use of durable materials, saving on the construction costs. Also, modular construction has recently been highlighted as contributing to increasing productivity and to tackling labor shortages in the housing sector. Whilst a range of off-site manufactured building technologies are already used for the housing construction, mass timber, which uses prefabricated solid wood panels for low- to mid-rise construction applications shows worldwide increasing commercial potential.

The overarching goal of this research is to contribute to the resolution of the housing crisis in the United States by exploring the potential of modular mass timber as a promising solution. Recognizing that modular technology is already making significant strides in addressing this issue, and that mass timber is gaining momentum due to its numerous benefits, we believe that the combination of modular technology and mass timber could be a highly effective approach to this problem.

One of the key goals is to popularize mass timber as a superior option that can be manufactured at scale. By demonstrating its advantages over traditional materials like concrete and steel, we aim to encourage its wider adoption in the construction industry.

Another important goal is to equip manufacturers with the knowledge they need to effectively utilize this technology. By identifying the critical success factors (CSFs) in the manufacturing process of modular mass timber, we aim to help manufacturers focus their strategies on the most impactful areas.

With these goals in mind, the specific objectives of this study are:

a) Understanding modular mass timber manufacturing and affordable housing
b) Establishing foundation for generation of CSFs in manufacturing process of modular mass timber for affordable housing
c) Developing the CSF in manufacturing of modular mass timber for affordable housing
d) Demonstrating the prioritized rubric of the CSFs to formulate effective strategies in manufacturing of modular mass timber for affordable housing.

The study aims to highlight the importance of modular mass timber and its benefits over traditional construction materials in the context of affordable housing projects. It further aims to guide decision-makers in determining the CSFs for manufacturing modular mass timber up to the delivery stage, leaving the investigation of the installation stage for future research. Ultimately, this study aims to provide a regulatory framework by determining the CSFs for building future modular mass timber affordable houses.

1.4 Work Plan

This study adopted a comprehensive and robust approach by carrying out an in-depth literature review analysis of manufacturing practices in modular and mass timber industry, in the first stage to identify initial drivers in the study. Understanding the relationships and complexities between factors was the intension behind using Multi-Criteria Decision-Making (MCDM) methods (Petrović et al. 2018). Finally in the last stage, the author proposes prioritized rubric to make inform decisions and construct framework and strategies around it by interpreting results from Spearman's Rank Correlation Coefficient and DEMATEL. Figure 18 summarizes steps in the methodology of the study and expected objective achieved through the steps.

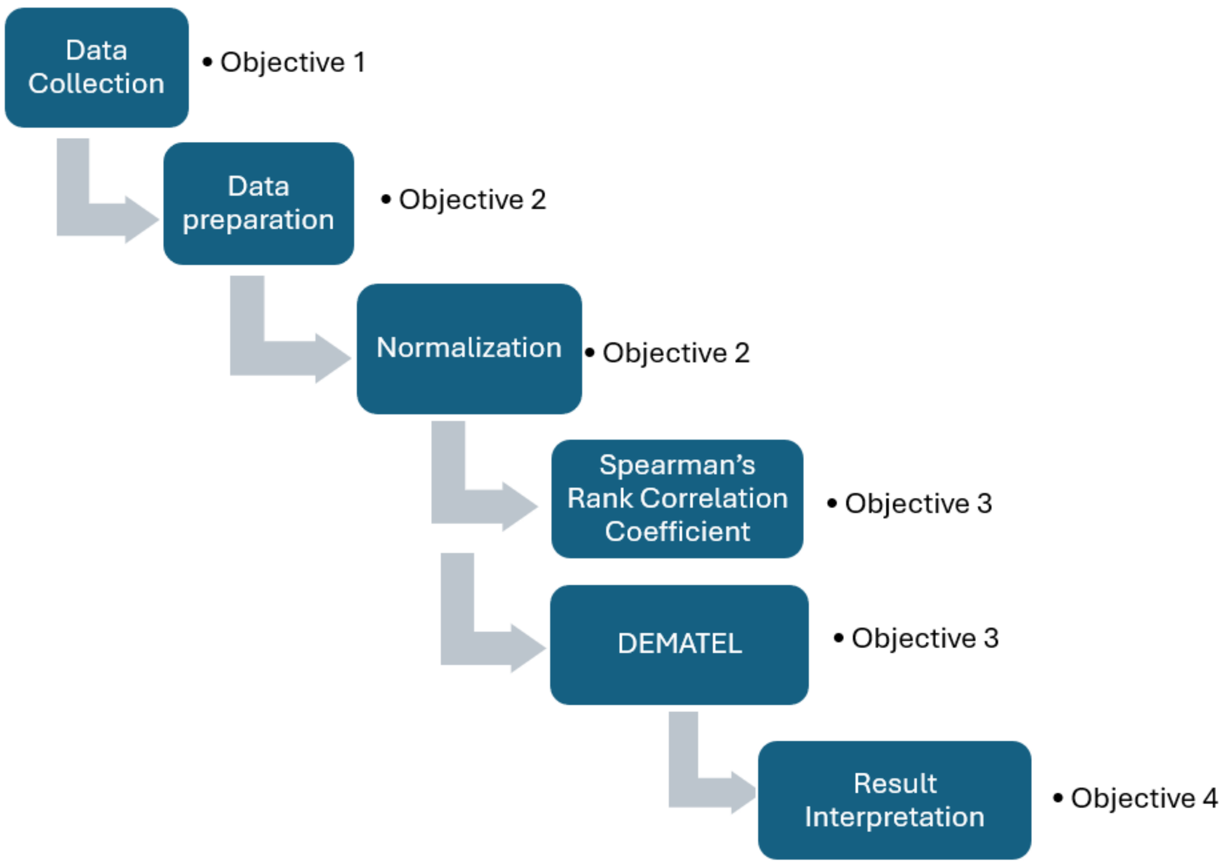

Figure 18 Proposed Work Plan of Study

To achieve the goals and objectives stated above, we will be reviewing the available literature on affordable housing, modular construction & Mass timber products and methodology. Understanding the key aspects in modular construction and Mass timber construction for affordable housing, the study will be able to frame our research question. The available literature and the archival cases describing with the characteristics of either modular or mass timber or both will help us analyze the key aspects to focus on in this study. The author will be using literature for establishing importance & relevance of the topic& identification of relevant evidence.

To generate verified & widespread data within this report, we will be using semi-structured interviews with the industry experts for data collection. Due to the limited number of modular mass timber construction projects developed till date in the US, the industry experts worked on these projects are limited. Thus, study participants will not be restricted to any geography. For the same reason, we will use snowball sampling or the network sampling method to recruit more participants for sufficient data collection. The collected data from the interview transcripts and audio-recordings will be analyzed. Peer comparison with differences in events and experiences will influence the different path.

1.5 Scope & Limitations

This study focuses on the affordability aspect of housing using modular mass timber, specifically Cross Laminated Timber (CLT). The scope is limited to the manufacturing of CLT, and the impact of Critical Success Factors (CSFs) developed on the installation process. However, it leaves room for future research to discover CSFs for the CLT installation process in affordable housing separately.

For this research purpose, affordable housing is defined from an investment perspective. Among many possible definitions, the investment point of view best suits this project. And from an investment perspective, “affordable housing” refers to properties that are priced in a way that allows for profitability, marketability, and favorable financing. Affordable housing can provide a steady stream of rental income and tends to have high demand due to the current housing shortage. The affordability of a property can impacts the terms of financing. Furthermore, investing in affordable housing can also have a positive social impact by providing housing for lower-income households. Investors can contribute to a short-run reduction in the vacancy rate of owner-occupied units and a medium-run positive response of construction, mitigating the effect on affordability. Price-to-Income and Price-to-Rent Ratios are important indicators of housing affordability from an investment perspective. The end use of these modules, as per the market, will be for residential purposes. The modules studied will be permanent types of housing, and the material under consideration is wooden modules, i.e. CLT modules. We are referring to multifamily housing units that are priced such that they do not exceed 30% of a household’s gross income, considering the regional variations in housing costs. We’re also acknowledging the current housing shortage and the need for policy interventions to incentivize the construction of more affordable, multifamily housing units.

In terms of module geometry, both 2D panelized and 3D volumetric modules are considered. As there are a limited number of projects developed with mass timber in modular form, it is currently challenging to conclude which geometry is better. As the number of projects increase soon, it will be an additional point of study to discover the success measures focusing on either type.

Geographically, the study focuses on encouraging the use of modular mass timber in affordable housing use cases by helping more manufacturers decide on critical success factors in manufacturing modular mass timber. Future scope of study may involve considering development within a particular geography and considering local considerations. This study will be treated as a starting point and a big picture, which can further be researched by focusing on certain specific parts.

Among the various engineered products in mass timber, CLT was a major part of the discussion. This adds to further research considering hybrid modules with other engineered wood products or with steel, or insulated panels. However, for the current study purpose, only CLT is considered.

This study aims to create a standard set of guidelines for mass timber modular manufacturing to scale production for future projects to satisfy the rising demand in the market. However, it will not forecast the exact percentage of scaled production. This study can be referenced in future innovations for product development using mass timber and modern methods of construction technology. With the development in technology and automation in the industry, certain CSFs may change with time.

CHAPTER II LITERATURE REVIEW

2.1 Introduction

The escalating demand for sustainable and economically viable housing solutions has propelled the construction industry to explore innovative methodologies. Another reason is that the construction sector is exploring creative methods due to the growing need for affordable and ecological housing alternatives (Van de Lindt et al. 2023). “Challenges such as production inefficiency and inadequate waste management hinder advancement in the construction industry” (Roxas et al. 2023). Of these, modular mass timber technology stands out as a game-changer, offering economic viability along with environmental sustainability (Thompson 2019). In the context of the United States, where the need for affordable housing solutions is more pressing than ever, the integration of modular CLT technology holds significant promise. This review of the literature aims to traverse the complex field of modular CLT building by focusing on the production perspective, which is frequently disregarded.

To uncover shared principles and contribute to the replication of successful projects, this literature review is undertaken in a unique landscape where mass timber projects for affordable housing and modular projects for affordable housing coexist, yet the intersection of the two remains notably sparse. Within this distinctive context, our exploration aims to identify commonalities between the few existing mass timber projects for affordable housing and the substantial body of modular projects in the affordable housing sector. By scrutinizing the literature, we seek to extract insights that bridge the gap and facilitate the emergence of modular CLT projects. Through this review, we aspire to distill shared practices, discern patterns of success, and lay the groundwork for future endeavors in the integration of modular mass timber technology within the affordable housing market.

2.1.1 Global Perspective on CLT Manufacturing: Insights of similar decision-making factor studies

In a comprehensive exploration of cross-laminated timber (CLT) manufacturing, various studies have delved into the key performance indicators (KPIs) that shape the success and challenges of this innovative construction material. Jonsson and Rudberg (2017) have been instrumental in synthesizing these KPIs, providing a foundational understanding. Building on this, (Quesada-Pineda et al. 2018)) spotlight the European CLT landscape, emphasizing the significance of unique production processes and collaborative operations as drivers of success. Despite its regional focus, this study serves as a valuable resource for my research, which seeks to establish a robust CLT industry in North America.

(Abiri 2020) contribute to this body of knowledge by employing discrete event simulation to unravel decision-making parameters in CLT modular construction operations. By understanding project needs, scale, and requirements, their work aids in adopting efficient frameworks for deciding between panelized and volumetric scales of modularity in construction operations.

Exploring the challenges faced in CLT manufacturing using hardwood lumber, Adhikari et al. (2020) shed light on critical factors. Drivers, including partnerships, market opportunities, and diverse financing options, are juxtaposed against challenges such as raw materials, technology, suppliers, education, and regulatory considerations.

Within the broader literature themes of structural performance, serviceability, and fire resistance in CLT, a nuanced focus on moisture control emerges as a recurrent and crucial theme. The collaborative aspect of CLT manufacturing is also accentuated, underlining the necessity of effective teamwork. This synthesis provides a comprehensive introduction to the multifaceted landscape of CLT literature, setting the stage for a deeper exploration of KPIs and operational dynamics.

2.1.2 The Intersection of Sustainability and Affordability

With the mounting challenges posed by climate change and the imperative to foster sustainable practices, modular mass timber construction stands at the intersection of environmental responsibility and affordability (Pei et al. 2016; Van de Lindt et al. 2023). The use of engineered wood products, such as cross-laminated timber (CLT) and glue-laminated timber (glulam), not only demonstrates a commitment to sustainable forestry but also presents a compelling alternative to traditional construction materials (Gijzen 2017). In this discovery, it becomes apparent that understanding the manufacturing intricacies of these materials is crucial for unlocking the full potential of CLT modular technology.

2.1.3 The Manufacturing Nexus

While prior research has delved into the architectural and environmental aspects of CLT construction, the manufacturing processes that underpin this technology remain a focal point of inquiry. This review contends that the efficiency, standardization, and productization of CLT modular manufacturing processes are pivotal considerations for ensuring the scalability and affordability of housing projects. By scrutinizing material properties, labor requirements, and equipment utilization, we aim to unravel the nuanced dynamics that shape the manufacturing landscape of modular mass timber technology.

2.2 Objectives of the Review

This literature review has two primary objectives. First, it endeavors to consolidate existing research on the manufacturing processes of modular and CLT, offering a comprehensive synthesis of the current state of knowledge. Second, it seeks to identify gaps and opportunities within literature, setting the stage for future research endeavors. As we navigate through material, labor, and equipment considerations, the overarching goal is to contribute insights that facilitate the integration of modular mass timber technology into affordable housing initiatives.

2.3 Structure of the Review

The subsequent sections of this review will delve into the material properties of mass timber, scrutinize the labor requirements involved in its construction, and explore the machinery and equipment that drive its manufacturing processes. Additionally, we will provide detailed insights into new technologies, designs, and methods identified in the literature, offering valuable knowledge for future projects. The critical nexus between modular technology and mass timber technology is uncovering pathways for sustainable and economically viable affordable housing construction practices.

2.4 Manufacturing Process of CLT

2.4.1 Raw Material Selection and Preparation

The process of raw material selection and preparation for Cross-Laminated Timber (CLT) production involves several key considerations. Firstly, exploring the types of wood species commonly used in CLT production is crucial along with the consistency in the lumber quality (FPI Innovation 2013). In the context of CLT production, it is imperative that the lumber grades in parallel layers meet a minimum standard of 1200f-1.2E MSR or achieve a visual grading of at least No. 2. For perpendicular layers, a visual grading of No. 3 is mandated (FPI Innovation 2013). The 2021 International Mass Timber Report highlights that manufacturers often choose dimensional lumber made from various softwood species. The report further quantifies the raw material requirement, estimating that each cubic foot of finished mass timber i.e. CLT necessitates 22.5 board feet of dimensional lumber. Strategic lumber procurement decisions are emphasized by Brandt et al. (2019), who suggest that acquiring cut-to-length finger-jointed lumber can optimize economics and performance, leading to operational efficiencies and improved product quality for

CLT facilities. Increasing the count of CLT buildings every two years from 2020 to 2030 would result in a projected rise in lumber demand reaching 3.25 billion board feet by 2030 ("Everything You Wanted to Know About CLT" 2021)

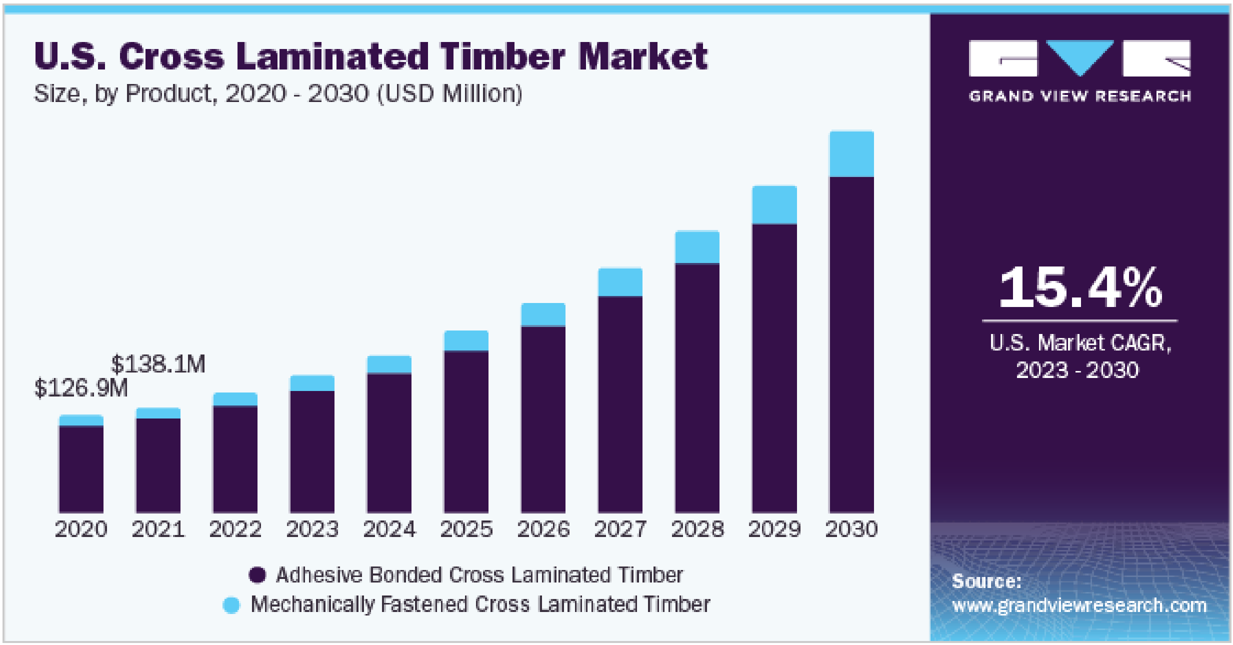

Figure 19 US CLT Market Projected Growth (Source: grandviewresearch.com)

However, it's essential to note that there are limitations on the accepted wood species for CLT panels. The CLT code currently accepts only certain softwood species, with hardwood species excluded from the raw material list (Quesada-Pineda et al. 2018). Addressing this limitation, Adhikari et al. (2020) argue that the successful incorporation of hardwood or hardwood-softwood hybrid CLT would necessitate hardwood sawmills producing dimensional grade hardwood lumber. Therefore, strategic considerations in raw material selection, including adherence to accepted wood species and exploring innovative wood processing techniques, play a pivotal role in optimizing CLT manufacturing processes.

In addition to lumber selection, several additional steps are undertaken in preparation. This includes lumber grouping to ensure both structural integrity and visual appearance, lumber planing for dimensional uniformity, and cutting the lumber to specified lengths in alignment with the intended orientation of layers (FPI Innovations 2013).

2.4.2 Lamination Process

In the intricate lamination process integral to CLT panel production, precision is paramount. The specified net lamination thickness ranging from 5/8 inch (16 mm) to 2 inches (51 mm) and width set at a minimum of 1.75 times the lamination thickness for parallel layers, as outlined by FPI Innovation in 2013, ensure optimal face bonding and alignment for parallel layers in the major strength direction of CLT. This lamination thickness varies per manufacturer and is dependent on species of lumber, structural and architectural requirements of the project, mentions CLT Handbook (FPI Innovation 2013). The adoption of structural cold-set adhesives like PRF, EPI, and PUR not only streamlines manufacturing by eliminating the need for heating but also contributes to the overall structural integrity of the panels (FPI Innovation 2013). In a typical through-feed process, where extruder heads apply parallel lines of adhesive, the production feed speed is carefully regulated. Moreover, the cross-lamination technique, a critical aspect, reinforces structural integrity by minimizing stress risers and gaps, leading to improved interlaminar shear strength and stiffness. However, despite a thorough scan of the literature, notable gaps in innovative contributions and studies for advancing the lamination process were identified. This highlights a potential area for future research and development within the realm of CLT manufacturing.

2.4.3 Pressing and Curing

In the pressing and curing phase, the critical step for proper bond development and CLT quality involves the use of vacuum and rigid hydraulic pressing methods, as typically employed in the industry (FPI Innovations 2013), play pivotal roles in this phase. A vacuum press, characterized by its simplicity and hand-operated nature, relies on a retractable rubberized membrane to create a vacuum seal, exerting pressure on the Panolam stack. On the other hand, the hydraulic press is a sophisticated, automated apparatus demanding substantial space and a robust foundation. It applies pressure to the stack until the adhesive between layers solidifies, excluding glue application between the 2 x 6s (Dovetail 2017).

Figure 20 Press line for CLT ("Kallesoe Machinery" n.d.)

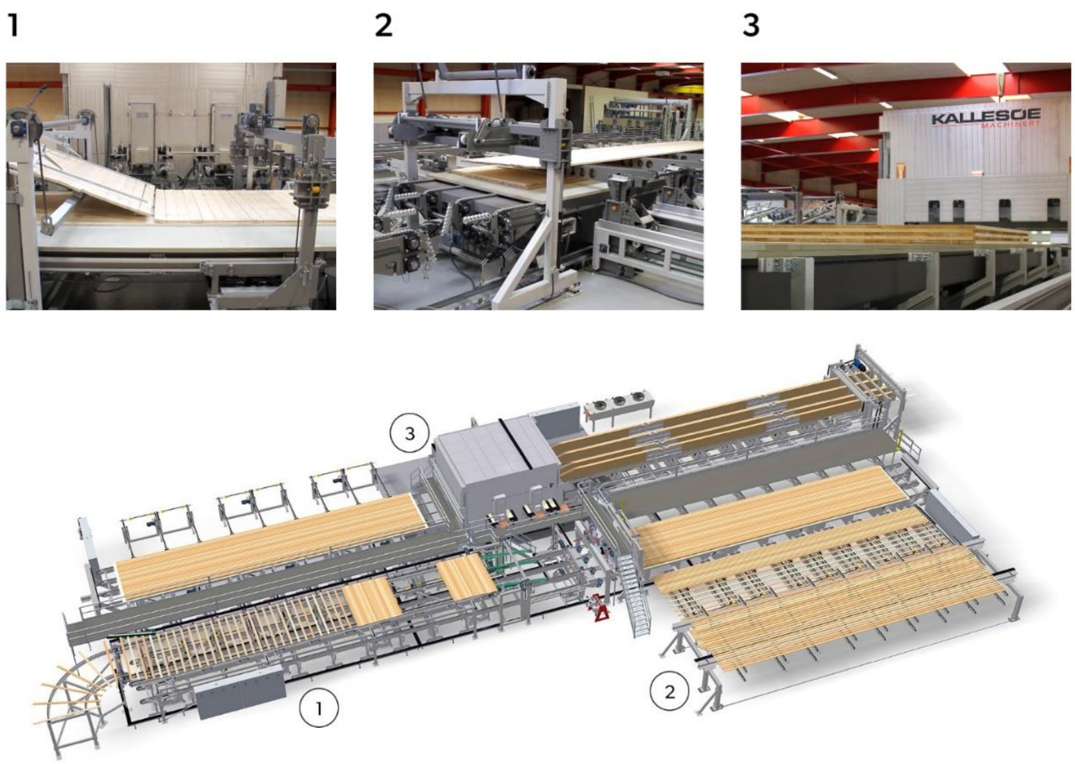

Figure 21 Press line process for CLT ("Kallesoe Machinery" n.d.)

The curing process, imperative for ensuring proper bonding and strength development, requires meticulous control of temperature and humidity conditions. Finger-jointing lines and CNC routers are utilized in this phase for precision (Brandt et al., 2019). Managing moisture is emphasized across literature, with pressing time dependent on ambient temperature, requiring it to be higher than 60ºF suggests CLT Handbook (FPI Innovations 2013). Lumber shrinkage relief is a crucial consideration for optimal CLT performance.

Beck (2015) proposes an interesting approach to meet CLT requirements by purchasing lumber with moisture tolerances aligned with manufacturing specifications, potentially eliminating the need for a dry kiln. This method, costing a premium of $11/m3 ($25/mbf), also considers the exclusion of No. 2 boards with low wane, avoiding visual grading and reducing costs. However, the utilization of hardwood lumber in CLT panels faces limitations, including moisture content, varied dimensions, and the caustic nature of some species(Adhikari et al. 2020).

The findings from literature emphasis on moisture control in this phase, emerges as a high contributor. New CLT manufacturers entering the market should undoubtedly prioritize attention to moisture management for optimal results.

2.4.4 Cutting and Finishing

In the critical phase of cutting and finishing CLT panels, precision is paramount, necessitating advanced cutting techniques such as CNC cutting for meticulous dimensions. Adherence to specified tolerances during manufacturing underscores the importance of quality control. Finished panels, with dimensions ranging from 4 to 12 feet in width and 20 to 60 feet in length, vary among manufacturers and shipping constraints. The permissible tolerances for thickness, width, and length are ± 1/16 inch (1.6 mm) or 2% of the CLT thickness (whichever is greater), ± 1/8 inch (3.2 mm) of the CLT width, and ± 1/4 inch (6.4 mm) of the CLT length. Achieving such precision is notably facilitated by employing CNC cutting technology, ensuring a level of accuracy nearly impossible to attain with traditional construction methods.

Figure 22 Joinery Machine K2 industry (“Cutting machines | Hundegger” n.d.)

Figure 23 Joinery Machine ROBOT-Drive (“Cutting machines | Hundegger” n.d.)

Figure 24 Panel processing machine PBA-E (“Cutting machines | Hundegger” n.d.)

Figure 25 Panel processing machine PBA-Industry (“Cutting machines | Hundegger” n.d.)

Additionally, the study by Adhikari et al. (2020) highlights challenges in using hardwoods, such as quick dulling of cutting tools due to higher density and longer pressing times compared to softwood operations. Moreover, decision-making considerations for panelized versus volumetric modules, as explored by Abiri et al. (2019), factor in CLT press duration, CNC process duration, and transportation distance. This underscores the nuanced choices involved in modular construction processes, where efficiency, precision, and material considerations intersect.

2.4.5 Quality Control Measures

Ensuring the quality of CLT panels involves a comprehensive approach, with quality control measures seamlessly integrated into each step of the manufacturing process. From the precise shaping achieved through planing machines, which target a thickness tolerance as fine as +0.004 inch (0.1 mm), to the utilization of multi-axis numerically controlled machines operating under controlled conditions for maximum accuracy, the manufacturing process adheres to meticulous protocols outlined in the CLT Handbook (FPI Innovations 2013). Manual interventions, when required, strictly follow these quality protocols. Beyond the manufacturing steps, quality control extends to the overall manufacturing plant, where pre-qualification criteria must be met as per the quality control guidelines mentioned in ANSI/PRG-320 standard. This standard criterion encompasses structural qualifications, process change validations, and overarching quality assurance measures making it a reliable choice for modern construction projects. Third party audits can provide an additional layer of validation and confidence in the product’s quality. The holistic implementation of these quality control measures underscores the commitment to ensuring structural integrity, dimensional stability, and the overall excellence of CLT panels at every stage of their production.

2.5 Environmental Considerations & Sustainability practices

The environmental considerations in CLT production are integral to sustainable construction practices. One key aspect is the sourcing of CLT from sustainably managed forests, aligning with eco-friendly and renewable construction principles, as emphasized by studies such as those conducted by Ahmed and Arocho (2020) and Gijzen (2017). Beyond raw material selection, the manufacturing process of CLT itself is designed to be environmentally conscious. Compared to traditional building materials like concrete and steel, the production of CLT typically involves less energy consumption, contributing to overall energy efficiency in construction processes. Moreover, studies, including that by Roax et al. (2023), suggest that integrating Design for

Manufacturing and Assembly (DfMa) and Design for Disassembly (DfD) principles from the inception of a project can further bolster sustainable development goals. By addressing sustainability at both the material-sourcing and manufacturing stages, CLT emerges as a pivotal component in fostering environmentally responsible construction practices.

2.6 Technological Innovations

In recent years, technological innovations have played a pivotal role in advancing Cross-Laminated Timber (CLT) production, contributing to increased efficiency, precision, and scalability. A significant trend is the integration of design methods with emerging technologies, particularly Building Information Modeling (BIM). Roxas et al. (2023) emphasizes the importance of BIM in the context of Design for Manufacturing and Assembly (DfMA), while Yuan et al. (2018) support this approach with their study on DfMA-oriented parametric designs crucial for prefabricated buildings. The concept of a digital twin, facilitated by BIM, is gaining prominence, offering a comprehensive model that spans the entire lifecycle of a building and integrates IoT sensing for real-time monitoring(Turner et al. 2021).

Turner et al. (2021) proposes a three-phase model of intelligent assets in the construction domain, particularly highlighting the use of sensor networks and information processing for mitigating pollution costs in the manufacturing of materials, a concept initially successful in concrete modular structures. The potential application of such sensor technologies in enhancing the efficiency of CLT production remains an intriguing area for exploration.

A notable innovation in CLT technology comes from Utah, where Pei et al. (2016) developed an interlocked CLT panel that eliminates the need for glue. While currently on a smaller scale, this development presents a promising modular initiative that could transform how CLT is used in construction. Furthermore, (Ortiz 2019) proposes a Hybrid Light Module design scheme, specifically tailored for mass timber in urban areas, showcasing adaptability to various building typologies. This innovation underscores the flexible and lightweight nature of modules, offering the manufacturing industry an avenue to expedite construction processes.

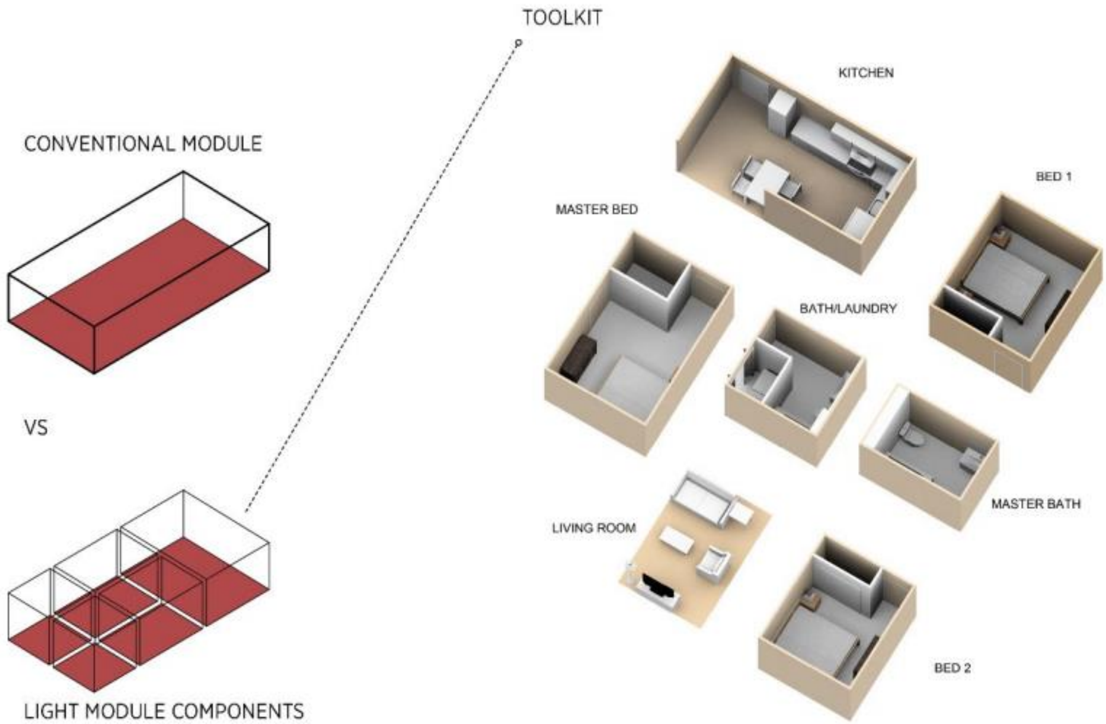

Figure 26 Hybrid Model (Ortiz 2019)

An additional noteworthy advancement is the development of Cross-Laminated Insulated Panels (CLIPs) by Element5, introducing a novel approach to enhance the thermal insulation properties of CLT panels.

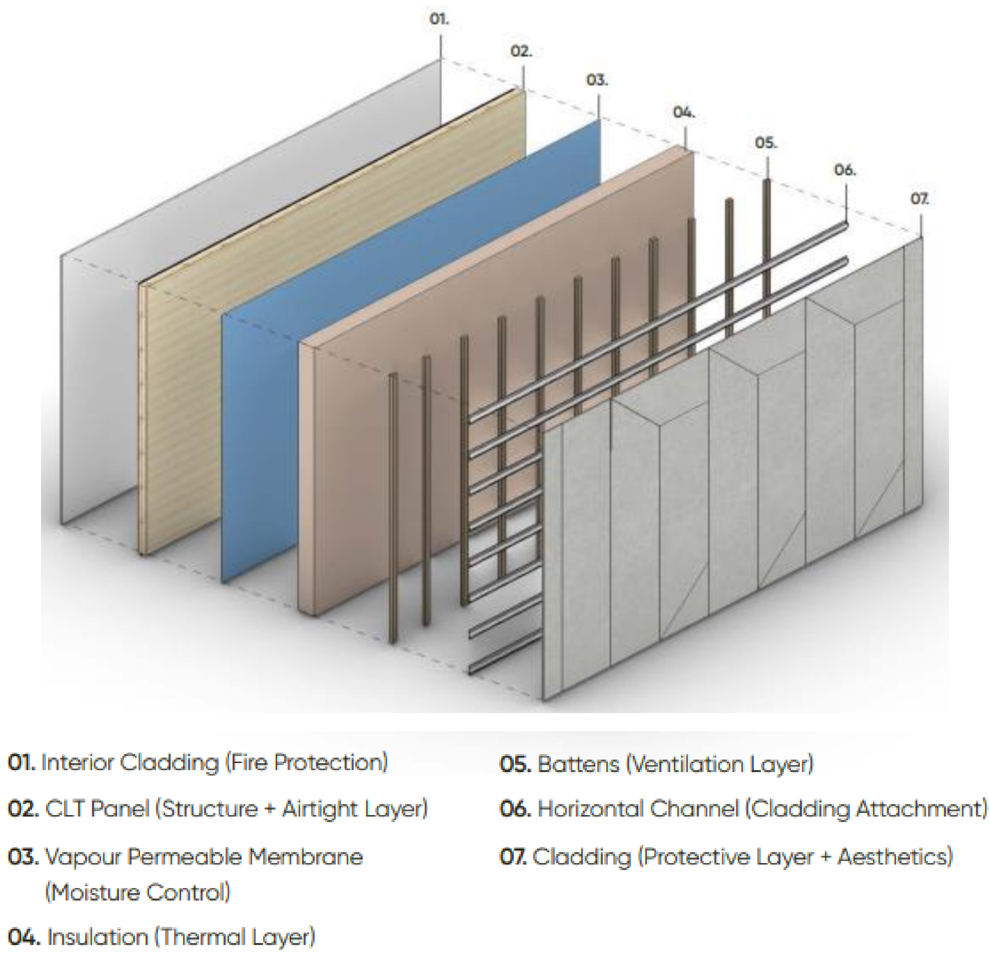

*Figure 27 Envelope and Cladding- Cross-Laminated Insulated Panels (CLIPs) (*Element5 Sustainable Affordable Housing Brochure *n.d.)*

These technological strides collectively reflect the dynamic landscape of CLT manufacturing, embracing advancements that not only streamline processes but also open new possibilities for sustainable and efficient construction practices.

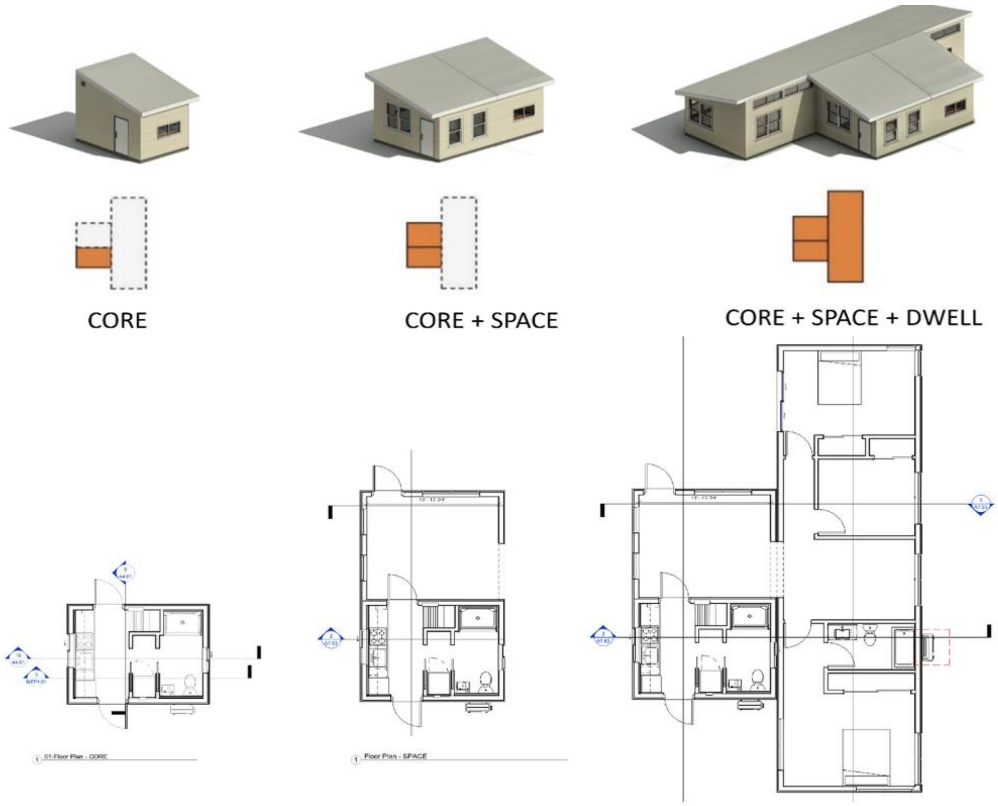

Figure 28 CORE+ Advanced Modular Seismic Designs (Source:(Carney et al. 2023))

In conclusion, the importance of continuous innovation in Cross-Laminated Timber (CLT) technology cannot be overstated. The potential to reduce production costs or add value propositions through these innovations is immense. If implemented in modular designs, these advancements could provide significant benefits and open new avenues for future research. The recent technological strides in CLT production, as discussed here, have not only increased efficiency, precision, and scalability but also paved the way for sustainable and efficient construction practices.

2.7 Market Trend and Challenges

The current landscape of Cross-Laminated Timber (CLT) production is marked by significant market trends and concurrent challenges. Notably, there is a discernible surge in the CLT market's growth, reflecting a robust demand for this innovative construction material. Factors contributing to this upswing include increasing awareness of sustainable construction practices and the environmental benefits of CLT, as underscored by Roxas et al. (2023) and corroborated by the insights from Baker (2018).

However, the industry faces multifaceted challenges that necessitate careful consideration. The challenges encompass various domains, such as unionization and corporate politics, financial intricacies, supply chain management, adherence to planning and construction code requirements, and navigating government rules and incentives (Edmonds et al. 2018; Roxas et al. 2023). The complexities of these challenges are further magnified by the intricate nature of Design for Manufacturing and Assembly (DFMA) challenges, as discussed by Roxas et al. (2023).

Decision-making processes within the CLT sector are hindered by the absence of pertinent information, creating hurdles for effective decision-making, and a notable lack of active participation from suppliers (Roxas et al. 2023). Ahmed and Arocho (2020) emphasize the need to promote mass timber products within the U.S. construction sector, stressing the importance of fostering a willingness among professionals to adopt CLT for contributing to a greener world.

Amid market dynamics, some manufacturers have faced setbacks and failures attributed to poor decision-making, inadequate planning, and undertaking risks beyond their financial capacity. These challenges underscore the critical need for strategic planning, risk management, and a comprehensive understanding of the dynamic factors influencing the CLT market. As the industry continues to evolve, addressing these challenges will be pivotal in ensuring the sustained growth and resilience of the CLT manufacturing sector.

Literature has emphasized early engagement among key project members with greater degree of collaboration among designers, manufacturers, and general contractors. This could ensure the constructability and prefabrication coordination as a part of the design process. Digging deep into the early engagement aspect (Ahmed and Arocho 2020; Quesada-Pineda et al. 2018) the author tries to discover from the literature, which professionals must be involved in this step. Pre-design thumb rules expect to start the design only after the involvement of factory or a DfMA consultant. Lu et al, 2021 mentions DfMA guidelines developed so far, we in manufacturing context without sufficient understanding the differences between construction and manufacturing. Having a suitable ecosystem and more research on intermediate prefabrication construction, it is possible to bring buildability evaluation, value management, lean construction using well developed DfMA guidelines (Lu et al. 2021). Due to divergent standards, varying module sizes, distinct layouts, specific connection details, installation prerequisites, and transportation constraints, coupled with the overarching influence of manufacturers' unique capabilities and efficiencies, the absence of their input poses a significant risk of extensive rework and frequent corrections, consuming valuable time in the process.

Key parties including general contractor/construction manager, mass timber manufacturer, structural steel/concrete core manufacturer, installer/erector (contracted by GCs or manufacturers), and mechanical/electrical/plumbing (MEP) and fire protection (FP) subcontractors, is critical. The literature finds gaps with HVAC installations in the modular systems with CLT components. This is important because engineers and architects are often burdened with making projects buildable, however, if the professionals who build the structure are involved beforehand, will realize the better results.

Construction professionals are getting used to the modular construction concept but working with Mass Timber is comparatively new and needs time and education (Ahmed and Arocho 2020; Ilgın et al. 2023; Pei et al. 2016) for everybody involved to be comfortable using this technology compared with typical approach. With sophisticated involvement of workforce in preconstruction will help to get things done right in the first time.

In the nascent stages of CLT emergence, modular construction has already established deep roots. The challenges faced in CLT construction, as highlighted, can be effectively mitigated by incorporating the best practices derived from the well-established principles of modular construction suggested by multifamily modular construction toolkit.

2.8 Construction and Design Considerations

In the realm of CLT modular projects, understanding the intricacies of design is paramount, especially as it differs significantly from traditional multifamily unit design. Woodworks has laid out a pattern for future modular multifamily projects in CLT construction. This underscores the importance of incorporating DfMA principles and integrating new advancements in design, such as seismic-tempered design enhancing CLT implementation.

2.8.1 Enhanced Structural Performance

Enhanced structural performance stands as a hallmark of Cross-Laminated Timber (CLT), underpinned by its remarkable strength and dimensional stability. The advantageous low weight-to-strength ratio of timber, compared to materials like steel and reinforced concrete, is a key contributor to CLT's structural prowess (Gijzen 2017). Well-engineered connection systems further enhance this strength, providing CLT with excellent seismic-resistant properties (Gijzen 2017). Recognizing the need for seismic performance factors tailored to earthquake-prone regions, initiatives like creating a comprehensive database for CLT research and performance are underway(Pei et al. 2016; Van de Lindt et al. 2023).

The structural integrity of CLT is intricately linked to the major and minor axis concept governing the strength of the panel. The wood grains in the two outer layers align parallel to the longer axis, defining the major strength direction, while the middle layer, oriented in a transverse direction, serves as the minor axis (Anderson et al. 2021). Understanding this axis concept is deemed crucial in the manufacturing process, providing a foundation for efficient design solutions. Architects and engineers can leverage the robust structural performance of CLT panels to explore innovative possibilities, pushing the boundaries of design.

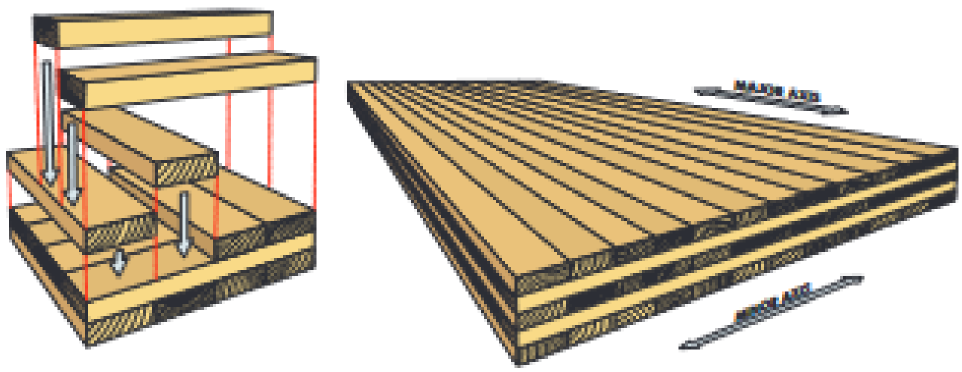

Figure 29 CLT Panel Assembly (Source: WoodWorks)

In the realm of CLT buildings, the structural behavior is not only contingent on the inherent properties of CLT but is also profoundly influenced by the connections between panels(Bhandari et al. 2023). Notably, the variation in module types plays a pivotal role in construction duration and logistics flexibility. Projects with a single module type streamline production and construction processes but may limit spatial and functional flexibility. Conversely, projects featuring multiple module types offer greater adaptability, allowing for custom plans and increased spatial diversity. This nuanced interplay between structural characteristics and modular variations underscores the intricate considerations essential for optimizing the construction of CLT buildings, unlocks opportunities for custom designs and spatial diversity to manufacture.

2.8.2 Architectural Versatility

Cross-laminated timber (CLT) stands out for its architectural versatility, allowing architects to explore diverse designs in terms of size, shape, and texture. This flexibility enables the creation of unique and aesthetically pleasing structures, contributing to the increasing popularity of CLT in contemporary construction, as noted by Ahmed (2021). Furthermore, the lightweight nature of

CLT, in comparison to traditional materials like concrete, makes it a preferred choice for projects where weight considerations are crucial. This reduced weight not only influences design considerations but also has implications for the construction of foundations and supporting structures, as highlighted by Baker (2018) and Pei et al. (2016). The adaptability of CLT extends to various construction types, encompassing residential, commercial, and industrial buildings. Its versatility makes it a suitable and scalable choice for projects of different scales and purposes, showcasing the immense potential of CLT as a foundational structure across diverse industry segments, as emphasized by Dovetail (2017). CLT has favorable fire resistance due to the charring effect, providing additional safety in case of fire incidents. The fire performance of CLT makes it a preferred choice in certain building applications (Gijzen 2017; Pei et al. 2016).

2.9 Cost Considerations

Despite initial perceptions of higher costs, cross-laminated timber (CLT) proves cost-effective, offering savings in construction time, labor, and site management. The prefabricated nature of CLT components contributes to overall project cost-effectiveness, particularly in projects with repetitive designs. Manufacturing efficiency is pivotal, balancing the "product approach" and "process approach" for optimal cost benefits (Yu 2011).

Studies by Ilgin et al. (2023) emphasize the importance of vertically integrated operations in countering fluctuations in raw material costs, crucial for the economic production of CLT. Lee et al. (2016) underscores the significance of efficient line production processes in modular construction factories, offering insights applicable to CLT modular manufacturing. This perspective aligns with principles of resource reduction and sustainability in construction, as highlighted in a report on modular affordable housing by WSP in 2018.

Examining cost equations in CLT manufacturing, regional lumber prices and challenges faced by high-investment manufacturers in supplying CLT across the country are noted (Brandt et al. 2019; Chouinard 2017). The advent of lower-cost CLT manufacturing equipment is breaking entry barriers, fostering the growth of smaller, locally operated CLT plants. However, despite discussions on CLT's importance and engineering, there's a scarcity of studies focusing on economic ripple effects in manufacturing. Liu et al. (2023) highlights the need to address sectors like timber, logs, road freight transport, and wholesale trade to navigate economic challenges successfully. Overall, understanding and managing these economic aspects are crucial for sustaining CLT manufacturing.

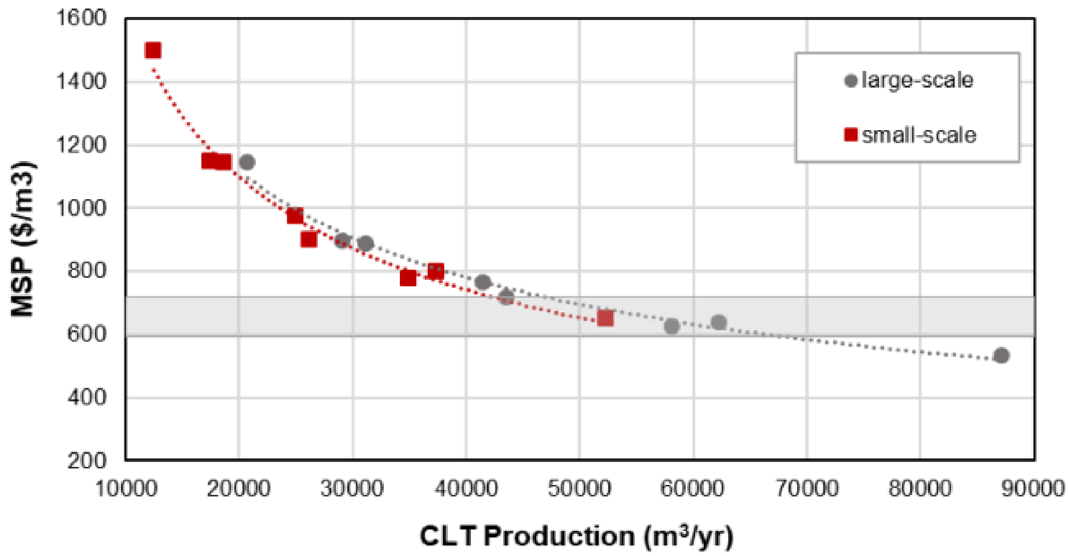

Figure 30 Relation of MSP with Plant Capacities (adapted from:(Brandner 2013))

While understanding the impacts of plant capabilities and uncertainties, Zhang, and Lan (2021) discovered economic performance of CLT production. The study concluded that the minimum selling price of CLT panels decreases significantly along with the increasing plant capacities. Moreover, fully automated CLT manufacturing lines come with a substantial cost, ranging from $10 million to $25 million or more, depending on the level of automation (Dovetail 2017). This investment underscores the industry's commitment to advanced technology for efficient and sustainable production processes.

The growth of cross-laminated timber (CLT) production not only fosters innovation in construction but also plays a vital role in job creation across forestry, manufacturing, and construction sectors. This not only supports the local economies but also aligns with the increasing demand for regionally sourced wood, driven by considerations such as LEED certification (Dovetail 2017).

Another significant aspect is the energy efficiency and insulation properties of CLT panels, contributing to improved thermal performance in buildings. This feature enhances overall energy efficiency, potentially reducing the reliance on additional heating or cooling systems. The affordability and sustainability of CLT are crucial for its wider adoption, with efforts to integrate CLT into US building codes deemed essential (Pei et al. 2016; Van de Lindt et al. 2023). A noteworthy example is the success story of Thomas Logan, where an affordable housing project in Idaho demonstrated that the structure, featuring a five-story wood over a two-level concrete podium, did not use fire-retardant-treated lumber for the exterior walls of the wood-framed portion. This decision not only added to affordability but also highlighted the constructability of CLT structures contributing to cost equation aspect.

2.10 Transportation and logistics

The researchers delve into the intricacies of optimizing logistic costs by determining the most cost-effective strategies, employing a Just-In-Time (JIT) operational approach, as noted by MacAskill et al. (2021).

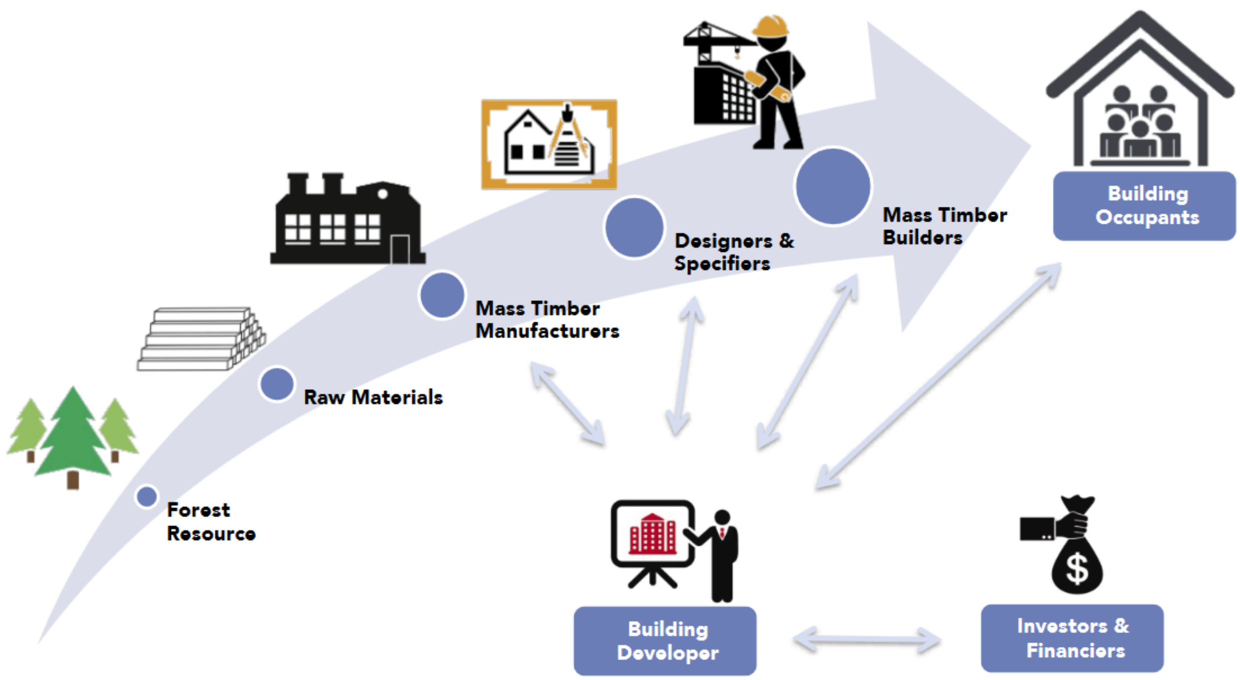

Figure 31 Supply chain of CLT (Source: (Anderson et al. 2021))

One significant aspect of the optimization process involves the assignment of modules to specific truck types considering dimensions, weight capacities, and transportation cost rates associated with different truck types (Almashaqbeh and El-Rayes 2022). Furthermore, practical constraints daily truck trips, weight capacities, non-overlapping of modules, weight distribution within shipments, aerodynamic drag reduction, installation day coordination, and the availability of storage space represent the real-world challenges and limitations that must be navigated to achieve an optimized, streamlined, and cost-effective modular construction logistics system (Almashaqbeh and El-Rayes 2022).

2.11 Conclusion

In conclusion, the literature review has provided a comprehensive overview of the multifaceted landscape of modular construction and CLT production, emphasizing key themes that shape the current discourse. One overarching theme highlights the optimization of the production process, wherein researchers and industry experts advocate for the integration of innovative and advanced machines. This strategic use of technology not only streamlines manufacturing but also enhances efficiency, precision, and scalability. Moreover, the study underscores the significance of embracing innovative designs that contribute to an overall optimization of the production process, allowing for increased flexibility, adaptability, and architectural creativity in CLT and modular construction.

The reviewed literature has also shed light on the vital role of transportation logistics and supply chain management, emphasizing the need for optimized strategies and just-in-time operations. Furthermore, various studies have explored the potential economic ripple effects in the manufacturing of cross-laminated timber (CLT), noting the importance of managing cost fluctuations and addressing challenges associated with supply chain, raw materials, and economic dependencies.

As we navigate the intricacies of modular and CLT construction, it is evident that addressing practical challenges within the industry holds the key to unlocking viable solutions for affordable housing. By leveraging the insights gained from optimizing production processes, incorporating advanced machinery, and embracing innovative designs, we can pave the way for a more sustainable, cost-effective, and scalable future in the realm of modular and CLT construction. Through collaborative efforts, continual innovation, and a commitment to overcoming challenges, the industry stands poised to not only meet the growing demand for affordable housing but also contribute significantly to the evolution of modern construction practices.

CHAPTER III METHODOLOGY

3.1 Introduction

Affordable housing remains the challenge in the US with growing need for cost-effective and sustainable solutions. While CLT modular technology holds promise for addressing affordability concerns, there is a lack of comprehensive research focusing on its manufacturing aspects. Therefore, the problem addressed in this study is the limited understanding of how CLT modular technology can improve the efficiency, standardization, and productization of affordable housing in the US from a manufacturing perspective.

Chapter I lays the groundwork for this study by introducing the research area and providing the necessary background. Chapter II delves into a comprehensive literature review, covering manufacturing and construction processes, as well as an analysis of cost prediction models. Building upon the foundation set by these two chapters, this chapter outlines the research approach and methodology. It further clarifies the objectives and delineates how the preceding chapters contribute to and connects with this research. This chapter thus serves as a bridge, linking the initial background and literature review with the research's objectives and methodology.

This chapter will outline the systematic approach for investigating the role of CLT modular technology in construction of affordable housing. The objectives and goals of the research, as well as the methodology used to achieve them, are described in this chapter. Data collection procedures such as Institutional Review Board (IRB) approval, semi-structured interviews are addressed in this chapter. The data analysis process is also covered in this chapter, including mixed analysis, and ensuring data quality through reliability checks. Content analysis is done qualitatively reviewing the project materials.

3.2 Research Goals

3.2.1 Research Goal-1: Exploring the Potential of Modular Mass Timber

The methodology will be designed to thoroughly investigate the potential of modular mass timber as a viable solution to the housing crisis in the United States. This will involve a comprehensive review of existing literature, case studies, and possibly primary research through interviews or surveys with industry experts.

3.2.2 Research Goal-2: Promoting Mass Timber

A significant part of this research will be dedicated to advocating for mass timber as a superior, scalable alternative to traditional construction materials like concrete and steel. The methodology will include a comparative analysis of these materials, highlighting the advantages of mass timber in terms of sustainability, cost-effectiveness, and other relevant factors.

3.2.3 Research Goal-3: Equipping Manufacturers with Necessary Knowledge

The research will also aim to provide manufacturers with the knowledge and tools they need to effectively utilize modular mass timber technology. This will involve identifying and analyzing the critical success factors (CSFs) in the manufacturing process, and developing guidelines or recommendations based on these findings.

3.3 Research Objectives

3.3.1 Objective-1: Understanding Aspects of Modular Mass Timber Construction and Affordable Housing

The preliminary objective of this study was to understand aspects of modular mass timber (CLT) construction. This Objective-1 was achieved by reviewing the existing literature available for the Modular Projects, or CLT Projects. The first two chapters of this study, Chapter-1 Introduction and Chapter-2 Literature Review, covered the foundational information and background required to understand the topic. The available information was synthesized and categorized to work on the next objective of this study.

3.3.2 Objective-2: Establishing Foundation for Generation of CSFs in Manufacturing of Modular Mass Timber for Affordable Housing

As the study focused on generating Critical Success Factors for a modular mass timber project, our second objective was to establish a foundation to generate these CSFs. For this, it is important to identify the literature patterns and underlying basics of past projects in Modular Construction and CLT Construction. With the understanding of concepts used to build these projects, key characteristics of Cross-laminated Timber (CLT) mentioned in past research were discovered. As there were numerous Modular Construction projects built in the past couple of years using materials like concrete and steel, we derived important attributes for the modular construction from the available literature. This study aimed to focus on Manufacturing Process, and it is important to understand behind the scenes of manufacturing for modular mass timber projects. This helped us to build a framework for questionnaire preparation around the central thought.

3.3.3 Objective-3: Developing the CSFs in Manufacturing of Modular Mass Timber Construction for Affordable Housing

The study's third objective was to develop the CSF in Manufacturing of Modular Mass Timber i.e.

Modular CLT Manufacturing. This goal was achieved by framing the research method in such a way that it will create a path to find correlation of those factors. Sophisticated data collection was further analyzed to generate critical success factors in a project. Spearman's Rank Correlation Coefficient was used to determine the strength of each paired relationship among the factors. Another method of Multi-Criteria Decision-Making (MCDM) tool called the Decision-Making Trial and Evaluation Laboratory (DEMATEL) technique was used to identify cause-effect relationship between factors in complex relationships.

3.3.4 Objective-4: Demonstrating Prioritized Rubric to conclude CSFs in Manufacturing of Modular Mass Timber for Affordable Housing

This study's final objective was to demonstrate the prioritized rubrics developed by prioritization of found CSFs. The rubrics were identified from the key CSFs found from data analysis which were further interpreted to formulate strategies and actions for improvements in this complex system. The identified interactive relationships among the CSFs will assist managers and decision-makers to incorporate effective strategies and target strong or weak CSFs to focus on improvements in CLT modular industry.

The main research questions that guide this study is as follows:

"What are the critical success factors (CSFs) that need to be considered to ensure the successful manufacturing of modular mass timber for affordable housing in the US?"

This main research question leads us to the following sub-questions which need to be addressed-

a. How do these CSFs correlate with each other, and what strategies can enhance their impact?
b. Among these CSFs, which ones are the causes or effects within the manufacturing system of modular CLT, and how should their influence be managed?
c. Which factors are the primary drivers in the manufacturing process of modular CLT?
d. What should be the prioritization sequence for addressing these factors?

3.4 Research Approach

This study initiated by carrying out an in-depth literature review analysis of manufacturing practices in modular and CLT industry, by completing the first stage to identify initial drivers in the study. Further, Fifteen semi-structured interviews from domain experts were targeted initially to derive a relation between different variables (Khan et al. 2022; Ruben et al. 2019; Syed 2020). But, after twelve interviews sufficient data was collected to initiate data analysis. The unit of analysis in this study was the manufacturing process in context of modular, mass timber products which was Cross-laminated Timber for this study. The population consisted of construction professionals with experience in modular and/or mass timber construction industry and served as either manufacturer, architects, structural engineers, or professionals working in any of these fields. As such affordable housing projects are less in number to expect having expert for this category, but professionals who worked on projects for affordable housing were an added advantage for us. For the participants selection, purposive sampling (Syed 2020), was used, ensuring that participants were the representative of the population and had the relevant expertise to provide insightful responses. To expand the data collection scope, the snowball sampling method turned out to be helpful to achieve the desired sample size. The study was not restricted to a particular geography due to limited availability of modular CLT projects for affordable housing in the US as stated earlier in sub-chapter 1.5. Finally in the last stage, we proposed the prioritized rubric of CSFs was demonstrated and possible improvement strategies were suggested for betterment of CLT modular manufacturing. Figure 32 represents the methodology of the study.

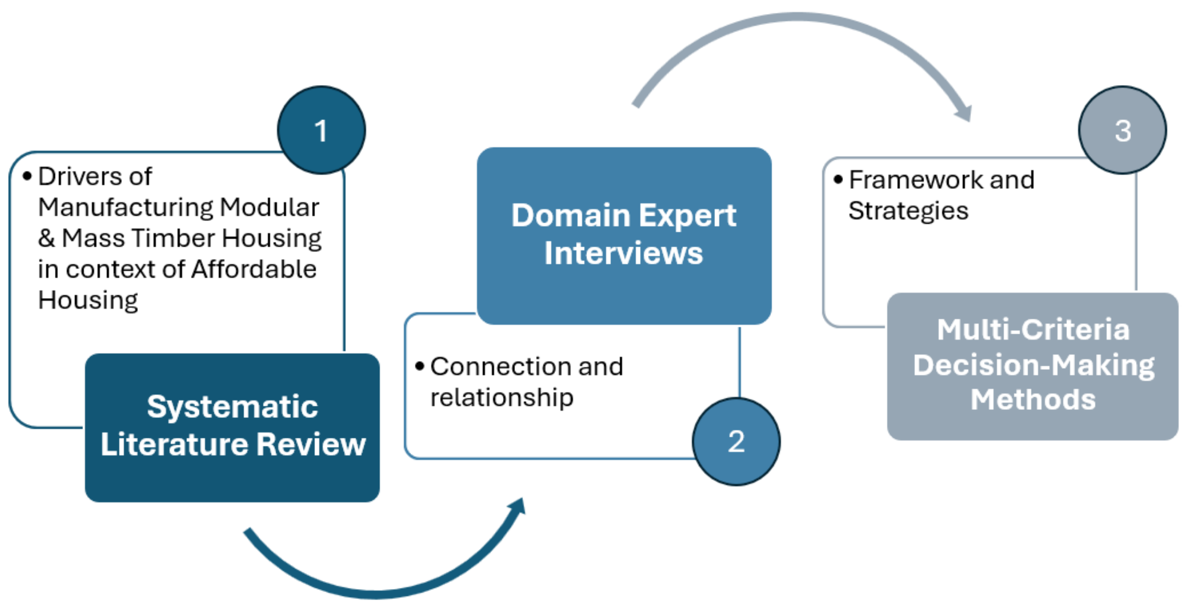

Figure 32 Methodology of proposed study (Adapted from (Khan et al. 2022))

3.4.1 Systematic Literature Review Process

We initiated a systematic review of relevant literature for the proposed study. A systematic data collection protocol of four steps, namely identification, eligibility and inclusion were followed. This is the common approach used by AEC industry for data extraction process (Khan et al. 2021).

3.4.1.1 Identification

The relevant publications for the study were identified using keywords related to the study based on unconstrained and unconstructed search. The previous studies in the same domain were helpful additionally. The ProQuest and Google Scholar database was used for the search as authentic search engines. The keywords identified were mainly Modular, Mass Timber, Affordable Housing, manufacturing, and drivers. Additionally, in Modular, other keywords such as 'prefabrication', 'manufactured housing', 'offsite construction', 'volumetric construction' 'panelized construction' 'modern method of construction', 'modular for affordable housing' were used. For Mass Timber keywords like 'CLT', 'manufacturing of CLT', 'tall timber construction', 'sustainable buildings' 'mass timber for affordable housing' helped. In the case of Manufacturing, keywords such as 'DfMA', 'standardization', 'industrialization', 'supply chain of modular construction', 'logistics', 'timber manufacturing' 'production strategy', 'production' were used. Similarly, for drivers, analogous words such as 'benefits', 'advantages', 'enablers', 'factors' were considered. Lastly, for affordable housing, specific keywords like 'sustainable housing' 'affordable housing' were used. This approach helped rigorous search on previous studies (Khan et al. 2022).

3.4.1.2 Screening & Eligibility

The screening process included (1) year of publication ranged from 2005 to present, as studies before that were deemed irrelevant because of the scope & scarcity of literature before the year 2005, (2) language was restricted to English only. Document type was not restricted because it I the latest topic and needs recent information, though, for the review, literature used was based on the hierarchy as journal article, then peer-reviewed articles, book, thesis, web-articles were used. A full abstract reading of all articles was crucial step to decide the eligibility criteria including, (1) Lack of focus on subject matter; (2) related sectors such as manufacturing (Khan et al. 2022).

3.4.1.3 Inclusion

Articles pertaining to the drivers were selected and were included for analysis. Articles critically analyzed and via synthesis following driving factors had categorized them: time, cost, productivity, efficiency, education, collaboration, standardization, scalability.

3.4.2 Domain Expert Semi-Structured Interview

As a data collection tool, we used semi-structured interviews. We provided the questionnaire beforehand to the interviewee to serve the purpose of getting key information about the topic by focused discussion in the interviews. The interview questionnaire is attached in Appendix-A.

These interviews were conducted virtually on Microsoft Teams and recorded with participants' consent for future references. The interviews lasted for an average of 45 to 60 minutes duration, allowing for an in-depth exploration of the participants' experiences, perspectives, and attitudes to define a project's success. The study used transcription of video-recorded interviews from built-in transcription feature of Microsoft Teams application and analyzed using mixed data analysis tools. The key findings and important insights were marked and saved in spreadsheet. The author read the transcripts and identified key themes and patterns in the collected data for further analysis. These are further discussed in sub-chapter 4.3. The author analyzed the data in a systematic and rigorous way, ensuring that the findings were grounded in the collected data.

3.5 IRB

Research involving human participation must get approval from Institutional Review Board (IRB) before starting the data collection. The approval letter from IRB for research is attached in Appendix-B. Participants consent to asking to conduct virtual interviews with their permission recorded in the interview. As the study was not intended to seek any private information from the participants and was conducted in a commonly accepted educational setting, it was determined to be exempt.

3.6 Data Analysis

3.6.1 Spearman's Rank Correlation Method

Spearman's rank correlation coefficient is a nonparametric measure of association between two variables (Assaf and Al-Hejji 2006; Gunduz and Yahya 2015; Petrović et al. 2018). It assesses the strength and direction of the monotonic relationship (whether it increases or decreases) between the ranks of the data points. Here's the equation to calculate it.

$$\rho = 1 - \frac{6 \times \sum d^2}{n(n^2 - 1)}$$

In typical Sperman's Rank Correlation Analysis we follow the following steps-

Step 1: Rank the Data

Assign ranks to each observation for both factors. If there are ties (i.e., equal values), assign the average rank to those tied observations (Wuni and Shen 2020).

Step 2: Compute Differences in Ranks

Calculate the difference between the ranks for each pair of observations. Based on the direction influence the difference will be either positive or negative (Wuni and Shen 2020).

Step 3: Square the Rank Differences obtained in step 2.

Step 4: Sum Up the Squared Rank Differences

Step 5: Apply the Formula

By using the equation stated above we determine Spearman's rho for each paired relation.

Step 6: Interpret the Results

As the value for Spearman's rho ranges from -1 to 1 the following guidelines will help to interpret the results (Gunduz and Yahya 2015; Petrović et al. 2018; Wuni and Shen 2020).

a. The positive value of Spearman's rho denotes monotonic increasing relationship.
b. The negative value of Spearman's rho denotes monotonic decreasing relationship.
c. The Spearman's rho value closer to 0 suggests no monotonic relationship.

As we used MATLAB for data analysis, the above steps were modified to best suit the MATLAB interface at the same time retaining the originality of the method (See Appendix-D).

3.6.2 Decision-Making Trial and Evaluation Laboratory (DEMATEL) Technique

The DEMATEL method is a well-established methodology used to understand the complex causal relationships among different factors (Petrović et al. 2018; Si et al. 2018). In our case, we used it to understand the key dependent factors and key driving factors out of the 10 CSFs.

In typical DEMATEL Analysis we follow the following steps-

Step 1: Construct the Direct Relation Matrix We constructed a direct relation matrix based on the questionnaire survey results of the survey. This matrix represented the direct influences among the CSFs.

Step 2: Normalize the Direct Relation Matrix We normalized the direct relation matrix to make the sum of all elements less than or equal to 1. This was done to ensure the feasibility and consistency of the matrix.

Step 3: Calculate the Total Relation Matrix We calculated the total relation matrix by adding the direct relation matrix and its successive powers until the matrix converged. This matrix represented the total influences (direct and indirect) among the CSFs.

Step 4: Analyze the Results We analyzed the results to identify the key dependent factors and key driving factors. The CSFs with higher row sums were the key driving factors, while those with higher column sums were the key dependent factors.

The results from the DEMATEL analysis provided additional insights into the interrelationships among the CSFs and their relative importance. As we used MATLAB for data analysis, the above steps were modified to best suit the MATLAB interface at the same time retaining the originality of the method. This is further explained in sub-chapter 4.8 and details of the code are provided in Appendix-D.

3.6.3 Method for Interpretations of Data Analysis Results

The data analysis led us to the next steps to discover the implications of these relationships from the results we achieved from Spearman's rank correlation coefficient method and DEMATEL technique. This not only corroborated the findings from the Spearman's rank correlation coefficient method but also highlighted some new aspects that were not evident earlier. The combined use of Spearman's rank correlation coefficient method and DEMATEL analysis provided a comprehensive understanding of the CSFs and their interrelationships. This dual-method approach made our case stronger and provided more robust evidence about the prominence of the factors.

In typical cases, these relationships were used for further analysis by:

1. Identifying Cause and Effect Groupings: This involved determining which CSFs had significant impacts on the system.
2. Interpreting the Results: This step involved understanding the implications of these cause-and-effect relationships.
3. Formulating Strategies or Actions: Based on the interpretation of the results, we formulated strategies or actions if the goal was to make informed decisions or gain insights into the problem we were studying.

To reach our final objective based on the representation of the heatmap of Spearman's rank correlation, we used the following steps:

Step 1: Find Key CSFs We identified the CSFs that had a significant impact on the system.

Step 2: Rank the CSFs We ranked the CSFs based on their impact on the system by summing up the correlation of each CSF. The CSF with the highest sum translated into the most influential one.

Step 3: Rank the Rubric We defined what constituted different levels of performance. This depended on the nature of the CSFs.

Step 4: Prioritize the Rubric We arrange the CSFs in the rubric according to their rank. The most influential one was at the top of the rubric.

For this, we used MATLAB, and the script and tables were attached in Appendix-D. This was implemented to achieve our goal. The idea of the rubric was to improve the performance of the system.

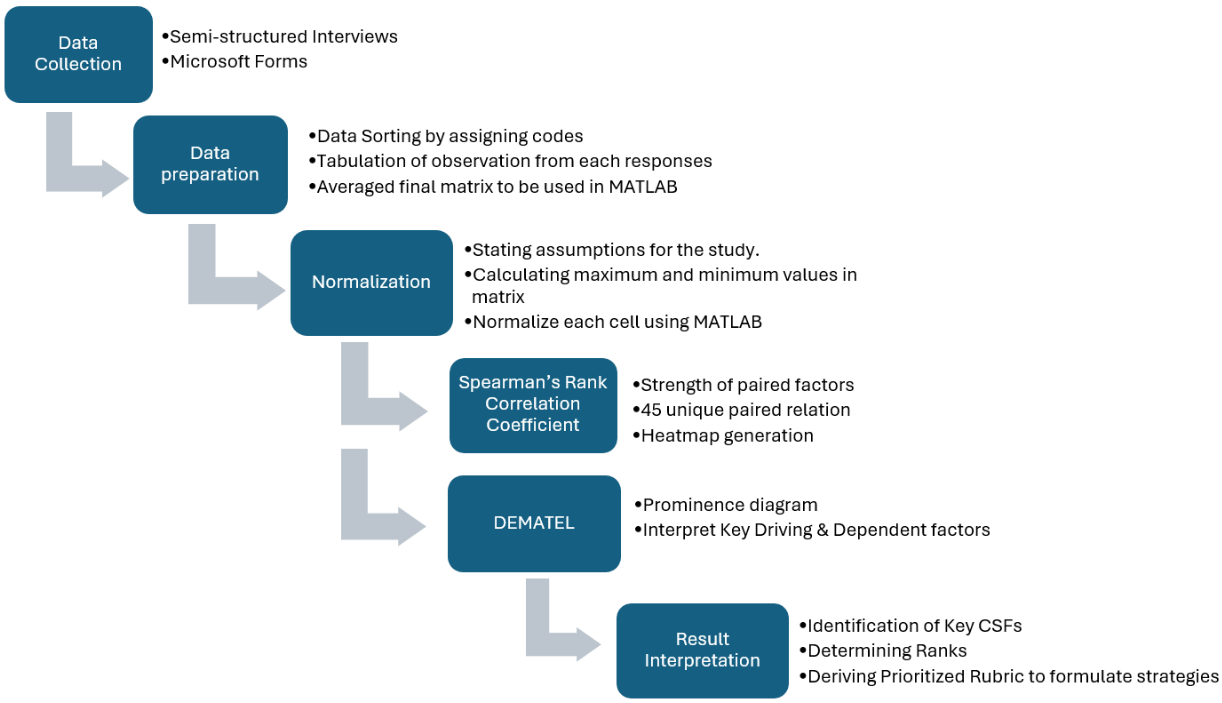

Figure 33 Final Representation of Research Method

3.7 Quality

The research ensured quality measures such as validity and reliability at various stages of the research. Clearly explained methods used for data collection and data analysis ensured methodological transparency. To ensure the quality of the data analysis, we conducted content validation by comparing the identified patterns against the research questions and objectives to ensure that they were relevant and accurate. In addition, compared results of our interviews and findings of literature review, multiple sources of methods to validate findings ensured the data triangulation. Using systematic and replicable methods for coding and analyzing the data maintained the reliability of this study. This helped to ensure consistency in the coding and analysis process. This approach minimized potential sources of bias or error in the study, thereby testing the construct validity (Yin, 2002). At the data collection stage, using the same questionnaire survey on same platform, maintained consistency, and tested internal validity. Clear audit trails and consistency in replicated data maintained the dependability of the research. The combination of manual review, and content analysis during the data analysis of open-ended responses of interview can enhance the rigor and depth of analysis. By employing this rigorous methodology, this study aims to provide valuable insights to the manufacturing of modular CLT into the affordable housing market.

3.8 Summary

This section discussed data collection procedures including the IRB review and approval, details of conducting semi-structured interview. Data analysis methods such as the process of systematic literature review, methods of MCDM such as Spearman’s Rank Correlation Coefficient, and use of DEMATEL; and data quality measures taken to provide rigor and depth of analysis in this research were also presented in this section.

CHAPTER IV FINDINGS AND DISCUSSION

4.1 Introduction

The purpose of this chapter is to present the findings of our data analysis. We begin by restating the important results of our literature review, which provided valuable insights to prepare background information and questionnaire for our semi-structured interviews.

Next, we present the discussions from our interviews with industry experts. These discussions revealed common themes and successful project management strategies, highlighted the influence of building codes on standardization, and identified critical aspects of coordination and collaboration in the industry.

Based on these discussions, we identified new Critical Success Factors (CSFs) and clustered them based on their similarities. We then used Spearman's Rank Correlation Coefficient to understand the interrelations among these CSFs.

Finally, we conducted a Decision-Making Trial and Evaluation Laboratory (DEMATEL) analysis to further explore the cause-effect relationships among the CSFs. This analysis helped us identify key driving factors and independent factors in the system.

The findings from our data analysis provide valuable insights and marks as a starting point for our results for decision-making and strategy formulation in CLT modular manufacturing. They highlight areas where improvement efforts could have the most impact and suggest areas for future work.

4.2 Literature Review Findings

The literature review offers an in-depth look at modular construction and CLT production, emphasizing the importance of production process optimization, innovative design adoption, and advanced machinery integration. It highlights the role of transportation logistics and supply chain management and explores the economic implications of cross-laminated timber (CLT) manufacturing. The review suggests that addressing industry challenges is key to developing affordable housing solutions. Insights from the review indicate that continual innovation and collaboration can lead to a sustainable, cost-effective, and scalable future in modular and CLT construction.

4.3 Background of Interview Subjects

In the pursuit of insights into modular Cross-Laminated Timber (CLT) manufacturing for affordable housing, a diverse group of experts had been assembled. The group included Subject 1, a founder of the Forest Business Network and a mass timber specialist with nearly 15 years of experience, who had been instrumental in organizing international mass timber conferences. Subject 2, the founder of Element5, brought a wealth of experience in business management, particularly overseeing operations, and manufacturing. Subject 3, the director of mass timber for Sterling Solutions, one of North America's leading CLT manufacturers, brought a unique perspective with her background in civil engineering and experience in CLT manufacturing. Subject 4, the COO of Forest Business Network LLC leveraged his educational background in forest resource management & communications to play a key role in organizing mass timber conferences. Subject 5, a mass timber structural engineer, had served as a technical director for Woodworks, a mass timber resource provider. Subject 6, an off-site construction business specialist from Simpson Strong-Tie, brought expertise in supply and fabrication. Subject 7, a regional director of Woodworks, had been educating the industry on sustainable solutions using mass timber. Subject 8, an architect, brought over 6 years of experience working on mass timber projects. Subject 9, a facility training coordinator, provided valuable knowledge to the industry by training laborers and installers of mass timber. Subject 10, an associate professor, and technical director for Vaagen Timber, had been contributing to the industry for over 15 years. Subject 11, the CEO of Timber Age Systems, provided affordable housing solutions. Lastly, Subject 12, a specialist in industrial automation for prefab construction, brought cutting-edge expertise to the field. Each of these experts, with their unique backgrounds and areas of expertise, provided invaluable insights into the research on modular CLT manufacturing for affordable housing.

4.4 Interview Discussions

During the interviews, each participant was asked questions in the context of the Critical Success Factors (CSFs) derived from the literature. The aim was to refine and finalize the set of CSFs. Participants were asked to define success in their own terms and discuss common themes observed in these types of projects.

The discussion focused on effective project management strategies that manufacturers should consider. Participants shared their opinions on standardization and its relation to efficiency. Given the importance and challenges highlighted in the literature regarding the strict requirements of building codes, participants also discussed their views on the influence of building codes and their impact on manufacturing components.

If we aim to strengthen manufacturing, increase supply, and scale production, understanding market perception is crucial. Thus, participants were asked about their opinions on the adoption of Cross-Laminated Timber (CLT) and the attributes developers typically look for when considering Mass Timber (MT).

In the context of the housing crisis, modular solutions have been able to address the problem to a certain extent. However, to provide a comprehensive solution that accounts for possible aspects while preserving the benefits of the modular system, participants were asked about the value proposition that CLT is adding.

Although not directly connected with manufacturing, participants were asked about satisfaction and feedback from end users. Even though end users are not the decision-makers in this process, their feedback can certainly influence the demand side, i.e., the demand for such sustainable living spaces, providing opportunities for investors to invest more in MT projects and scale manufacturing.

The interview concluded with remarks on key lessons learned and best practices implemented so far, or those that should be considered in the future to utilize this system to its full potential.

4.4.1 Overview of Successful Projects and Common Themes

When participants were asked to define success and discuss common themes observed in successful CLT modular projects, a broad consensus emerged. Everyone measured and defined success in their own way, often in terms of project budget and timeline.

As the study is primarily focused on affordable housing, Subjects 2 and 3 linked successes to the number of homes provided, or in other words, the fulfillment of housing demand and potential increased occupancy. Extending this point, Subject 6 mentioned that seeing multiple projects getting built was a measure of success.

Subject 10 added more details, stating that success is often regarded in terms of sustainability or affordability, but the real cost is hidden in fabrication. The design of the module and its reproducibility were highlighted by Subjects 1, 3, 4, 8 and 10.

Subjects 1, 2, and 9 linked successes to the delivery of material and logistics aspects. Another important point raised by Subjects 1, 2, 3, 6, 8, and 10 was about the collaborative efforts and the team involved. This gives us a broader idea that project budget, timeline, team and collaborative efforts, modularization, and logistics planning are translated as common themes of the project which are represented in the figure below.

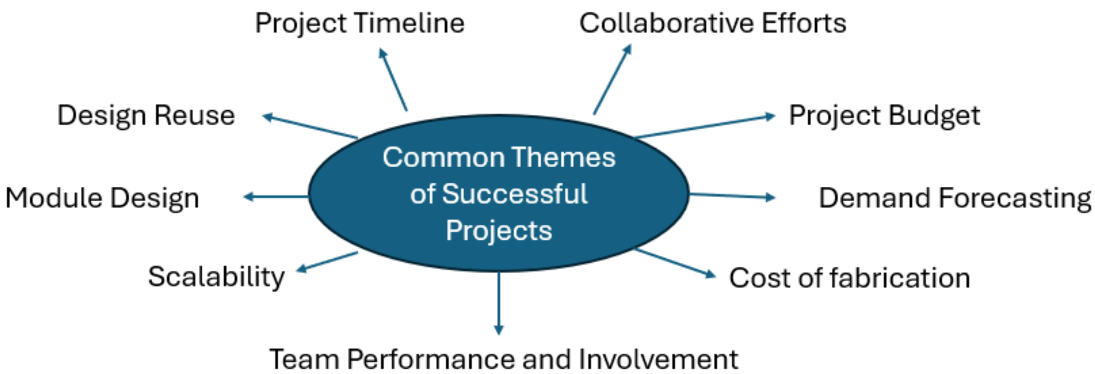

Figure 34 Highlights of Common Themes Discussion

The overarching fact that emerged from the interviews is that knowing the intent of the project and having a clearly defined approach at the very beginning will decide the success of the project.

4.4.2 Project Management Strategies for Manufacturers

In the interviews, participants discussed various project management strategies. The most common insights were related to 1) Project Delivery Methods, 2) Scheduling, Planning, and Logistics, 3) Design for Manufacture and Assembly (DFMA) Strategies, and 4) Integrated Building Information Modeling (BIM) Models.

1. Project Delivery Methods: Subjects 2, 7, 8, and 11 discussed how Design-Build delivery methods or Integrated Project Delivery (IPD) methods are better suited for modular CLT projects. These methods involve discussing the intent of the project beforehand and starting the design process early. Subject 4 added that in public projects, where the delivery method is often predetermined as design-bid-build, it's important to leave some flexibility in the drawings. Subject 10 seconded this point, emphasizing the need for flexibility throughout the project and not locking in one solution unless every detail is known from the beginning. Despite the benefits of these project delivery methods, Subject 11 highlighted the challenge of using IPD as the affordable housing projects are not built on large scale and suggested implementing lean principles to minimize waste.

2. Scheduling, Planning, and Logistics: Subjects 4, 5, 8, 9, 10, 11, and 12 emphasized the importance of efficient scheduling and well-thought-out planning for cost-effectiveness in the project. Subject 12 suggested using the waterfall methodology, which aims to lock in the timeline as early as possible.

3. DFMA Strategies: The incorporation of DFMA strategies was a significant point of discussion

among Subjects 2, 3, 5, 7, 8, and 10. They discussed the importance of penciling out the project first and letting the client know the most efficient layout using the Cross-Laminated Timber (CLT) panels. As manufacturers, it's crucial to communicate their limitations and capabilities to all involved parties.

4. Integrated BIM Models: In the discussion of project management strategies, the importance of team collaboration was highlighted again, with a focus on working on a single integrated BIM model and using the technology to its full potential.

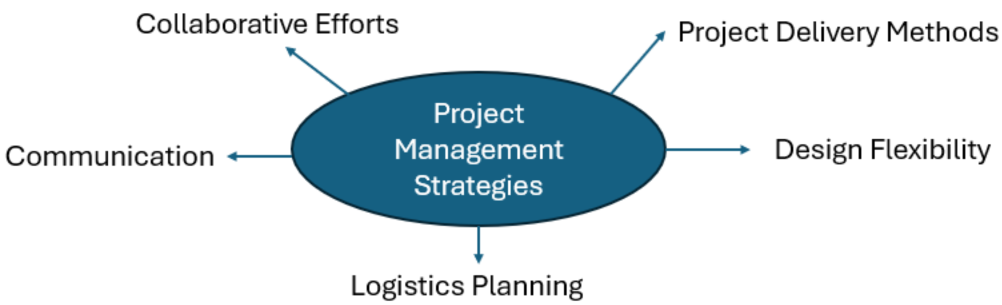

Figure 35 Highlights of the discussion from Project Management Strategies

These discussions provided valuable insights into the project management strategies that contribute to the success of modular CLT projects.

4.4.3 Standardization and Efficiency Outcomes

The participants were asked about their views on customization versus standardization and its impacts on manufacturing efficiency and outcomes. The majority expressed a positive opinion on standardization. They agreed that when trying to solve a problem on a national level, with demand in the millions, we need a robust solution that can be standardized, sizable, and repeated multiple times to yield the same efficient outcome.

While discussing standardization, the participants generally agreed that there should be either product standardization or process standardization. Subject 3 emphasized that standardization should be the key factor ensuring industry growth and competitiveness. They noted that the current market is supplying highly custom products, making it difficult and inaccessible from a cost perspective for general projects. They suggested educating designers for a more standard format that can be replicated across all manufacturers. Agreeing to the same opinion subject 11 added about highlighted importance of assessing trim loss, starting with a big panel, and balancing cutting versus actual selling to keep things tight.

Subjects 2 and 4 discussed the importance of optimizing structural design to reduce the overall cost of design and facilitate speed of construction. They highlighted the need to work within structural design parameters while still allowing flexibility within those limits. They also pointed out the transportation limitations of volumetric standard units and how standardization offers more architectural freedom and flexibility in design.

Subjects 5, 7, and 8 discussed the impact of customization on cost and design. They noted that if customization is not well thought out, it will lead to more tailor-made versions. They suggested starting with a standard kit as an economical solution and emphasized the importance of the right planning of components.

Subject 11 shared that they use a unique panel size of 5’x10’ to create larger assemblies. They mentioned that panelized manufacturers focus more on outer envelopes, and the project price depends on the envelope size. They also expressed hope that 60 to 70% of what they do is repeatable designs, and the other 30% is bespoke at a higher margin, allowing them to continue research and design efforts that are somewhat subsidized by the higher cost.

Subject 12 discussed the implications of working with this material. They noted that it doesn’t hinder creativity but puts a different set of constraints on it. They pointed out that tailor-made systems are made to accommodate any situation, whereas if you have a standardized modular system, you know what’s being handled within the scope of your system. They emphasized the importance of avoiding edge cases and anything falling outside the scope of your system so that you’re sticking to the nature of the modular system. They also stressed the need to understand the implications of these choices and how they affect manufacturing sequencing, installation, and everything else.

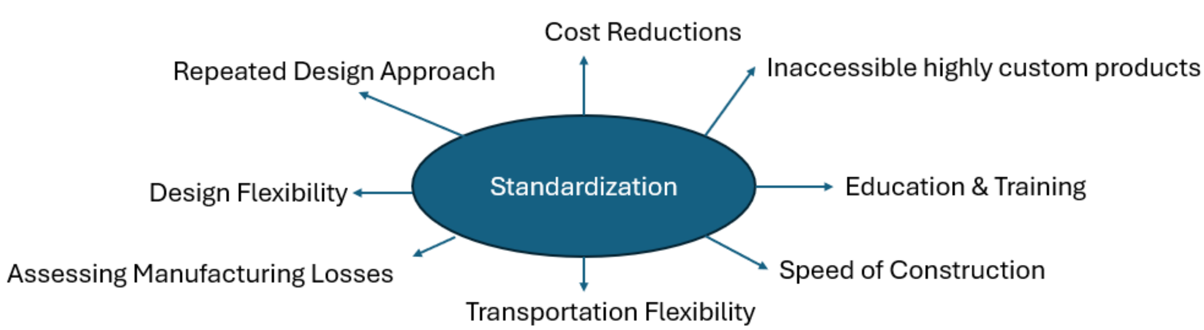

Figure 36 Highlights of discussion on Standardization.

In all, the participants agreed that the choice between customization and standardization depends on what you want to achieve. However, they leaned towards standardization as it lends itself to productivity, changes economic equations, and helps in achieving more consistent outcomes, especially for multifamily projects.

4.4.4 Influence of Building Codes Over Standardization

Continuing the conversation on standardization, participants were asked about the implications and provisions in building codes and their relation to standardization. Those who work closely with such code regulations and serve as architects or structural engineers provided their valuable opinions. Some subjects preferred not to answer this topic due to a lack of expertise.

For manufacturing, Subject 3 felt that building codes don't significantly affect how the industry is going to work towards standardization, other than the need to comply with codes. A significant hurdle comes when it comes to wide acceptance, as mentioned by Subjects 4 and 12. Subject 4 added that the building code is a game-changer but should be applied at the local jurisdiction level. Current efforts of authorities have already made provisions in the new code; it's a matter of areas or regions accepting it.

Subject 7 mentioned extra specific requirements for manufacturing, such as special inspection requirements, which might influence the standardization process. Subject 8 questioned whether it is plausible and okay to have the standardization of details and parts, and whether manufacturers are going to be receptive to that. They also discussed the potential benefits, such as increased exposure from what is available in the options we have, avoiding CLT at concealed spaces, and adhering to height limitations.

Subject 9 emphasized how high you can build the building and how much you can expose - all these factors will affect efficiency. Inspections are smoother as well and that really is going to come with codes and time and everything. Subject 10 added that one of the limiting factors for the adoption of CLT at any level was largely from a fire perspective, a point seconded by Subject 3. The development and adoption of building codes through the International Building Code (IBC) is the most important in terms of standardization, being largely prescriptive for performance. You must be able to design and be allowed to build with a product, so that manufacturers can then sell, develop, and sell the product.

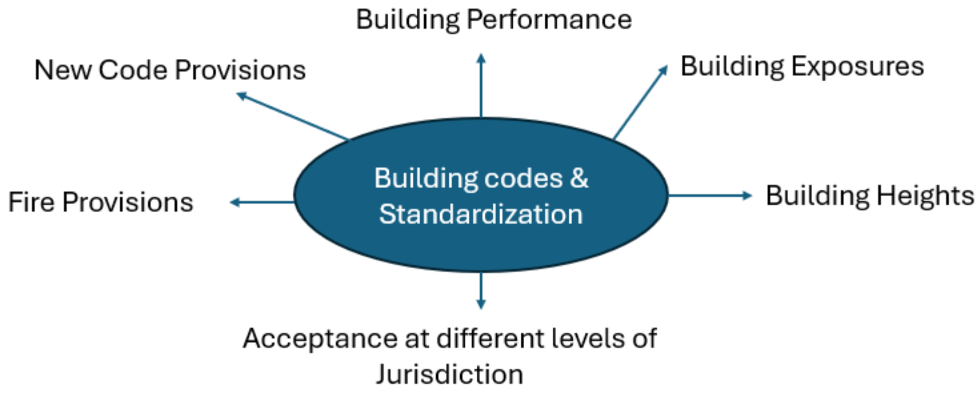

Figure 37 Highlights if Building Codes and Standardization Discussion

4.4.5 Critical Aspects of Co-ordination and Collaboration

Coordination and collaboration emerged as crucial topics throughout the interviews, with all participants discussing them in one way or another.

1. **Planning and Team Consistency:** Subjects 1 and 2 stressed the importance of planning and team consistency. They agreed that efficient planning, which requires a high level of coordination, translates into project success. Subject 2 emphasized the benefits of using the same team repeatedly to work efficiently and avoid mistakes.

2. **Role of Authorities and Feasibility Checking:** Subjects 2 and 9 highlighted the advantages of having a housing sanctioning authority on the project team and conducting feasibility checks beforehand. They agreed that these practices can lead to more successful outcomes.

3. **Project Delivery Methods:** Subjects 2, 4, and 12 discussed the importance of early collaborations from the beginning, leading to success. They mentioned that everyone should be at the table, trying to modify designs to fit the whole manufacturing process. However, Subject 4 added that in public projects, where the delivery method is often predetermined, it’s important to leave some flexibility in the drawings.

4. **Geography and Logistics:** Subjects 4 and 11 pointed out that geography plays an important role, particularly in terms of where the material is being delivered from. The proximity of suppliers can significantly impact logistical costs.

5. **Implications of Customization:** Subjects 7 and 12 discussed the implications of customization. They noted that as we transition from a lot of job-site coordination to offsite, the responsibility of coordination shifts to the one who is fabricating these modules, adding an extra layer of complexity.

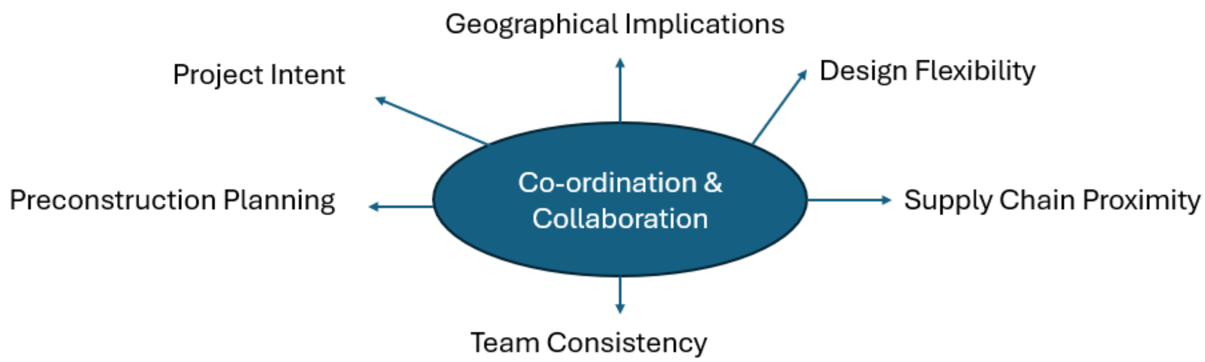

Figure 38 Highlights of Co-ordination & Collaboration Discussion

The participants highlighted the importance of planning, team consistency, early collaborations, understanding geographical implications, and managing the complexities introduced by customization and agreed that coordination and collaboration are critical aspects of modular CLT projects.

4.4.6 Adoption of CLT

The discussion so far has covered various aspects of modular CLT manufacturing. Now, it's important to understand the opportunities for CLT modular in the market from a development standpoint. We have discussed multiple times how modular technology has evolved over time as a solution to the housing crisis. Now, it's crucial to understand the adoption of CLT in the market by developers and what attributes developers are looking for when choosing materials.

The discussion highlighted that most developers are primarily concerned with the budget and timeline of the project, which will convert into a profitable business. Thus, there is a general perception that MT is expensive or often treated as a premium product. Subject 1 suggested that this misconception should be removed by educating developers from the initial planning stage which assured that MT projects are close to parity with conventional ones.

Subject 3 mentioned another factor driving affordability is how we can limit labor on site as much as possible due to regional inaccessibility, which will eventually cut down the cost. They also mentioned that there is a different equation for operating cost everywhere, and having conversations typically with engineers, architects, and developers regarding speed, aesthetics, and cost is important. They agreed with Subject 1's opinion that developers need to start rebalancing their priorities after learning throughout the process.

On the other hand, some developers are concerned about the sustainability aspect as well, and because of carbon storing, biophilic nature, and its uniqueness, as well as the distinguishable ability, MT holds stronger consideration for use. Subject 9 advocated choosing MT due to its lightweight nature and faster assembly ability, which makes it cheaper than traditional methods. This indicates the scope is increasing, and as Subject 10 says, when we're talking for the most part about residential buildings, particularly single-family, when we move over to multifamily, it's a different discussion.

4.4.7 Value Proposition added by CLT

Understanding the value proposition of Cross-laminated Timber (CLT) is crucial as it drives the manufacturing process. The use of top-notch equipment such as CNC routers, high-quality maintenance, and quality assurance and quality control in a controlled environment add value to using MT.

Subjects 1, 2, 3, and 4 mentioned that not interrupting the community with concrete trucks, sourcing raw materials from local forests, and avoiding material delivery from distances can drive down costs, providing cost-effective options. They suggested that the success of modular affordable homes is predicted by the need for CLT.

The sustainable benefits of MT were mentioned by almost all the subjects, indicating that this adds driving potential from the MT end. Subject 8 added that the sequestered carbon can be used for monetary benefits by using carbon credits for developers. This policy could make it more affordable for buildings with CLT in the future if some tax incentives were included. In addition to these benefits, the aesthetics and speed of MT construction also contribute to its value proposition.

The value proposition of MT lies in its cost-effectiveness, sustainability benefits, potential for monetary gains through carbon credits, and its aesthetic appeal and speed of construction. These factors make MT an attractive choice for developers and contribute to the success of modular affordable homes.

4.4.8 Satisfaction and Feedback of End Users

All the subjects who answered this question were very positive about the feedback received from end users. Cross-Laminated Timber (CLT) is a socially accepted mass timber product, and users feel connected with the space, happy, and more satisfied due to its biophilic and health benefits. People are experiencing these benefits in spaces where CLT is used, often without knowing the reason behind their improved well-being.

End users may not be sophisticated enough to understand the benefits of CLT, but makers and developers are capitalizing on this opportunity. This can correct the perception of affordable housing as a premium space rather than cheap housing. This will drive researchers and others to learn more about it, providing a good future scope to discover more about built users' perception. It may also lead to an increased demand for more manufacturing. The positive feedback from end users underscores the potential of MT in creating spaces that are not only efficient and sustainable but also enhance the well-being of the people who use them.

4.4.9 Case Study on CLT Module Manufacturing Steps

During our literature scan, we identified a noticeable gap in the discussion about the process of manufacturing modules with Cross-laminated Timber (CLT). To address this, we conducted an additional round of interviews with a participant who had expertise in this area. The interview provided valuable insights into various aspects of setting up a manufacturing unit for CLT modules.

Key Findings:

1. Types of Modules: The participant discussed two types of modules: 2D panels that are shipped to the site and assembled like IKEA furniture, and 3D modules that are transported directly to the site. Each type has its own advantages and disadvantages.
2. Choosing Between Panelized and Volumetric: The choice between panelized and volumetric modules depends on the use case. Volumetric modules work well for hotels, student housing, and apartment blocks, while panelized modules are suitable for smaller structures with a higher amount of variability in their design.
3. Market Contextualization: Understanding the market context is crucial for deciding between the two types of modules. For instance, multifamily housing works well with volumetric modules, but urban infill might require a different approach.
4. Production Sequencing: The participant emphasized the importance of production sequencing. Products should ideally land in the staging yard in the proper sequence for distribution to the job site.
5. Manufacturing Assembly for 3D Modules: The participant suggested a process timing sequence to balance the assembly line and avoid bottlenecks downstream. The assembly of the structure would typically start with the volume, then move down the line where other trades would step in.

6. Fishbone Shape Assembly Line: The participant suggested a fishbone-shaped assembly line with the main line and some assembly lines feeding into it. This setup works well when there is a high level of standardization across the product platform.
7. Space Optimization: In terms of space optimization, the participant suggested sequencing when different trades come in on different days. This low-tech solution can be effective when there is no technology to move modules.
8. Machinery and Automation: For a CLT panel system, the participant mentioned the need for a fastening system to join the edges together. Since there is no industrial robot big enough to lift these panels, an overhead crane would be necessary. While automation is seen in panelized assemblies, volumetric modules involve a lot of manual work.

These findings provide a foundation for developing a logical diagram for a possible assembly line structure. These insights of these interview and related literature (Banerjee et al. 2006; Mehrotra et al. 2005) were synthesized into a coherent model for setting up a manufacturing unit for CLT modules, explained in the Figure 39 & 40 here.

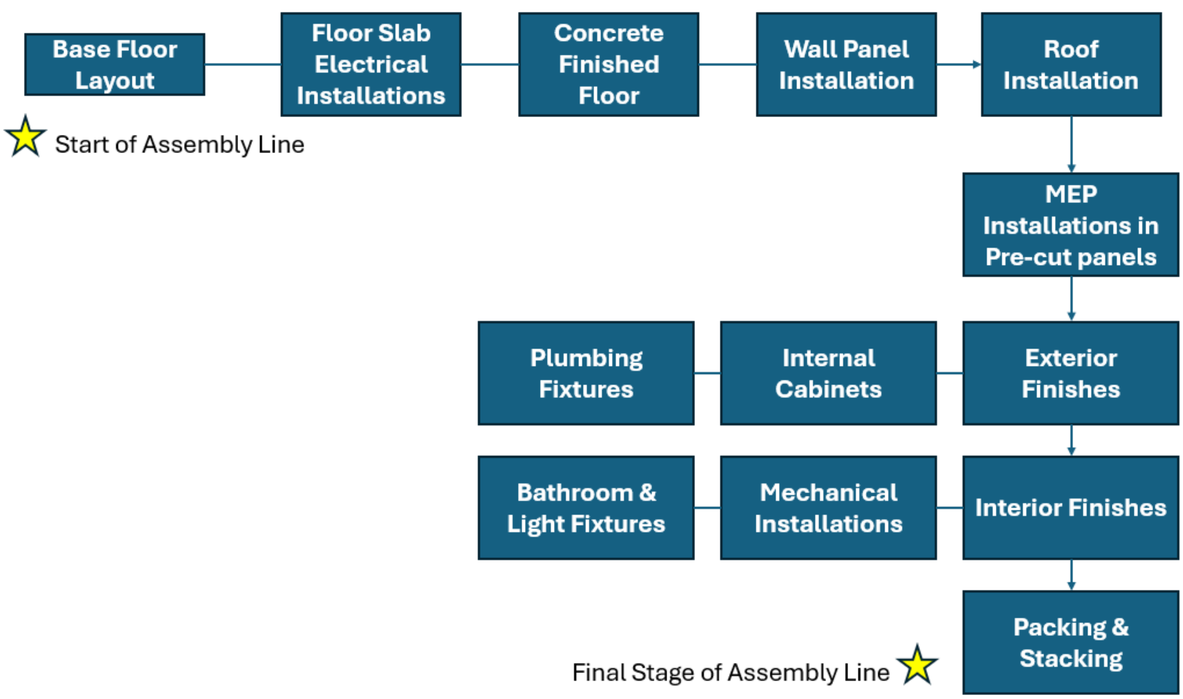

Figure 39 Possible Option for MT Module Assembly Line

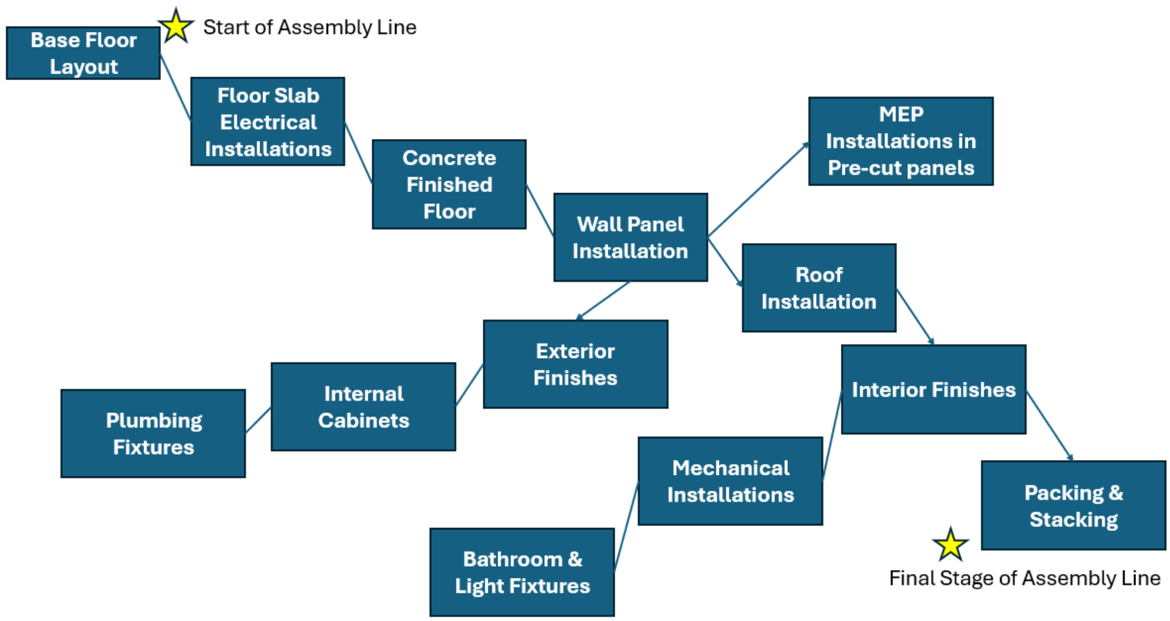

Figure 40 Other possible MT Module Assembly Layout (Inspired from Fish bone type assembly for Space Optimization)

4.5 New CSFs from Interviews

After analyzing the interview transcripts, we identified certain Critical Success Factors (CSFs) that were not previously discussed in the literature. All the interviews provided additional direction and input to the CSFs, enriching our understanding of what contributes to the success of CLT modular manufacturing projects. The literature review highlighted key terms such as time, quality, operations, efficiency, cost considerations, project management strategies, and logistics. However, during the interviews, new terminologies and themes emerged repeatedly.

Participants discussed the importance of supply chain management, effective planning, collaboration, replicability of units, reuse of designs, training and education, risk management strategies, research initiatives, team performance efficiency, and change management. The lack of standardization was pointed out as a significant issue, sparking further discussion, and highlighting the need for research in this area. The conversation also touched upon product standardization and the standardization of the overall process.

Cost, being a crucial driving factor in any successful project, was another major theme in the interviews. Participants highlighted various cost parameters such as managing the overall building cost, modular unit production cost, component expenses, and manufacturing cost per unit. Time parameters such as assembly time, changeover time, and lead time were also discussed.

4.6 Clustering of CSFs

Through interviews and literature reviews, our discussion highlighted numerous terminologies that are pivotal to the CLT modular industry. It's crucial to concentrate on these success factors. The primary objective of this study is to identify the critical success factors (CSFs). To achieve this, we decided to cluster similar terminologies for conciseness. The rationale behind this clustering approach was to organize the CSFs in a manner that simplifies understanding and analysis. Grouping similar CSFs allowed for easier pattern recognition, theme identification, and focused analysis. This method aided in refining the CSF list by eliminating redundancies and emphasizing the most significant factors. Furthermore, it offers a structured way to present findings, enhancing their accessibility.

Clustering similar Critical Success Factors (CSFs) together involved a process of categorization based on shared characteristics or themes. Here's a general overview of how we worked on this process:

1. Identify Common Themes: We started by reviewing each CSF and identified common themes or characteristics. This was based on the nature of the factor (e.g., related to cost, time, quality, etc.).
2. Group CSFs Based on Themes: Once we identified the common themes, we grouped the CSFs accordingly. Each group contained CSFs that shared a common theme.
3. Refine the Groups: We reviewed the groups and the CSFs within them. If a CSF seems to fit into more than one group, we also considered whether a new group was needed or if the themes need to be refined.
4. Name the Clusters: Finally, we give each cluster or group a name that accurately represents the common theme of the CSFs within it.

4.7 Final List of CSFs

After clustering, we arrived at the following list of CSFs:

1. **Modularity Index:** This term represents the combined measure of modularization rate and modular reusability, indicating the degree to which modular components are utilized and reused within a system or process.
2. **Time Optimization:** A set of measures aimed at optimizing time-related factors within manufacturing processes, including reducing time to market, minimizing changeover time, streamlining assembly processes, and improving customization lead time.

3. **Quality:** The term includes the product quality on the fabrication end as well as the construction end.
4. **Supply Chain Flexibility:** The term includes supply chain and logistic strategies, and logistics planning.
5. **Standardization:** The term includes both the ideas of the standardization of the product and the standardization of the overall process.
6. **Cost Control Framework:** A structured approach to controlling costs within construction or manufacturing operations, encompassing strategies for managing overall building costs, modular unit production costs, component expenses, and manufacturing costs per unit.
7. **Operational Efficiency:** This term encompasses various aspects of efficiency within an organization or project, including manufacturing processes, team performance, project management practices, and achieved outcomes.
8. **Comprehensive Planning Framework:** This term encompasses the various elements involved in the planning phase of construction projects, including preconstruction planning, collaborative efforts, design strategies, risk management, and change management.
9. **Capability Enhancement:** The term emphasizes the focus on improving the knowledge, skills, and capabilities of employees through education, training, and ongoing research initiatives.
10. **Capacity Management & Demand Optimization:** The term encapsulates scalability, demand forecasting, and capacity utilization to maximize production efficiency and effectively meet customer demand.

This list was then circulated among the participants to identify interrelations between each factor. Maintaining this list also ensured consistency when asking participants about the factors, enabling all participants to respond to all relations in the same manner.

4.8 Interrelation among CSFs through Spearman's Rank Correlation Coefficient

In this chapter, we delve into the interrelations among the Critical Success Factors (CSFs) that we have identified so far. We aim to understand how these factors interact with each other, their hierarchical relations, their relative importance, and their mutual influences.

To achieve this, we shared a short questionnaire survey with the same participants from whom we derived the CSFs. We provided the definitions for all the 10 CSFs, as mentioned in Subchapter 4.6, and asked them to identify the relationships among these factors. The possible relations were “influencing”, “getting influenced by”, “mutually influence”, or “no influence”(Wuni and Shen 2020). Questionnaire is attached in Appendix-A.

For better representation, we translated these relations into Likert forms or assigned code based on the direction of influence. For every relation where factor A influences factor B, we represent this relation by assigning code of 1. If factor A gets influenced by B, we represented it as -1, 0 for no influence, and 2 for mutual influence, denoting a higher power in the relationship. The survey responses recorded in Microsoft Forms are attached in Appendix-C.

We translated all the 11 responses into individual matrices. Though we interviewed 12 participants, only 11 responded to the survey, thus we initiated our analysis with these 11 responses. Despite several reminders, due to low response, we proceeded with the count of 11 respondents.

Next, we derived a final relation matrix or final ranked matrix for each cell by averaging all the responses for each cell. To refine our results, we needed a normalized matrix, which was done in MATLAB to have all its elements in the range [0,1]. The translated response matrices and final rank matrix are attached in Appendix-C.

We then decided to find the correlation between each pair of factors. Thus, we used Spearman’s rank correlation coefficient to find the statistical dependence between the rankings of two variables (Wuni and Shen 2020). It helped to assess how well the relationship between two variables can be described using a monotonic function.

We created a 10x10 matrix where each element represents the relationship between pairs of CSFs. We ran the code for data vector X & Y i.e., for each CSF pair, and the correlation coefficient for each pair was found out using a nested loop. This gave us a 10x10 matrix ‘rho’ where each element is Spearman’s rank correlation coefficient.

We initially decided to create a scatter plot for each pair, but with 10 CSFs, we would have 45 unique pairs, making it difficult to visualize effectively on a single plot. Thus, for a better approach, we decided to use a color-coded heatmap to visualize the correlation matrix (Kaiser 2022; Li et al. 2021). The created heatmap represents the Spearman’s rank correlation coefficient using a color scheme for each pair. The color bar on the right represents correlation values corresponding to colors. A positive correlation is represented by points that tend to go from the bottom left to the top right of the plot. For negative correlation, the points tend to go from the top left to the bottom right. If there is no correlation, the points will be spread out. Figure 41 represents results derived from MATLAB and heatmap of ranked correlation.

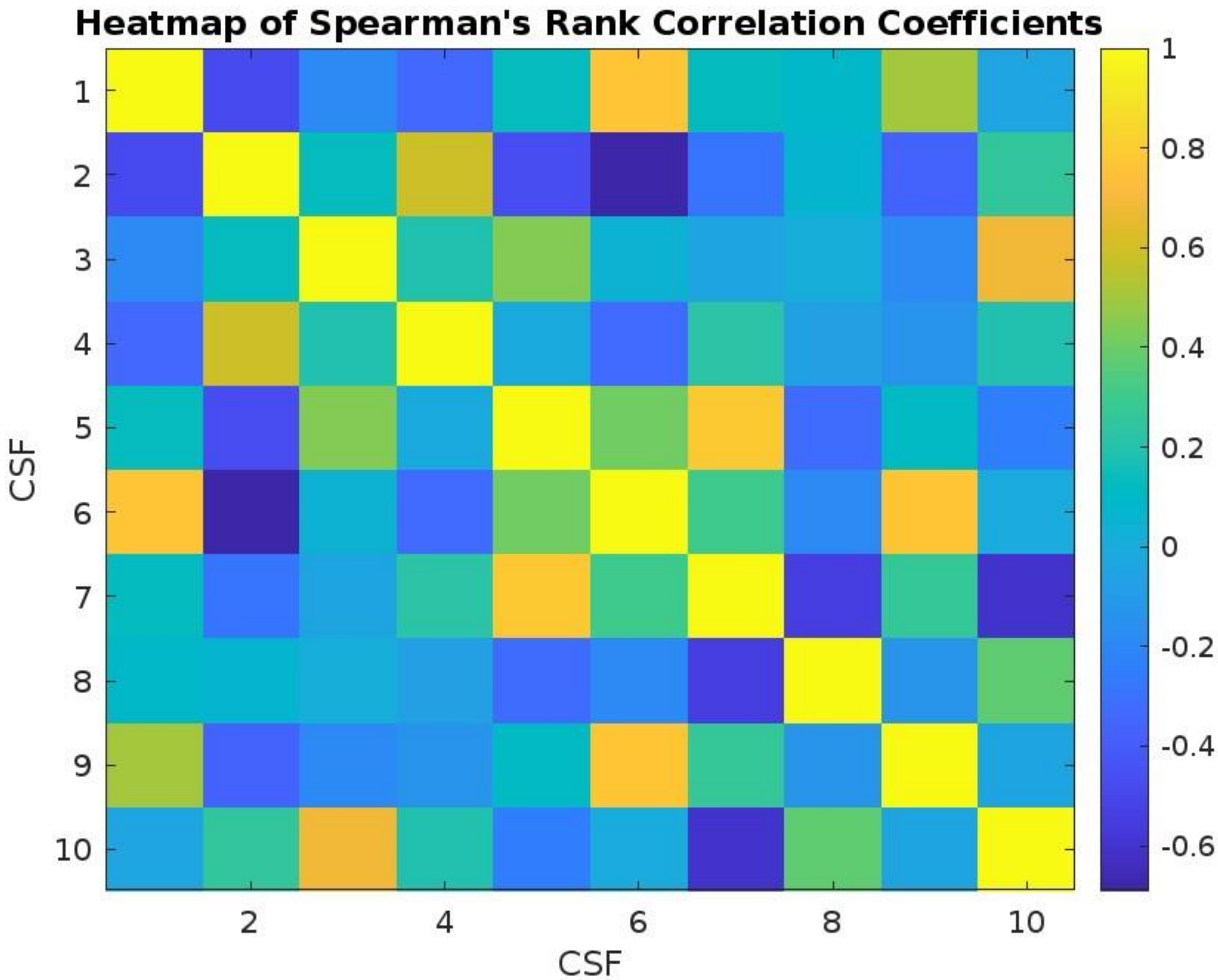

Figure 41 Heatmap of Spearman's Rank Correlation Coefficient

The script details for MATLAB and corresponding tables in each step table are attached in Appendix-D.

4.9 DEMATEL Analysis

In addition to the Spearman's rank correlation coefficient method, we also decided to run a parallel analysis using the Decision-Making Trial and Evaluation Laboratory (DEMATEL) method. This was done to strengthen our case and provide additional evidence about the prominence of the factors.

Here for DEMATEL as well, we made use of MATLAB (See Appendix-D) for calculations and other results. We initiated this method from earlier normalized matrix. The Analysis was conducted as follows:

Table 2 Matrix X - Average Ranked Matrix

	CSF1	CSF2	CSF3	CSF4	CSF5	CSF6	CSF7	CSF8	CSF9	CSF10
CSF1	0	1	0.91	0.82	0.73	0.73	1	0.82	0.45	0.91
CSF2	0.45	0	0.55	0	0.64	1.18	0.82	0.64	0.36	0.27
CSF3	0.55	0.55	0	0.73	0.36	0.82	0.82	1.18	0.64	0.55
CSF4	0.64	0.36	0.73	0	0.55	1.27	0.64	1.27	0.82	1.09
CSF5	0.36	0.82	0.36	0.55	0	0.91	0.55	0.82	1.09	1
CSF6	0.36	1	0.27	0.55	0.18	0	0.73	0.82	0.09	0.73
CSF7	0.45	1	0.64	0.45	0.18	0.73	0	1.18	0.18	1
CSF8	0.64	0.45	0.64	0.55	0.64	1.36	1	0	1	0.91
CSF9	-0.09	0.73	0.82	0.64	0.36	0.64	0.55	1	0	1.18
CSF10	0.18	0.45	0.18	0	0.45	0.73	0.82	0.91	0.64	0

Table 3 Matrix X - Normalized Matrix

	CSF1	CSF2	CSF3	CSF4	CSF5	CSF6	CSF7	CSF8	CSF9	CSF10
CSF1	0.06	0.75	0.69	0.63	0.57	0.57	0.75	0.63	0.37	0.69
CSF2	0.37	0.06	0.44	0.06	0.50	0.88	0.63	0.50	0.31	0.25
CSF3	0.44	0.44	0.06	0.57	0.31	0.63	0.63	0.88	0.50	0.44
CSF4	0.50	0.31	0.57	0.06	0.44	0.94	0.50	0.94	0.63	0.81
CSF5	0.31	0.63	0.31	0.44	0.06	0.69	0.44	0.63	0.81	0.75
CSF6	0.31	0.75	0.25	0.44	0.19	0.06	0.57	0.63	0.12	0.57
CSF7	0.37	0.75	0.50	0.37	0.19	0.57	0.06	0.88	0.19	0.75
CSF8	0.50	0.37	0.50	0.44	0.50	1.00	0.75	0.06	0.75	0.69
CSF9	0.00	0.57	0.63	0.50	0.31	0.50	0.44	0.75	0.06	0.88
CSF10	0.19	0.37	0.19	0.06	0.37	0.57	0.63	0.69	0.50	0.06

Step 1: Calculate the Sum of Rows and Columns.

This sum of rows will give us the vector D and sum of columns will give us another vector R.

Table 4 Prominence Relation Calculation on Matrix X _Normalized

	CSF1	CSF2	CSF3	CSF4	CSF5	CSF6	CSF7	CSF8	CSF9	CSF10	D
CSF1	0.06	0.75	0.69	0.63	0.57	0.57	0.75	0.63	0.37	0.69	5.70
CSF2	0.37	0.06	0.44	0.06	0.50	0.88	0.63	0.50	0.31	0.25	4.01
CSF3	0.44	0.44	0.06	0.57	0.31	0.63	0.63	0.88	0.50	0.44	4.90
CSF4	0.50	0.31	0.57	0.06	0.44	0.94	0.50	0.94	0.63	0.81	5.70
CSF5	0.31	0.63	0.31	0.44	0.06	0.69	0.44	0.63	0.81	0.75	5.08
CSF6	0.31	0.75	0.25	0.44	0.19	0.06	0.57	0.63	0.12	0.57	3.88
CSF7	0.37	0.75	0.50	0.37	0.19	0.57	0.06	0.88	0.19	0.75	4.63
CSF8	0.50	0.37	0.50	0.44	0.50	1.00	0.75	0.06	0.75	0.69	5.58
CSF9	0.00	0.57	0.63	0.50	0.31	0.50	0.44	0.75	0.06	0.88	4.64
CSF10	0.19	0.37	0.19	0.06	0.37	0.57	0.63	0.69	0.50	0.06	3.63
R	3.06	5.01	4.14	3.58	3.44	6.39	5.40	6.58	4.26	5.89	

Step 2: Calculate The Total Prominence and The Net Prominence.

Table 5 Results of DEMATEL Analysis

	T=D+R	N=D-R
CSF1	8.766	2.641
CSF2	9.014	-1
CSF3	9.035	0.759
CSF4	9.283	2.124
CSF5	8.517	1.635
CSF6	10.28	-2.51
CSF7	10.03	-0.772
CSF8	12.16	-1
CSF9	8.897	0.386
CSF10	9.517	-2.262

Step 3: Plot The Prominence and Relation Diagram.

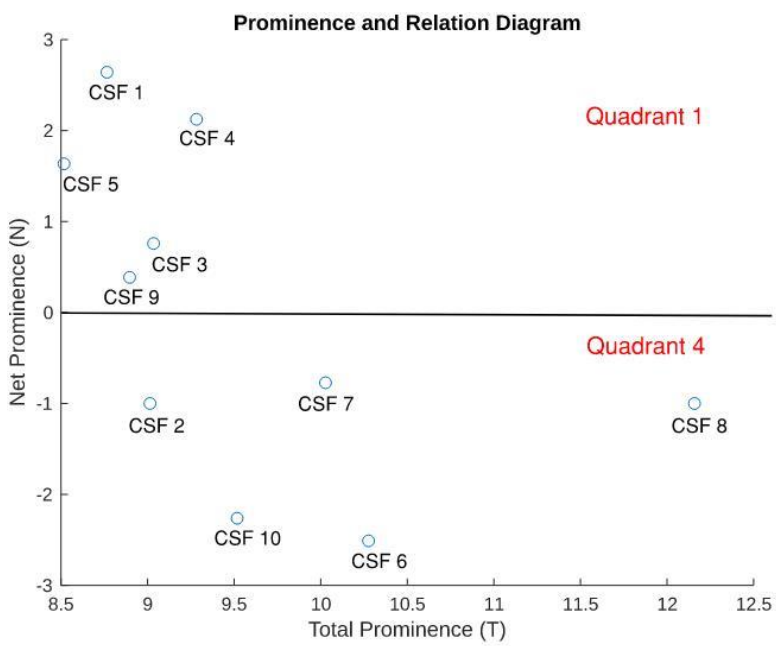

Figure 42 Prominence and Relation Diagram

We calculated the total relation matrix by adding the direct relation matrix and its successive powers until the matrix converged. This matrix represented the total influences (direct and indirect) among the CSFs.

4.10 Conclusion

In conclusion, this chapter has presented a comprehensive analysis of the critical success factors

(CSFs) that influence the successful manufacturing of CLT modules. The findings from the literature review and interviews have highlighted the importance of project management strategies, standardization, efficiency outcomes, and the influence of building codes. The value proposition added by CLT, and the satisfaction of end users further underscore the potential of this approach.

The interrelation among CSFs, as revealed through Spearman's Rank Correlation Coefficient and DEMATEL Analysis, provides valuable insights into the dynamics of these factors. The new CSFs identified from the interviews and their subsequent clustering have enriched our understanding of the field.

This chapter has thus provided a robust framework for understanding the complexities of CLT modular manufacturing, setting the stage for further research and practical applications in the realm of affordable housing.

CHAPTER V RESULTS, SUMMARY AND COTRIBUTIONS

5.1 Overview

The primary outcome of this study was to identify the critical success factors for the manufacturing of CLT modules for affordable housing in the US. Chapter 1 laid the groundwork by discussing the background and defining the key terms, thereby highlighting the purpose of the study. Chapter 2 built upon this foundation by reviewing relevant literature, which not only fulfilled our first objective but also provided a starting point for achieving the second objective. Chapter 3 delved into the research methods, describing the mixed-use of qualitative and quantitative approaches employed in this study. This chapter elucidated the appropriate methodology and identified who could assist us in answering our research questions. Chapter 4 detailed the execution of the analysis, thereby fulfilling our fourth objective. This brought us to the conclusion of the research, where we explained the outcomes of the study, its contribution to the body of knowledge, and the future scope. This final chapter summarized the output and marked the end of our research journey.

5.2 Results and Conclusion

5.2.1 Heatmap Results and Conclusion

The heatmap analysis (Figure 41) revealed significant correlations among the Critical Success Factors (CSFs) for the successful manufacturing of CLT modules. The analysis had shown both strong positive and negative correlations, which are crucial to understand the interplay between these factors.

1. **Modularity Index (CSF 1)** shows a strong positive correlation with **Cost Control Framework (CSF 6)** and **Capability Enhancement (CSF 9)**, and a strong negative correlation with **Time Optimization (CSF 2)** and **Supply Chain Flexibility (CSF 4).**
2. **Time Optimization (CSF 2)** has a strong positive correlation with **Supply Chain Flexibility (CSF 4)** and **Capacity Management and Demand Optimization (CSF 10).** It also shows strong negative correlations with several factors, most notably with **Cost Control Framework (CSF 6).**
3. **Quality (CSF 3)** has a strong positive correlation with **Capacity Management and Demand Optimization (CSF 10)** and a slightly positive relationship with **Standardization (CSF 5)**.
4. **Supply Chain Flexibility (CSF 4)** mostly shows neutral relationships with other factors.
5. **Standardization (CSF 5)** has a strong positive correlation with **Operational Efficiency (CSF 7)** and moderate positive relationship with **Cost Control Framework (CSF 6)**. It shows

noticeable negative relationships with **Comprehensive Planning Framework (CSF 8)** and **Capacity Management and Demand Optimization (CSF 10).**

6. **Cost Control Framework (CSF 6)** has a strong positive correlation with **Capability Enhancement (CSF 9)** and **Operational Efficiency (CSF 7)**, and a noticeable negative correlation with **Comprehensive Planning Framework (CSF 8).**
7. **Operational Efficiency (CSF 7)** shows strong negative correlations with **Comprehensive Planning Framework (CSF 8)** and **Capacity Management and Demand Optimization (CSF 10).**
8. **Comprehensive Planning Framework (CSF 8)** has a fair positive correlation with **Capacity Management and Demand Optimization (CSF 10).**

Weak relationships among the Critical Success Factors (CSFs) are also significant and warrant attention.

A weak correlation could indicate several possibilities:

1. **Lack of Relationship**: The two factors may not significantly influence each other. This could mean that changes in one factor do not necessarily result in changes in the other.
2. **Independence**: The factors might operate independently of each other. In such cases, improving or modifying one factor may not have a direct impact on the other.
3. **Need for Improvement**: A weak relationship might suggest that there is room for improvement. For instance, if two factors are expected to be related but show a weak correlation, it might indicate that strategies need to be implemented to strengthen this relationship.
4. **Need for Further Investigation**: Weak correlations could also suggest that the relationship between the factors is complex and not linear, or that other variables are influencing the relationship. This could call for further investigation to understand the nuances of these relationships.

The correlations among these CSFs provided valuable insights into the dynamics of CLT modular manufacturing. Understanding these relationships was crucial for prioritizing and managing these factors effectively. While strong correlations provide direct insights, weak correlations also offered valuable information and could guide strategies for improvement and further research. Understanding the full spectrum of relationships among CSFs is crucial for a comprehensive understanding of CLT modular manufacturing.

5.2.1.1 Inferences

Interdependence of CSFs: The strong positive and negative correlations among the CSFs indicate that these factors do not operate in isolation. Changes in one factor can significantly impact others. In a manufacturing plant, the Modularity Index (CSF 1) might refer to the degree to which different product models share common parts. If this index is high (strong positive correlation with Cost Control Framework (CSF 6)), it means the plant can produce parts in bulk, reducing costs. However, this might negatively impact Time Optimization (CSF 2) and Supply Chain Flexibility (CSF 4), as the plant may take longer to switch between models and may struggle to adapt to changes in demand for specific models.

Importance of Balance: Given the interplay between the CSFs, it's crucial to maintain a balance. For instance, while improving the Modularity Index (CSF 1), attention should be paid to Time Optimization (CSF 2) and Supply Chain Flexibility (CSF 4) due to their strong negative correlation. For instance, Time Optimization (CSF 2) might involve rapid production and deployment of products. However, if this is done without considering the Cost Control Framework (CSF 6), it could lead to financial inefficiencies. For instance, rushing to release products might lead to more defects, requiring additional resources to fix.

Potential for Improvement: The weak correlations suggest areas where relationships between CSFs could be strengthened for better overall performance. In a manufacturing system, suppose Quality (CSF 3) and Standardization (CSF 5) show a weak correlation. This could indicate that the quality of products varies significantly, even though the production processes are standardized. This suggests a potential area for improvement, such as better training for workers or stricter quality control measures.

5.2.1.2 Suggestions

Use of Correlation Matrix: The industry can use this correlation matrix as a guide to understand how changes in one factor might impact others. This can help in decision-making and strategy formulation. A CLT manufacturer could use the correlation matrix to optimize its operations. For example, if Operational Efficiency (CSF 7) and Comprehensive Planning Framework (CSF 8) have a strong negative correlation, the company might need to balance efficiency with thorough planning. Rapidly executing operations without sufficient planning could lead to mistakes and inefficiencies.

Focus on Strongly Correlated CSFs: Prioritize efforts on CSFs that have strong correlations. For instance, efforts to improve the Modularity Index (CSF 1) could also enhance the Cost Control Framework (CSF 6) and Capability Enhancement (CSF 9).

Address Weak Correlations: For weakly correlated CSFs, strategies could be developed to strengthen these relationships. Alternatively, if they are intended to operate independently, this could be an opportunity to reassess and redefine these factors. If a CLT Manufacturer finds a weak correlation between Quality (CSF 3) and Capacity Management and Demand Optimization (CSF 10), it might indicate that product quality does not improve during less busy periods. The company could then implement strategies to ensure consistent quality regardless of production volume.

Continuous Monitoring and Assessment: Regularly monitor and assess the relationships among CSFs. This can help in identifying shifts in correlations over time and adjusting strategies accordingly. A CLT manufacturing firm needs to continuously monitor and assess the relationships among CSFs. For example, if the correlation between Supply Chain Flexibility (CSF 4) and Time Optimization (CSF 2) weakens over time, it might indicate that the company is becoming less agile in responding to changes in demand.

5.2.2 Prominence Diagram Results and Conclusion

The prominence diagram (Figure 42), a key component of the DEMATEL method, had been instrumental in identifying the key driving and dependent factors among the Critical Success Factors (CSFs).

Quadrant 1 typically contains factors with a high level of prominence and are highly influential. These factors are part of the cause group and drive the system. They have a high impact on other factors and are less influenced by them. These factors are **cause factors of perceived benefits** (Si et al. 2018). Thus, in our study, **factors 1, 3, 4, 5, and 9,** which fall in Quadrant 1, were identified as the cause group and are the **key driving factors of the system**.

For example, the Modularity Index (CSF 1) might refer to the degree to which different CLT modules share common parts. If this index is high, it means the plant can produce parts in bulk, reducing costs. However, this might negatively impact Time Optimization (CSF 2) and Supply Chain Flexibility (CSF 4), as the plant may take longer to switch between models and may struggle to adapt to changes in demand for specific modules.

Quadrant 2 typically contains factors that have a high influence on other factors but are also highly influenced by others. These factors are both cause and effect, and their management can be complex due to their dual role. In other words such factors are cause factors of perceived risks (Si et al. 2018). For Quadrant 3, usually includes factors that have low influence on others and are also less influenced by other factors. These factors may require less immediate attention as they neither strongly influence nor are strongly influenced by other factors. This also signifies that such factors are effect factors of perceived risks (Si et al. 2018). In our study we did not identify any other factors in quadrant 2 and 3, also because the study is more focused on perceived benefits rather than risk.

Quadrant 4 usually includes factors that are highly influenced by other factors but have less influence on them. These factors are part of the effect group and are dependent on the system. They are mainly the result of the actions and influences of the factors in the cause group. These factors signify **effect factors of perceived benefits** (Si et al. 2018). Thus, in our study we identified factors **2, 6, 7, 8, and 10**, which were in Quadrant 4, form the effect group and were **key dependent factors**.

For instance, Time Optimization (CSF 2) in the context of CLT manufacturing might involve rapid production and deployment of CLT modules. However, if this is done without considering the Cost Control Framework (CSF 6), it could lead to financial inefficiencies. For instance, rushing to release modules might lead to more defects, requiring additional resources to fix.

5.2.2.1 Suggestions

Balancing Key Driving and Dependent Factors: The manufacturing industry should strive to balance the key driving factors with the dependent factors. For instance, while improving the Modularity Index (CSF 1), attention should be paid to Time Optimization (CSF 2) and Supply Chain Flexibility (CSF 4) due to their strong negative correlation.

Continuous Monitoring and Assessment: Regularly monitor and assess the relationships among CSFs. This can help in identifying shifts in correlations over time and adjusting strategies accordingly.

Focus on Quadrant 1 Factors: Prioritize efforts on CSFs that fall in Quadrant 1 as they are the key driving factors. Improving these factors can have a significant impact on the overall system.

Address Quadrant 4 Factors: For factors in Quadrant 4, strategies could be developed to manage their dependence on the key driving factors. This could involve improving their resilience to changes in the driving factors or developing strategies to reduce their dependence.

5.2.3 Prioritized Rubric Results

The prioritized rubric results derived from the heatmap, and prominence diagram outputs provide valuable insights into the relative importance of the Critical Success Factors (CSFs) (See Appendix-D).

From results of this study, it was clear that Quality (CSF 3) is the highest-ranked CSF, indicating its paramount importance in the manufacturing of CLT modules. This is followed by Cost Control Framework (CSF 6) and Standardization (CSF 5), which also play significant roles in the process. On the other hand, Time (CSF 2) has the least importance among these factors, suggesting that the ripple effects of other factors are more prominent.

Table 6 Prioritized Rubric Result

Rank	CSF	
1	CSF3	Quality
2	CSF6	Cost Control Framework
3	CSF5	Standardization
4	CSF9	Capability Enhancement
5	CSF10	Capacity management and demand optimization
6	CSF1	Modularity Index
7	CSF4	supply chain flexibility
8	CSF7	operational efficiency
9	CSF8	Comprehensive Planning framework
10	CSF2	Time Optimization

These results also supported the fact that the high importance of Quality could reflect stringent industry standards or customer expectations. The high ranking of the Cost Control Framework might be due to its influence on other factors such as Quality and Standardization. The lower importance of Time might suggest a focus on quality and cost efficiency over speed. As this is an exclusively first attempt to find Critical Success factor particular for 'CLT Modular Manufacturing', the consistency of rankings could be determined by multiple attempts on discovering these relationships timely.

5.2.3.1 Inference

Quality is Paramount: The high ranking of Quality (CSF 3) indicates that it is a critical factor in the manufacturing of CLT modules. This could be due to stringent industry standards or high customer expectations.

Cost Control and Standardization are Key: The significant roles of Cost Control Framework (CSF 6) and Standardization (CSF 5) suggest that these factors are crucial in the process. The high ranking of the Cost Control Framework might be due to its influence on other factors such as

Quality and Standardization.

Time is Less Prominent: The lower importance of Time (CSF 2) could indicate that in the context of CLT modular manufacturing, the industry prioritizes quality and cost efficiency over rapid production. This suggests that the industry is willing to invest more time in the manufacturing process to ensure high-quality outputs and cost-effective operations. It also implies that the influence of other factors, such as Quality (CSF 3), Cost Control Framework (CSF 6), and Standardization (CSF 5), is more significant in shaping the overall performance and success of the manufacturing process. Therefore, while time efficiency is a consideration, it does not supersede the importance of these other critical success factors.

5.2.3.2 Suggestions

Prioritize Quality: Given the high importance of Quality (CSF 3), the industry should prioritize maintaining high-quality standards in the manufacturing of CLT modules. This could involve investing in quality control measures, training for employees, and high-quality materials.

Implement Cost Control and Standardization Measures: The industry should implement effective cost control measures and standardize processes to improve efficiency and reduce costs. This could involve bulk purchasing of materials, standardizing production processes, and implementing cost tracking systems.

Balance Time with Other Factors: While Time (CSF 2) is less important, it should not be neglected. The industry should strive to balance time efficiency with quality and cost control. This could involve optimizing production schedules, implementing efficient production techniques, and balancing production speed with quality control.

Use the Rubric for Decision Making: The industry can use this rubric as a guide for decision making. By understanding the relative importance of these factors, the industry can make informed decisions about where to invest resources and efforts.

Continuous Monitoring and Assessment: The industry should continuously monitor and assess these factors. As the industry evolves, the importance of these factors might change, and strategies should be adapted accordingly.

5.3 Research Contributions

The primary objective of this study was to raise awareness about CLT modular technology as a potential solution to the housing crisis and to provide affordable housing. To substantiate this claim, we needed robust evidence, leading us to identify and measure parameters that could contribute to the success of these projects. This led to the discovery of critical success factors (CSFs), providing valuable insights for manufacturers. The rubric was designed as a strategic tool for driving decisions in modular mass timber manufacturing. This section discusses the significant contributions of this study to the expanding body of knowledge.

5.3.1 Creating Background Information for Modular Mass Timber Manufacturing

Given the limited number of such projects and manufacturers offering this solution in the market, this study compiled relevant information intersecting 'modular', 'mass timber', 'manufacturing', and 'affordable housing'. This information can be illustrated in Figure 43 below.

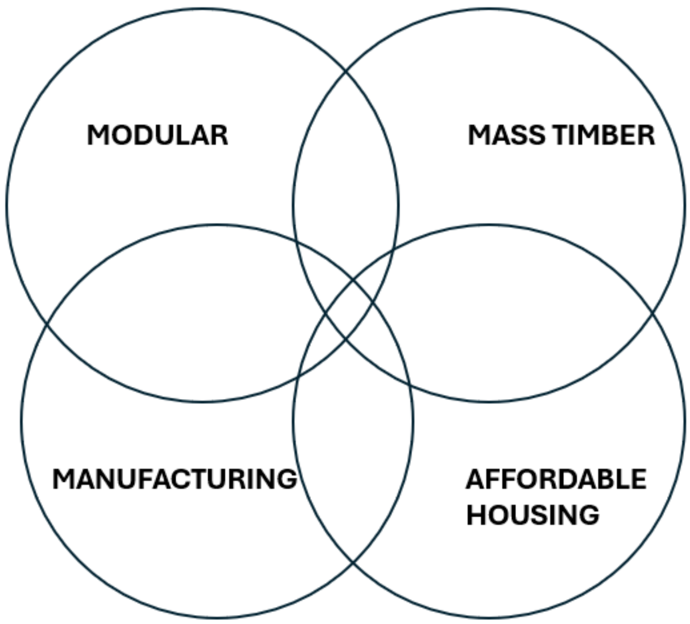

Figure 43 Terminology Overlap

5.2.2 Use of Heatmaps for Visualizations and Interpretation of Results

During the analysis stage, we uncovered complex relationships among the CSFs. To represent these 45 unique pairs, we employed heatmaps for better visualization and interpretation of the results rather than constructing a complicated model like Figure 44.

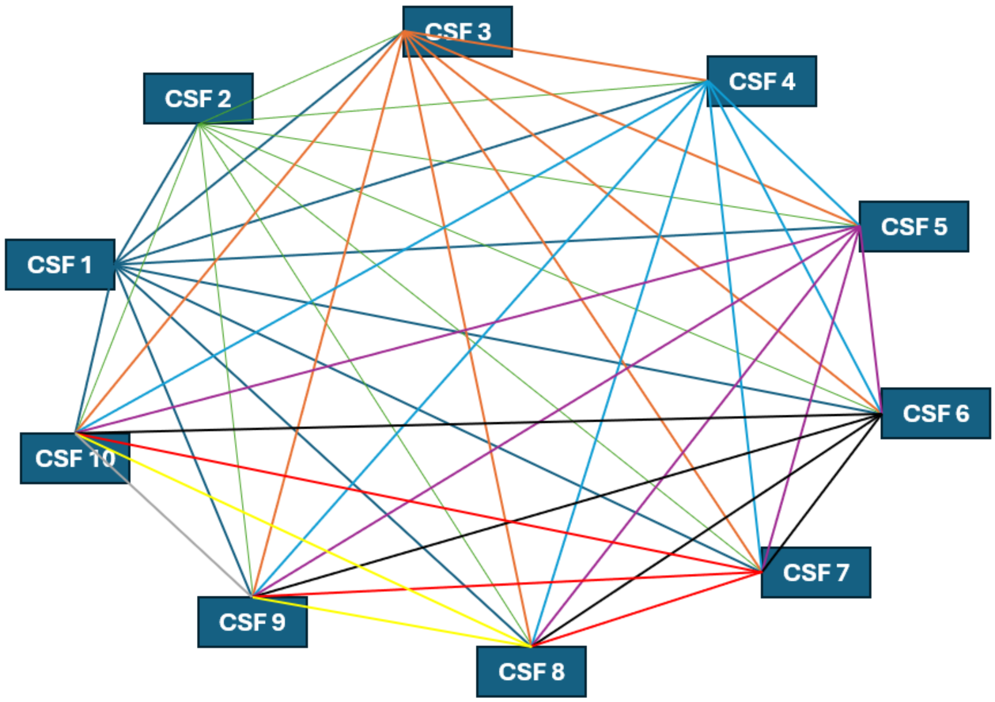

Figure 44 Representation of Complex Interrelation between CSFs

Although the use of heatmaps is a relatively new technique mentioned in other studies, it was deemed appropriate for representing these complex scenarios in this study.

5.2.3 Use of Additional Methods to Strengthen the Results

The author found it logical to include an additional layer of analysis using a prominence diagram to reinforce the findings. This helped to validate the conclusions about critical success factors. Future researchers are encouraged to use more than one method if it enhances the study's findings.

5.2.4 Use of MATLAB Software

As highlighted in earlier chapters, the importance of technological innovation is paramount in modular mass timber studies. This applies to research methods as well. In this technologically advanced era, using technology like MATLAB software for data analysis was deemed more appropriate than traditional approaches. This eliminated the chances of manual calculation errors and bias in results, preserving the authenticity of the method.

5.2.5 Rubric for the Industry

As stated at the outset of the study, the author aimed to create a guideline for the industry to follow regarding the factors to consider. The prioritized rubric will assist industry users in making informed decisions for improvements.

5.2.6 Volumetric CLT Module Manufacturing

During the background reviews in this study, we identified gaps in the literature that would have provided clear guidelines for 'module manufacturing'. While there was ample literature about 'modular manufacturing' or other use cases with different materials, we appreciated the contributions of other authors for providing inputs for panel manufacturing. With similar concepts, we attempted to suggest how a volumetric module production facility for mass timber might look like. Apart from the simulation model created by (Abiri 2020), this was a unique attempt to suggest a layout for an assembly line.

5.3 Future Research Scope

This study laid the groundwork for understanding the critical success factors (CSFs) in modular mass timber manufacturing. It acknowledged its limitations and opens avenues for future research. The study served as a starting point and offered a broad overview of CSFs. Future researchers could delve deeper into specific aspects of this exploration. Future research in the field of Modular CLT manufacturing could benefit from a more granular focus on geographical regions. For instance, they could focus on a particular geography such as Pacific Northwest of the United States, where timber resources are abundant, to those in a region like the Southwest, where timber resources might be less available but advanced manufacturing technologies could be more prevalent. This comparison could provide valuable insights into the regional variations in the CSFs for modular CLT manufacturing within the United States. In addition to regional comparisons, this study could also be conducted at a more granular level by focusing on a particular state, such as Michigan. This would allow for a more detailed examination of the CSFs in the context of the specific local conditions and resources available in that state, thereby aiding local manufacturers in making informed decisions.

The study identified several paired relationships among the CSFs. Future research could explore these relationships further for example examining other factors involved in a paired relation of operational efficiency and capability enhancement and discovering all the possible aspects related to this paired relation for enhancement of the system. This will help further to formulate strategies and improve the system. In addition to this, the next researcher can investigate potential scenarios to understand cause and effect beyond the relations mentioned in this study to formulate effective strategies.

While this study aimed to determine Critical Success Factors which translate primarily on 'benefit' parameters, future researchers could also analyze the potential ‘risk’ parameters which will define Critical Risk Factors to the system. The way this study suggests certain guidelines to be followed to achieve better outcomes, the risk parameter study will guide the industry to particularly avoid certain steps and make aware the decision-makers for careful decisions.

The study was primarily focused on Cross-Laminated Timber (CLT) as this is the only engineered wood product which is ANSI/APA PRG-320 certified product. This leaves room for future research to explore hybrid modules with other engineered wood products such as combination of CLT and Glulam or other suitable products for module components. Further, there remains a scope to figure out whether CLT-steel hybrid modules are probable future solutions based on the intent of the project. These studies will open the way to multiple possibilities which could significantly contribute to the industry. to get the benefit of both materials and it will keep an option open for the developers.

The study also calls for further investigation into weak correlations among CSFs, the influence of contextual factors, and the exploration of other potential CSFs not included in this study, such as the effects of automation. Use of advanced automated machinery integration and advanced 3D modelling software will be a game changer in coming years. These areas could provide valuable insights and further enhance our understanding of CLT modular manufacturing.

In conclusion, this study has paved the way for a more detailed and nuanced understanding of the factors influencing the successful manufacturing of modular mass timber. Future research in this area has the potential to significantly contribute to the industry and guide its growth and development.

5.4 Summary of Outputs

The study began with the collection of relevant data, fulfilling the first objective of raising awareness about modular mass timber technology defined in research needs. This data was then prepared and normalized, meeting the second objective of identifying parameters that could lead to the success of these projects. The application of Spearman’s Rank Correlation Coefficient and the Decision-Making Trial and Evaluation Laboratory (DEMATEL) method allowed for a comprehensive analysis of the relationships among the Critical Success Factors (CSFs), achieving the third objective. The results from these analyses were interpreted to provide insights into the dynamics of modular mass timber manufacturing, thereby meeting the fourth objective. The use of MATLAB software for data analysis ensured the accuracy of the results and preserved the authenticity of the method. The findings from the study were used to create a prioritized rubric to guide strategic decisions in the industry. In conclusion, the study systematically explored the critical success factors influencing the successful manufacturing of modular mass timber for affordable housing in the US, making significant contributions to the field.

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APPENDIX A - INTERVIEW SCRIPT SHARED WITH PARTICIPANTS

Greetings of the day! I am Shreya Ghodekar, second year graduate student in Construction Management program studying at MSU. I am currently involved in a research project on Modular Mass Timber Construction for Affordable Housing in the US. In this study, I examine the critical success variables for a project to be successful from a manufacturing perspective and the key performance indicators. To expand this sector and meet the enormous demand for affordable housing, one of my goals from this study is to identify the factors that are necessary to guarantee the effective production of this entity. Your insights are valuable in understanding the prospects and challenges in modular mass timber construction for affordable housing. With your consent these interviews will be audio-recorded and transcribed for further documentation. Please answer the following questions to the best of your knowledge and experience.

To begin our interview, first I would like to ask a few questions regarding your involvement in this industry and your background.

- How many Modular/Mass Timber/Both construction projects have you been involved in throughout your career?
- What is your current job title or role in the construction industry related to modular/mass timber/ both projects?
- What are your qualifications or educational background relevant to Modular/mass timber/ both Construction?
- Which City and State are you based in?
- What geographic scope or region falls under your professional responsibilities or expertise?

Thank you for sharing your background and industry involvement with me. Now I would like to ask a few questions related to the projects you were involved in. The questions are framed in context of seeking information related to project overview, project management perspective, industry perspective, collaboration and stakeholder engagement, regulatory viewpoint, performance tracking, value proposition and affordability, technology, and sustainability, building codes. I would want you to think about these topics in perspective of Critical success factors/key performance indicators and answer my following questions.

1. Can you provide an overview of the successful modular/mass timber projects you were involved in, including size, location, and key features?

2. In your opinion, how do you define success for these projects in context of affordable housing? What were the common themes from your perspective for the success of these projects? (Specific criteria/metrics to measure success)
3. In project management, what strategies or methods have you seen as effective in ensuring the successful delivery of Modular/Mass Timber Project for affordable housing?
4. What differences do you observe between the supply of standard modular/mass timber products and tailor-made designs? How does this affect project efficiency and outcomes?
5. How do building codes influence your standardization process and the manufacturing of modular mass timber components?
6. In your experience, what are the critical aspects of coordination and collaboration between design, manufacturing, and installation teams to ensure project success? In your opinion, what do you believe the level of involvement with the installation team & stakeholders should be to run a project effectively?
7. From a manufacturing perspective, how do you perceive the adoption of mass timber in the construction of affordable housing? How would you characterize the current demand-supply balance for mass timber in affordable housing projects? What attributes or qualities developers typically look for when considering mass timber construction for affordable housing?
8. In your opinion, what value propositions does modular/mass timber offer to address the rising demand for affordable housing? What strategies or measures can be implemented to make modular mass timber construction more cost-effective and affordable?
9. How do you assess the satisfaction and feedback of end-users, such as residents of affordable housing units, in relation to project success?
10. From your experience, what are the key lessons learned or best practices that can be applied to future modular mass timber projects for affordable housing?
11. Can you please refer to me the other five professionals working in this same field to help me gather more information on this topic?
12. 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 LETTER

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.

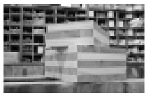
[1]Exempt categories (1), (2), (3), (4), (5), (7), and (8) cannot be applied to activities that are FDA-regulated.

[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



Contextual Relationship Between CSF for Modular Mass Timber

Welcome to the survey on **Critical Success Factors (CSFs)** for implementing modular mass timber construction methods in **manufacturing** affordable housing.

As part of an independent research study, we have interviewed experts in the field like you to identify 10 critical success factors (CSFs) from the **manufacturing perspective**. These factors are crucial for ensuring the successful implementation of modular mass timber construction methods in affordable housing manufacturing.

Your participation in this survey is highly valued, as we seek your opinion on how these critical success factors interact within the context of modular mass timber construction.
Your insights will contribute significantly to understanding the interdependencies and dynamics among these factors.

Please review the list of identified critical success factors (CSFs) below and provide your opinion on the relationships between them. Your responses will remain anonymous and confidential.

Guide to Answer the survey-
If **'A'** are the terms mentioned in each question. **'B'** are the options listed below in each question.
You have 4 choices to provide the relationship among the terms.
A will **influence** B
A will **get influenced by** B
A will have **equal influence** over B
A will **not influence** B

List of CSFs-
Modularity Index: This term represents the combined measure of *modularization rate and modular reusability,* indicating the degree to which modular components are utilized and reused within a system or process.
Time Optimization: A set of measures aimed at optimizing time-related factors within manufacturing processes, including reducing *time to market, minimizing changeover time, streamlining assembly processes, and improving customization lead time.*
Quality: The term includes the *product quality* on the fabrication end as well as the construction end.
Supply Chain Flexibility: The term includes *supply chain and logistic strategies, and logistics planning.*
Standardization: The term includes both the ideas of the *standardization of the product* and the *standardization of the overall process*.
Cost Control Framework: A structured approach to *controlling costs* within construction or manufacturing operations, encompassing *strategies for managing overall building costs, modular unit production costs, component expenses, and manufacturing costs per unit.*
Operational Efficiency: This term encompasses various aspects of efficiency within an organization or project, including *manufacturing processes, team performance, project management practices, and achieved outcomes.*
Comprehensive Planning Framework: This term encompasses the various elements involved in the planning phase of construction projects, including *preconstruction planning, collaborative efforts, design strategies, risk management, and change management.*
Capability Enhancement: The term emphasizes the focus on improving the knowledge, skills, and capabilities of employees through *education, training, and ongoing research initiatives.*
Capacity Management & Demand Optimization: The term encapsulates *scalability, demand forecasting, and capacity utilization* to maximize production efficiency and effectively meet customer demand.

* Required

1. **CSF1- Modularity Index** will *

(Modularity Index: This term represents the combined measure of *modularization rate and modular reusability*, indicating the degree to which modular components are utilized and reused within a system or process.)

	Influence	Get influenced by	Equally influence	No influence
Capacity Management and Demand Optimization				
Capability Enhancement				
Comprehensive Planning Framework				
Operational Efficiency				
Cost Control Framework				
Standardization				
Supply Chain Flexibility				
Quality				
Time Optimization				

2. **CSF2- Time Optimization** will *

(Time Optimization: A set of measures aimed at optimizing time-related factors within manufacturing processes, including reducing *time to market, minimizing changeover time, streamlining assembly processes, and improving customization lead time.)*

	Influence	Get influenced by	Equally influence	No influence
Capacity Management and Demand Optimization	○	○	○	○
Capability Enhancement	○	○	○	○
Comprehensive Planning Framework	○	○	○	○
Operational Efficiency	○	○	○	○
Cost Control Framework	○	○	○	○
Standardization	○	○	○	○
Supply Chain Flexibility	○	○	○	○
Quality	○	○	○	○

3. **CSF3- Quality** will *

(Quality: The term includes the *product quality* on the fabrication end as well as the construction end.)

	Influence	Get influenced by	Equally influence	No influence
Capacity Management and Demand Optimization	○	○	○	○
Capability Enhancement	○	○	○	○
Comprehensive Planning Framework	○	○	○	○
Operational Efficiency	○	○	○	○
Cost Control Framework	○	○	○	○
Standardization	○	○	○	○
Supply Chain Flexibility	○	○	○	○

4. **CSF4- Supply Chain Flexibility** will *

(Supply Chain Flexibility: The term includes *supply chain and logistic strategies, and logistics planning.*)

	Influence	Get influenced by	Equally influence	No influence
Capacity Management and Demand Optimization	○	○	○	○
Capability Enhancement	○	○	○	○
Comprehensive Planning Framework	○	○	○	○
Operational Efficiency	○	○	○	○
Cost Control Framework	○	○	○	○
Standardization	○	○	○	○

5. **CSF5- Standardization** will *

(Standardization: The term includes both the ideas of the *standardization of the product* and the *standardization of the overall process.*)

	Influence	Get influenced by	Equally influence	No influence
Capacity Management and Demand Optimization	○	○	○	○
Capability Enhancement	○	○	○	○
Comprehensive Planning Framework	○	○	○	○
Operational Efficiency	○	○	○	○
Cost Control Framework	○	○	○	○

6. **CSF6- Cost Control Framework** will *

(Cost Control Framework: A structured approach to *controlling costs* within construction or manufacturing operations, encompassing *strategies for managing overall building costs, modular unit production costs, component expenses, and manufacturing costs per unit.*)

	Influence	Get influenced by	Equally influence	No influence
Capacity Management and Demand Optimization	○	○	○	○
Capability Enhancement	○	○	○	○
Comprehensive Planning Framework	○	○	○	○
Operational Efficiency	○	○	○	○

7. **CSF7- Operational Efficiency** will *

(Operational Efficiency: This term encompasses various aspects of efficiency within an organization or project, including *manufacturing processes, team performance, project management practices, and achieved outcomes.*)

	Influence	Get influenced by	Equally influence	No influence
Capacity Management and Demand Optimization	○	○	○	○
Capability Enhancement	○	○	○	○
Comprehensive Planning Framework	○	○	○	○

8. **CSF8- Comprehensive Planning Framework** will *

(Comprehensive Planning Framework: This term encompasses the various elements involved in the planning phase of construction projects, including *preconstruction planning, collaborative efforts, design strategies, risk management, and change management.*)

	Influence	Get influenced by	Equally influence	No influence
Capacity Management and Demand Optimization	○	○	○	○
Capability Enhancement	○	○	○	○

9. **CSF9- Capability Enhancement** will *

(Capability Enhancement: The term emphasizes the focus on *improving the knowledge, skills, and capabilities* of employees through *education, training, and ongoing research initiatives.*)

	Influence	Get influenced by	Equally influence	No influence
Capacity Management and Demand Optimization	◯	◯	◯	◯

10. Full Name *

11. Please provide if you have any specific comments or additions for the critical success factors

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Microsoft Forms

Data Collection Responses

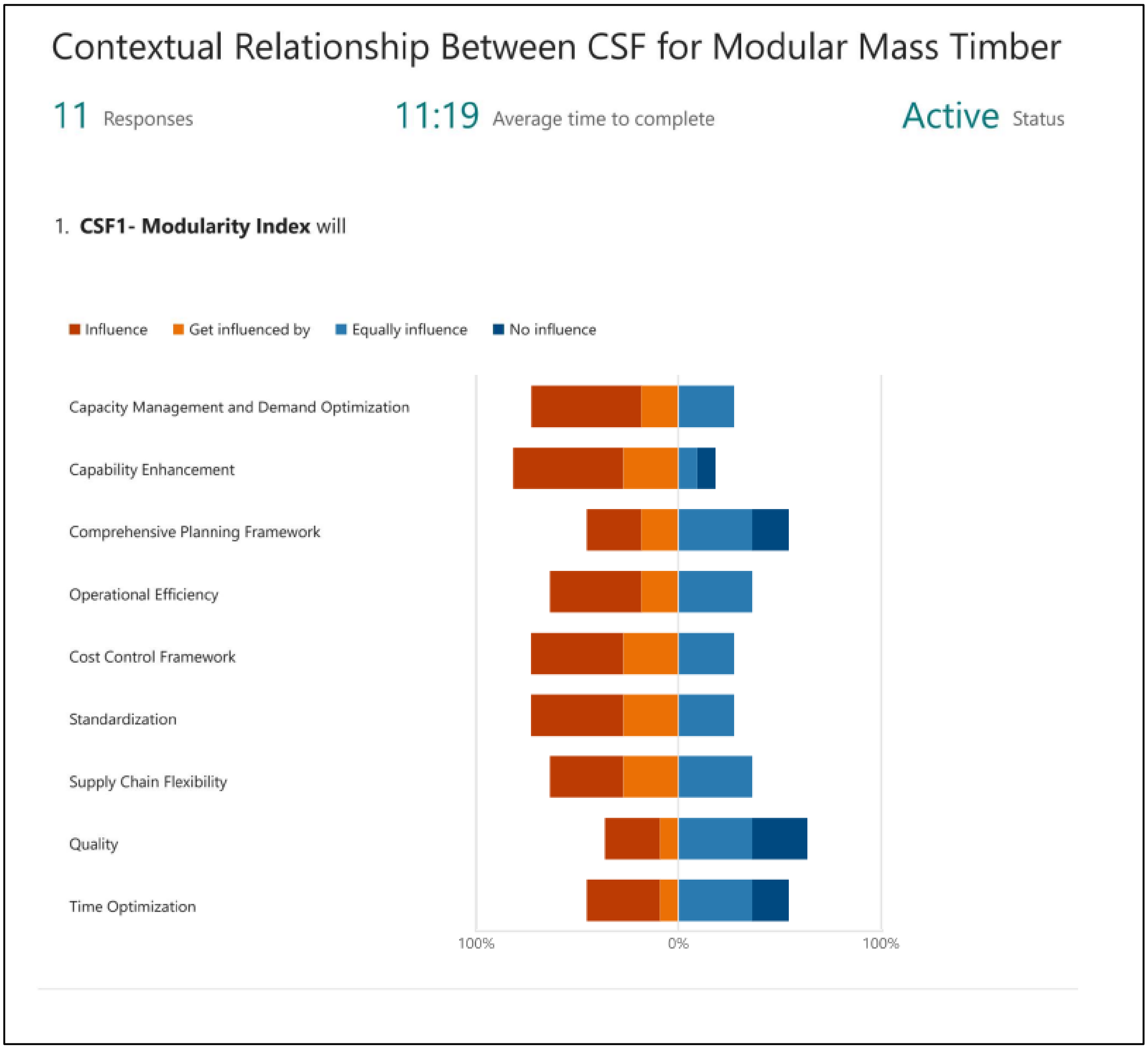
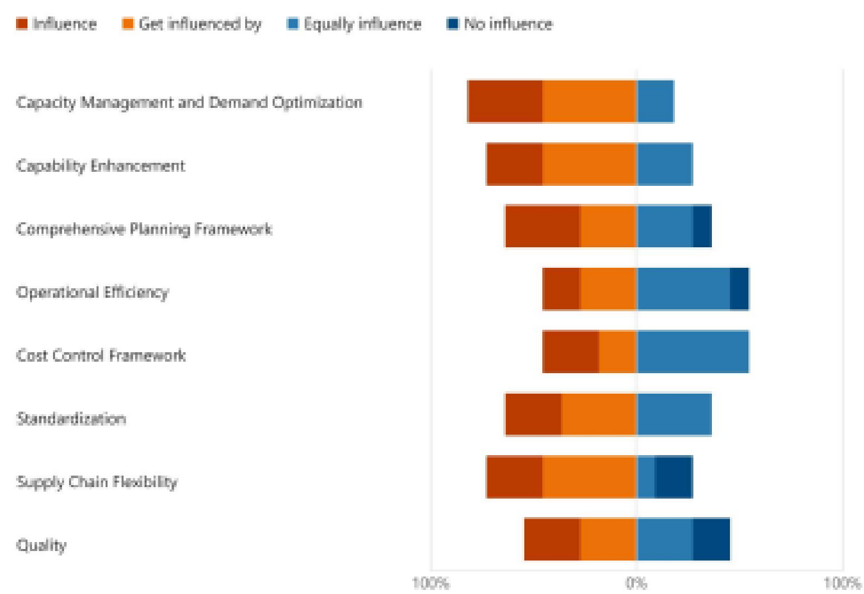


Figure 45 Data Collection Response

Figure 45 (cont'd)

2. **CSF2- Time Optimization** will



3. **CSF3- Quality** will

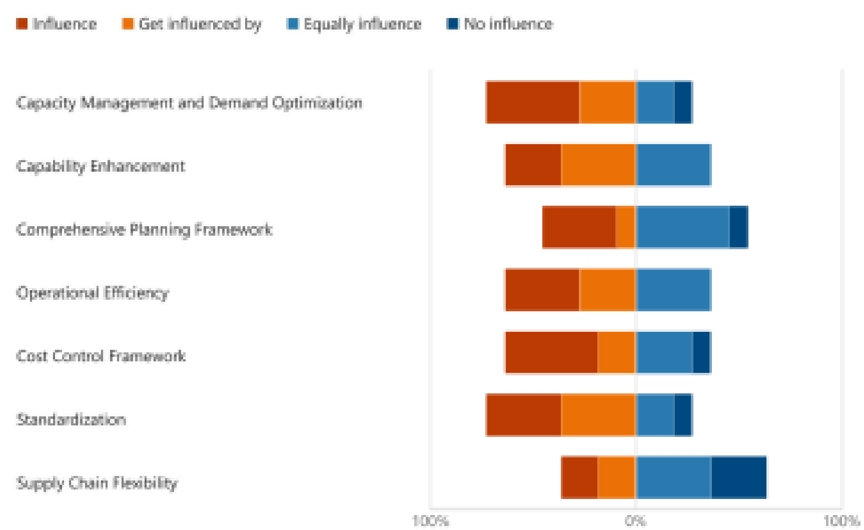
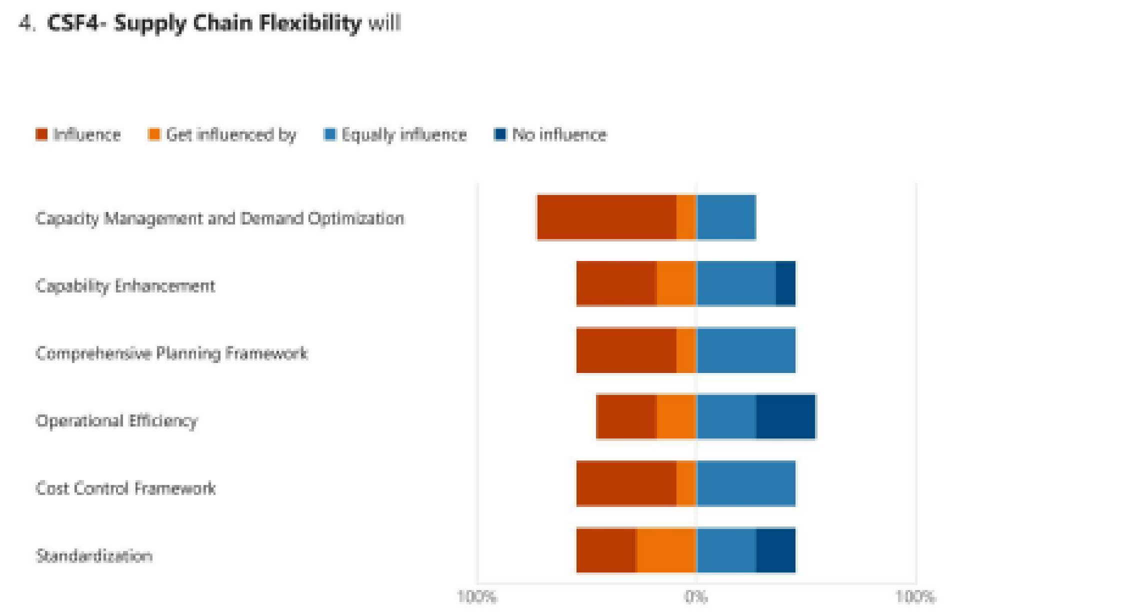


Figure 45 (cont'd)



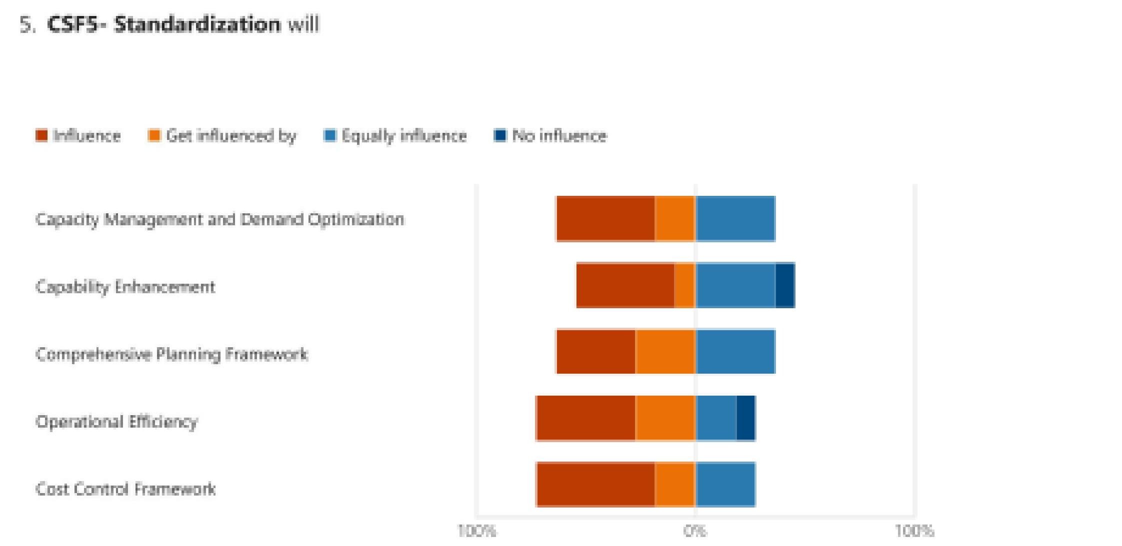
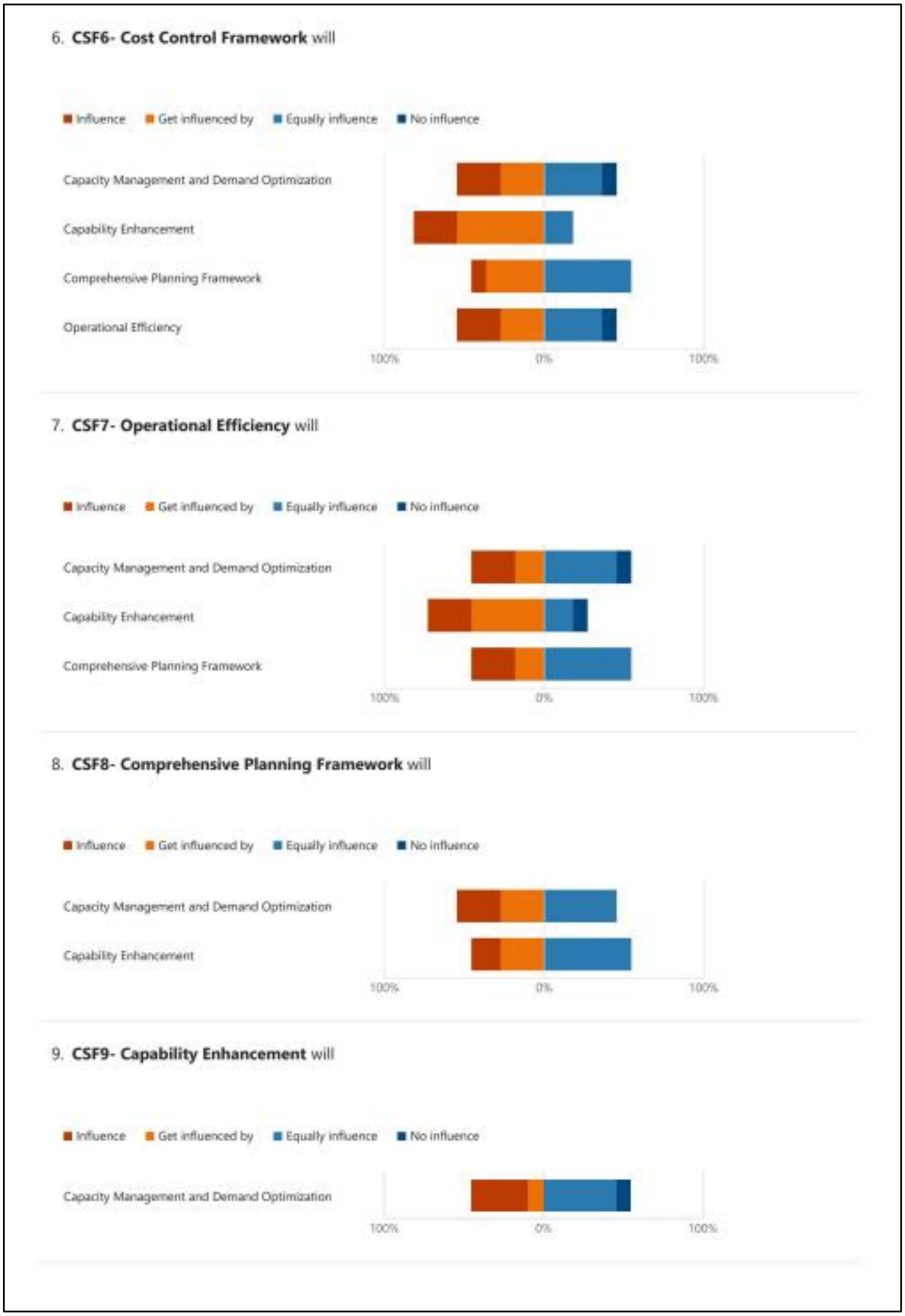


Figure 45 (cont'd)



APPENDIX D - MATLAB SCRIPT

Data entry and normalized matrix

```
X(1,1) = 0;
X(2,1) = 0.45;
X(3,1) = 0.55;
X(3,1) = 0.64;
X(3,1) = 0.55;
X(4,1) = 0.64;
X(5,1) = 0.36;
X(9,1) = -0.09;
X(10,1) = 0.18;
X(:,2) = 0;
X(1,2) = 1;
X(3,2) = 0.55;
X(4,2) = 0.36;
X(5,2) = 0.82;
X(6,2) = 1;
X(7,2) = 1;
X(8,2) = 0.45;
X(9,2) = 0.73;
X(10,2) = 0.45;
X(1,3) = 0.91;
X(2,3) = 0.55;
X(4,3) = 0.73;
X(5,3) = 0.36;
X(6,3) = 0.27;
X(7,3) = 0.64;
X(8,3) = 0.64;
X(9,3) = 0.82;
X(10,3) = 0.18;
X(1,4) = 0.82;
```

X(3,4) = 0.73;

X(5,4) = 0.55;

X(6,4) = 0.55;

X(7,4) = 0.45;

X(8,4) = 0.55;

X(9,4) = 0.64;

X(1,5) = 0.73;

X(2,5) = 0.64;

X(3,5) = 0.36;

X(4,5) = 0.55;

X(6,5) = 0.18;

X(7,5) = 0.18;

X(8,5) = 0.64;

X(9,5) = 0.36;

X(10,5) = 0.45;

X(1,6) = 0.73;

X(2,6) = 1.18;

X(3,6) = 0.82;

X(4,6) = 1.27;

X(5,6) = 0.91;

X(7,6) = 0.73;

X(8,6) = 1.36;

X(9,6) = 0.64;

X(10,6) = 0.73;

X(1,7) = 1;

X(2,7) = 0.82;

X(3,7) = 0.82;

X(4,7) = 0.64;

X(5,7) = 0.55;

X(6,7) = 0.73;

X(8,7) = 1;

X(9,7) = 0.55;

X(10,7) = 0.82;

X(1,8) = 0.82;

X(2,8) = 0.64;

X(3,8) = 1.18;

X(4,8) = 1.27;

X(5,8) = 0.82;

X(6,8) = 0.82;

X(7,8) = 1.18;

X(9,8) = 1;

X(10,8) = 0.91;

X(1,9) = 0.45;

X(2,9) = 0.36;

X(3,9) = 0.64;

X(4,9) = 0.82;

X(5,9) = 1.09;

X(6,9) = 0.09;

X(7,9) = 0.18;

X(8,9) = 1;

X(10,9) = 0.64;

X(1,10) = 0.91;

X(2,10) = 0.27;

X(3,10) = 0.55;

X(4,10) = 1.09;

X(5,10) = 1;

X(6,10) = 0.73;

X(7,10) = 1;

X(8,10) = 0.91;

X(9,10) = 1.18;

Data Entry Output

Table 7 MATLAB Output-1 (Matrix X)

	CSF1	CSF2	CSF3	CSF4	CSF5	CSF6	CSF7	CSF8	CSF9	CSF10
CSF1	0	1	0.91	0.82	0.73	0.73	1	0.82	0.45	0.91
CSF2	0.45	0	0.55	0	0.64	1.18	0.82	0.64	0.36	0.27
CSF3	0.55	0.55	0	0.73	0.36	0.82	0.82	1.18	0.64	0.55
CSF4	0.64	0.36	0.73	0	0.55	1.27	0.64	1.27	0.82	1.09
CSF5	0.36	0.82	0.36	0.55	0	0.91	0.55	0.82	1.09	1
CSF6	0.36	1	0.27	0.55	0.18	0	0.73	0.82	0.09	0.73
CSF7	0.45	1	0.64	0.45	0.18	0.73	0	1.18	0.18	1
CSF8	0.64	0.45	0.64	0.55	0.64	1.36	1	0	1	0.91
CSF9	-0.09	0.73	0.82	0.64	0.36	0.64	0.55	1	0	1.18
CSF10	0.18	0.45	0.18	0	0.45	0.73	0.82	0.91	0.64	0

Normalization of Matrix

X_min= min(X(:));

X_max = max(X(:));

X_normalized = (X - X_min) / (X_max - X_min);

Normalized Matrix Output:

Table 8 MATLAB Output-2 (Matrix X Normalized)

	CSF1	CSF2	CSF3	CSF4	CSF5	CSF6	CSF7	CSF8	CSF9	CSF10
CSF1	0.06	0.75	0.69	0.63	0.57	0.57	0.75	0.63	0.37	0.69
CSF2	0.37	0.06	0.44	0.06	0.50	0.88	0.63	0.50	0.31	0.25
CSF3	0.44	0.44	0.06	0.57	0.31	0.63	0.63	0.88	0.50	0.44
CSF4	0.50	0.31	0.57	0.06	0.44	0.94	0.50	0.94	0.63	0.81
CSF5	0.31	0.63	0.31	0.44	0.06	0.69	0.44	0.63	0.81	0.75
CSF6	0.31	0.75	0.25	0.44	0.19	0.06	0.57	0.63	0.12	0.57
CSF7	0.37	0.75	0.50	0.37	0.19	0.57	0.06	0.88	0.19	0.75
CSF8	0.50	0.37	0.50	0.44	0.50	1.00	0.75	0.06	0.75	0.69
CSF9	0.00	0.57	0.63	0.50	0.31	0.50	0.44	0.75	0.06	0.88
CSF10	0.19	0.37	0.19	0.06	0.37	0.57	0.63	0.69	0.50	0.06

Spearman’s Rank Correlation Coefficient (Rho)

```
[n, ~] = size(X); % Get the number of CSFs
rho = zeros(n); % Initialize a matrix to store the results

for i = 1:n
    for j = 1:n
        rho(i, j) = corr(X(:, i), X(:, j), 'Type', 'Spearman');
    end
end
imagesc(rho); % Create a heatmap
colorbar; % Add a color bar
title('Heatmap of Spearman''s Rank Correlation Coefficients');
xlabel('CSF');
ylabel('CSF');
```

Output:

Table 9 MATLAB Output-3 (Rho Matrix)

	CSF1	**CSF2**	**CSF3**	**CSF4**	**CSF5**	**CSF6**	**CSF7**	**CSF8**	**CSF9**	**CSF10**
CSF1	1.00	-0.48	-0.19	-0.34	0.13	0.77	0.12	0.09	0.50	-0.04
CSF2	-0.48	1.00	0.13	0.59	-0.47	-0.69	-0.29	0.06	-0.37	0.26
CSF3	-0.19	0.13	1.00	0.19	0.44	0.04	-0.05	0.01	-0.20	0.69
CSF4	-0.34	0.59	0.19	1.00	-0.01	-0.33	0.22	-0.08	-0.14	0.19
CSF5	0.13	-0.47	0.44	-0.01	1.00	0.41	0.79	-0.32	0.11	-0.25
CSF6	0.77	-0.69	0.04	-0.33	0.41	1.00	0.30	-0.19	0.77	0.00
CSF7	0.12	-0.29	-0.05	0.22	0.79	0.30	1.00	-0.55	0.27	-0.61
CSF8	0.09	0.06	0.01	-0.08	-0.32	-0.19	-0.55	1.00	-0.13	0.37
CSF9	0.50	-0.37	-0.20	-0.14	0.11	0.77	0.27	-0.13	1.00	-0.05
CSF10	-0.04	0.26	0.69	0.19	-0.25	0.00	-0.61	0.37	-0.05	1.00

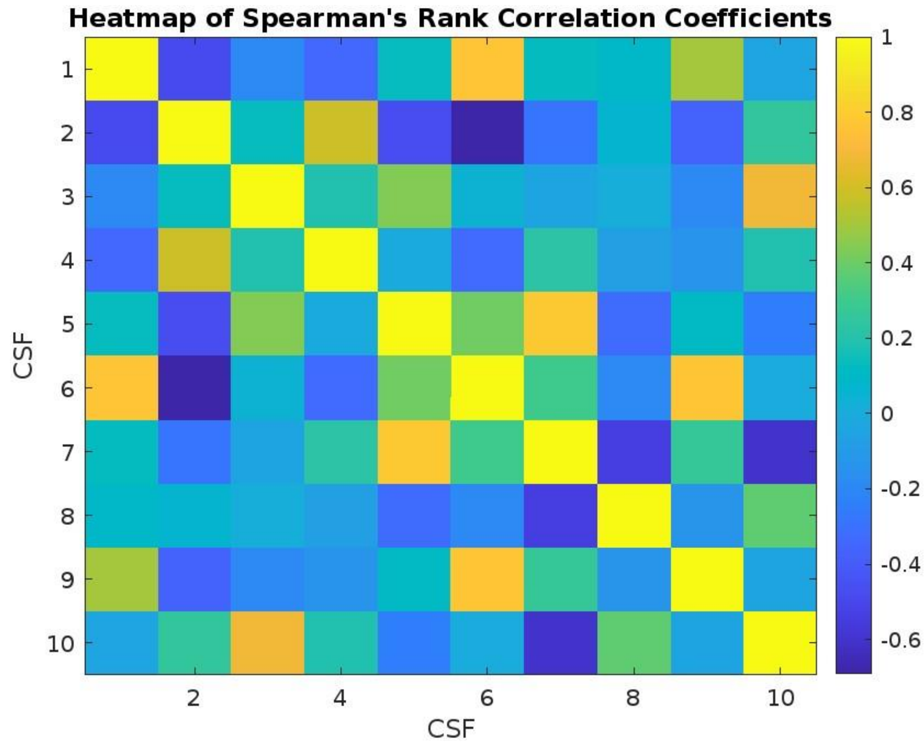


Figure 46 MATLAB Output-4 (Heatmap of Sperman's Rank Correlation Coefficient)

Prominence and Relation (DEMATEL Analysis)

D = sum(X_normalized, 2); % Sum of rows

R = sum(X_normalized, 1); % Sum of columns

T = D + R'; % Total prominence

N = D - R'; % Net prominence

scatter(T, N);

title('Prominence and Relation Diagram');

xlabel('Total Prominence (T)');

ylabel('Net Prominence (N)');

Output:

Table 10 MATLAB Output-5 (Prominence Relation Calculation on Matrix X _Normalized)

	CSF1	CSF2	CSF3	CSF4	CSF5	CSF6	CSF7	CSF8	CSF9	CSF10	D
CSF1	0.06	0.75	0.69	0.63	0.57	0.57	0.75	0.63	0.37	0.69	5.70
CSF2	0.37	0.06	0.44	0.06	0.50	0.88	0.63	0.50	0.31	0.25	4.01
CSF3	0.44	0.44	0.06	0.57	0.31	0.63	0.63	0.88	0.50	0.44	4.90
CSF4	0.50	0.31	0.57	0.06	0.44	0.94	0.50	0.94	0.63	0.81	5.70
CSF5	0.31	0.63	0.31	0.44	0.06	0.69	0.44	0.63	0.81	0.75	5.08
CSF6	0.31	0.75	0.25	0.44	0.19	0.06	0.57	0.63	0.12	0.57	3.88
CSF7	0.37	0.75	0.50	0.37	0.19	0.57	0.06	0.88	0.19	0.75	4.63
CSF8	0.50	0.37	0.50	0.44	0.50	1.00	0.75	0.06	0.75	0.69	5.58
CSF9	0.00	0.57	0.63	0.50	0.31	0.50	0.44	0.75	0.06	0.88	4.64
CSF10	0.19	0.37	0.19	0.06	0.37	0.57	0.63	0.69	0.50	0.06	3.63
R	3.06	5.01	4.14	3.58	3.44	6.39	5.40	6.58	4.26	5.89	

Table 11 MATLAB Output-6 (Results of DEMATEL Analysis)

	T=D+R	**N=D-R**
CSF1	8.766	2.641
CSF2	9.014	-1
CSF3	9.035	0.759
CSF4	9.283	2.124
CSF5	8.517	1.635
CSF6	10.28	-2.51
CSF7	10.03	-0.772
CSF8	12.16	-1
CSF9	8.897	0.386
CSF10	9.517	-2.262

Prominence and Relation Diagram

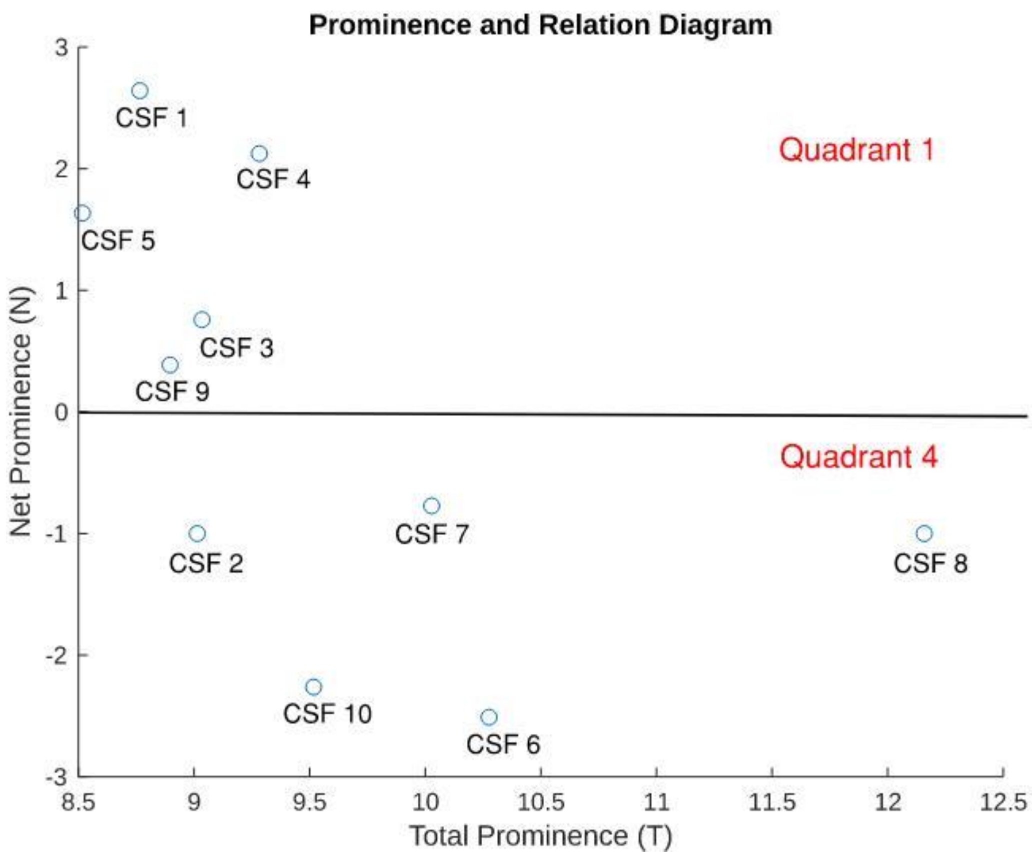


Figure 47 MATLAB Output-7 (Prominence and Relation Diagram)

Prioritized Rubric

```
total_influence = sum(rho, 2);
 [~, ranking] = sort(total_influence, 'descend');
CSFs = {'CSF1', 'CSF2', 'CSF3', 'CSF4', 'CSF5', 'CSF6', 'CSF7', 'CSF8', 'CSF9', 'CSF10'}; %
Replace with your actual CSF names
prioritized_rubric = CSFs(ranking);
T = table((1:10)', prioritized_rubric', 'VariableNames', {'Rank', 'CSF'});
writetable(T, 'prioritized_rubric.txt');
```

Output:

Table 12 MATLAB Output-8 (Prioritized Rubric Result)

Rank	CSF
1	CSF3
2	CSF6
3	CSF5
4	CSF9
5	CSF10
6	CSF1
7	CSF4
8	CSF7
9	CSF8
10	CSF2