Research Analysis

Modular Mass Timber for Housing Construction

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This research aims to understand the intricacies deploying mass timber as an element of modular construction, and their potential integration into the housing market. However, the successful implementation of Modular Mass Timber (MMT) depends on understanding the complex interplay of technical, economic, and managerial factors. This research aims to identify, evaluate, and model the Critical Success Factors (CSFs) that influence MMT adoption in housing projects in the United States. A multi-method approach was employed, combining a systematic literature review and semi-structured expert interviews to collect qualitative and contextual data. Fifteen CSFs were identified, seven from the literature and eight additional factors from expert insights. The interrelationships among these factors were analyzed using Total Interpretive Structural Modeling (TISM), supported by MICMAC analysis to classify factors based on their driving and dependence powers. The resulting hierarchical framework reveals sustainability and logistics as dominant drivers, with time, quality, and efficiency serving as foundational operational enablers. The study further develops a strategic implementation guide to assist developers, designers, manufacturers, and policymakers in prioritizing interventions, optimizing resources, and improving project outcomes. Overall, the findings advance theoretical understanding by providing a structured, system-level view of CSFs for MMT adoption and offer practical insights to facilitate scalable, cost-effective, and environmentally sustainable housing solutions.

Keywords: *Mass Timber, Modular Construction, Housing*

Introduction

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

Enter mass timber and modular construction - two paradigms reshaping the future of construction through their potential for sustainability and efficiency. Mass timber products, such as Cross-Laminated Timber (CLT) and glue-laminated timber (glulam), offer renewable, carbon-sequestering options for building, aligning with the global shift towards greener materials (Werner et al. 2007). Modular construction, characterized by off-site manufacturing and on-site assembly, presents a streamlined, less resource-intensive approach, promising significant reductions in construction time and waste, thus contributing to the affordability and accessibility of housing (Adabre et al. 2020; Khan et al. 2022). The amalgamation of these two innovative strategies - Modular Mass Timber (MMT) - appears as a promising solution to the intertwined challenges of climate change mitigation, efficient resource use, and the provision of housing. This paper aims to explore the Critical Success Factors (CSFs) for the successful adoption of MMT in housing in the United States.

Mass Timber Construction

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

Reduced climate impact: According to Pierobon et al. (2019), the adoption of mass-timber construction has the potential to diminish the global warming impact of buildings by as much as 26.5%, because of reduced waste, energy efficiency, and material optimization.

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

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

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

MTC has been proven to reduce construction durations on projects by as much as 20% in comparison to more conventional methods, a factor particularly relevant when the timing of building approvals impacts returns on investment (Abed et al. 2022). Beyond its positive forest management benefits, CLT offers various advantages within the construction industry. It stands out as a promising construction material due to its demonstrated energy efficiency, environmental friendliness, suitability for constructing high-density built environments, and ability to accelerate construction timelines. CLT serves as a thermal mass, storing heat during the day and releasing it at night, thereby reducing overall building energy consumption (Laguarda-Mallo & Espinoza, 2018). Furthermore, CLT is a renewable material that sequesters carbon throughout its service life (Laguarda-Mallo et al. 2016). A key attribute of CLT is its high strength- to-weight ratio, resulting in smaller building foundations for comparable structural capabilities, enabling the construction of added floors with the same structural weight (Laguarda-Mallo et al. 2016). Additionally, CLT can be prefabricated in a controlled environment, thereby enhancing construction safety (Abed et al. 2022).

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

Modular Construction

Modular Construction involves the planning, design, manufacturing, fabrication, and preassembly of diverse building elements, components, and modules in a controlled environment, commonly referred to as factory production. These components are then transported to the construction site for final installation. It is known by various terms worldwide, such as offsite construction, offsite manufacturing, offsite production, offsite fabrication, prefabrication, industrialized construction, etc. (Khan et al. 2022).

Modular Construction methods draw from the theories of modularity and modularization. Modularity, defined as breaking down complex systems into smaller components, that interact based on specific standards and rules, suits the construction industry well, allowing each element to be examined in isolation before integration into a complex building system. Modularization, on the other hand, is the pre-manufacturing of a complex system, creating large modules that are further broken down into smaller elements before being transported to the construction site (Amer and Maul 2019). Modular construction involves stacking different modules next to or on top of each other during the installation process to complete the structure. The rise of modular construction in recent years can be attributed to its substantial advantages over traditional construction methods. This method has found application in various building projects, including houses, hospitals, hotels, offices, retail outlets, universities, and supermarkets. Although the modular construction accounts for less than 4% of current U.S. housing stock (Blanco et al. 2023), many researchers believe that modular construction is the future of the construction industry, offering extensive benefits and addressing challenges posed by traditional construction methods (Blismas and Wakefield 2009).

Modular Mass Timber (MMT)

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

Speed of construction: Modular construction allows faster construction times compared to traditional methods. Prefabricated Mass Timber components can be manufactured and assembled off-site simultaneously with construction site preparation, contributing to speed and robustness (Fernandes et al. 2020).

Reduced site disruption: With a sizable part of construction work completed off- site, on-site disruption is minimized. The precision-manufactured components, materials, and systems bring advantages such as superior quality control, improved energy performance, reduced onsite deliveries, noise, pollution, and less disruption to communities (Yip et al. 2022).

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

The integration of modular construction and mass timber into a unified strategy for addressing the housing crisis stands out for its unique combination of speed, sustainability, and scalability. It enables housing units to be prefabricated in controlled environments, which significantly speeds up construction times, reduces waste, and cuts overall costs. MMT further complements modular construction by adding sustainability and durability to the mix. As a construction material, mass timber has well-known carbon-storage capabilities, making it a cornerstone for green building practices. Its compatibility with prefabrication aligns perfectly with modular construction, allowing for the efficient production of durable, fire-resistant, and aesthetically pleasing housing units. This combination promotes not just faster but also environmentally responsible construction practices.

The rapid assembly and environmental sustainability of MMT provide a comprehensive solution to the multifaceted challenges of housing. The distinct qualities of MMT such as efficiency from Modular Construction and the sustainability of mass timber enable this approach to overcome the conventional barriers of cost, time, and environmental impact in the housing sector.

Research Need and Objectives

MMT construction is increasingly adopted in U.S. affordable housing due to its cost-efficiency, sustainability, and speed of construction. However, its successful implementation depends on understanding the interplay of multiple technical, economic, and managerial factors. Critical Success Factors (CSFs) provide a structured framework to assess building performance both on-site and off-site, enabling stakeholders to evaluate feasibility, compare modular systems with conventional methods, and guide decision-making. Key performance indicators include construction and material costs, labor productivity, energy efficiency, carbon footprint, waste reduction, structural stability, seismic and fire performance, thermal and acoustic behavior, and post-disaster resilience (Bhandari et al., 2023a).

While prior research on modular construction has largely focused on steel systems (Thai et al., 2020; Lacey et al., 2018; Lawson et al., 2014), these studies do not fully address structural connections or performance in modular Cross-Laminated Timber (CLT) buildings. Limited studies on CLT modules, such as Gijzen (2017), offer insights but remain narrow in scope. This highlights the need for a comprehensive framework of CSFs specifically for MMT in affordable housing.

To analyze the interdependencies among CSFs, multi-criteria decision-making (MCDM) tools were considered, including AHP, ANP, DEMATEL, and ISM. ISM was preferred due to its ability to model complex systems using expert judgment without requiring precise numerical correlations, reducing bias, and improving reliability (Gardas et al., 2018a; Venkatesh et al., 2015). ISM transforms ambiguous, poorly structured models into visible hierarchies, guiding the identification of ‘what’ and ‘how’ relationships among factors (Jha et al., 2018). However, ISM has limitations in clarifying causal links between variables (Patil & Warkhedkar, 2016; Sushil, 2012).

To overcome these limitations, Total Interpretive Structural Modeling (TISM) was employed. TISM extends ISM by integrating interpretive logic, explicitly capturing causal relationships and dependencies to produce a transparent hierarchical framework of interrelated factors (Sushil, 2012, 2018). By leveraging systems thinking and graph theory (Suprun et al., 2018; Yadav et al., 2015), TISM uses directed graphs to map complex interactions, providing actionable insights into implementation pathways and influence patterns. This makes TISM particularly suitable for analyzing the multidimensional factors affecting MMT adoption, where technical, organizational, and managerial elements are deeply interconnected. TISM has been successfully applied in AEC research, such as studies on lean construction barriers (Chaple et al., 2021). Application of TISM for this research is further discussed in the Research Method section.

The overall purpose of the present study is to develop a standardized Critical Success Factors (CSFs) rubric and assessment framework to support the evaluation and adoption of Modular Mass Timber (MMT) construction for housing construction in the United States. The specific objectives include:

1. Comprehensive understanding of MMT adoption in housing construction
2. Identification, analysis, and categorization of Critical Success Factors (CSFs)
3. Development of a prioritized CSF rubric and implementation strategy

Methodology

To address the multifaceted nature of MMT adoption, the research adopts a Critical Success Factors (CSFs) based approach. CSFs represent the essential technical, economic, organizational, and regulatory conditions that must be effectively managed to ensure successful project outcomes. In the context of MMT housing, CSFs provide a structured lens for evaluating feasibility, performance, and implementation readiness across both off-site manufacturing and on-site installation stages. The identification and analysis of CSFs enable a holistic assessment of MMT adoption beyond isolated performance indicators.

Following the identification of CSFs through literature review and expert interviews, the study employs Total Interpretive Structural Modelling (TISM) to examine the interrelationships among these factors. TISM is a systems-based modelling technique that structures complex variables into a hierarchical framework based on expert judgment and interpretive logic. Unlike traditional listing or ranking approaches, TISM explains how and why one CSF influences another, thereby revealing the underlying structure governing MMT adoption. This makes TISM particularly suitable for analyzing interconnected construction systems involving technical, managerial, and policy-driven factors.

To complement the TISM framework, MICMAC (Matrice d’Impacts Croisés Multiplication Appliquée à un Classement) analysis is used to classify CSFs based on their driving power and dependence power (Sushil 2012). MICMAC analysis supports the identification of dominant drivers, dependent factors, linkage variables, and autonomous factors within the system. This classification strengthens the interpretation of the TISM hierarchy by highlighting which CSFs act as foundational enablers and which are primarily outcomes of system interactions.

Identification of the Critical Success Factors (CSFs)

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

In addition to an extensive literature review, eleven detailed interviews were conducted with industry experts. Experts were selected from key functional domains, including project management, manufacturing, architecture, engineering, safety, and on-site execution, to ensure comprehensive coverage of the subject matter. This multidisciplinary selection was undertaken to incorporate diverse viewpoints, MT expertise, and specialized technical knowledge. Such a balanced expert panel enhanced the robustness, credibility, and overall reliability of the study's outcomes. Experts were identified using purposive sampling techniques, where representative experience and high levels of expertise were sought out to ensure richness of responses, as opposed to random sampling techniques more commonly used in survey research. Interviews were coded individually for emerging themes. This process was repeated iteratively; as new themes emerged in subsequent interviews, prior interview transcripts were reviewed for the same themes.

Seven foundational CSFs were identified through the literature review. An additional eight CSFs were identified through the course of the expert interviews; these were deemed by experts to be integral to the successful adoption of MMT in housing (Thakare 2024; Abdul Nabi and El-Adaway 2020; NLIHC 2023; Agarwal et al. 2016; WoodWorks 2024; Khan et al. 2022; Zhang et al. 2021; Bhandari et al. 2023b; Passarelli 2019; United Nations 2023; Bekdik 2024; Statista 2023; Cann 2018; Bibeau et al. 2020; AIA 2023; Nova 2023; Wuni and Shen 2023; Liebetanz 2022; Himes 2020; Loizou et al. 2021; Gustavsson et al. 2010; Pervez et al. 2021; Teng and Pan 2019; Vanclay et al. 2015; Sunday et al. 2021; Pan et al. 2020; UNEP 2022; Krone 2023; Cesnik 2022; Pan et al. 2019; Thomas 2024; AWC 2022; Chan et al. 2021; Wuni et al. 2022; Yazdani et al. 2021; Wuni et al. 2019, Hussein et al. 2021; Blismas and Wakefield 2009; Ezzeddine and Soto 2021; Fernandes et al. 2020; The Eden Group 2023; Li et al. 2018; Leishman et al. 2012; Le 2021; Atta et al. 2021; Mao et al. 2013; Hannah and Hunter 2018).

Foundational CSFs identified through the literature review included:

- Cost
- Time
- Quality
- Efficiency
- Demand
- Sustainability
- Legislation

Additional CSFs identified through expert interviews included:

- Safety
- Logistics
- Training
- Customization
- Coordination
- Commoditization
- Standardization
- Research

This expanded list of CSFs appeared by the sixth interview, after which no further unique factors were found, showing a saturation point in the data collection. This saturation signified a comprehensive capture of the relevant CSFs, prompting a transition towards synthesizing the expert feedback to form a consensus on the prioritized CSFs essential for guiding future MMT housing projects.

Critical Success Factors (CSFs) Prioritization

After obtaining the list of CSFs, the immediate goal was to begin data analysis, but with the sample size obtained and the number of variables, the prediction methods offered a challenge for the accuracy and suitability of the methods for the prioritized rubric. Various multi-criteria decision making (MCDM) tools were considered for this purpose, including Analytical Network Process, Decision Making Trial and Evaluation Laboratory, Analytic Hierarchy Process, and Interpretive Structural Modelling (ISM).

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

Total Interpretive Structural Modelling (TISM)

Total Interpretive Structural Modeling (TISM) was employed in this study to develop a conceptual framework for identifying and structuring the drivers influencing the adoption of MMT in housing projects. TISM is a systematic modeling technique used to examine complex systems by organizing interrelated variables into a hierarchical structure based on expert interpretation and logical relationships (Warfield 1974). It enables a comprehensive understanding of how different factors interact within a multifaceted problem by explicitly representing their interdependence and directional relationships.

TISM originated as an extension of Interpretive Structural Modeling (ISM). ISM is a well-established modeling approach that focuses on identifying relationships among variables in complex systems through the judgments and interpretations of expert groups (Warfield 1974, Dalvi et al. 2017). While ISM is effective in recognizing associations among variables, it does not adequately explain the underlying causal mechanisms or the nature of influence between them (Sushil 2012). To address this limitation, TISM was developed to enhance ISM by incorporating interpretive logic that clarifies causal links, resulting in a more transparent hierarchical representation of variables along with their interactions and dependencies (Sushil 2012, 2018).

Building upon principles of systems thinking (Suprun et al. 2018) and graph theory (Yadav et al. 2015), TISM employs directed graphs (digraphs) to visualize and map the relationships among variables within a system. This feature allows TISM to provide deeper insights into implementation pathways and influence patterns, making it particularly suitable for analyzing multidimensional systems such as MMT adoption in housing projects, where outcomes are driven by interconnected technical, organizational, and managerial factors. Due to its ability to capture complex interrelationships, TISM has been increasingly applied in AEC-related research, including studies on barriers to lean construction implementation (Chaple et al. 2021). Figure 1 illustrates the key steps involved in the TISM methodology.

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

Step 1 - The first step in TISM is to identify, list and define CSFs. Identification of CSFs involves a two-step process. Initially, a comprehensive literature review is conducted, followed by experts' opinions to compile, list, and define these CSFs.

Step 2 - The second step is to establish a pairwise and contextual relationship between different variables to develop

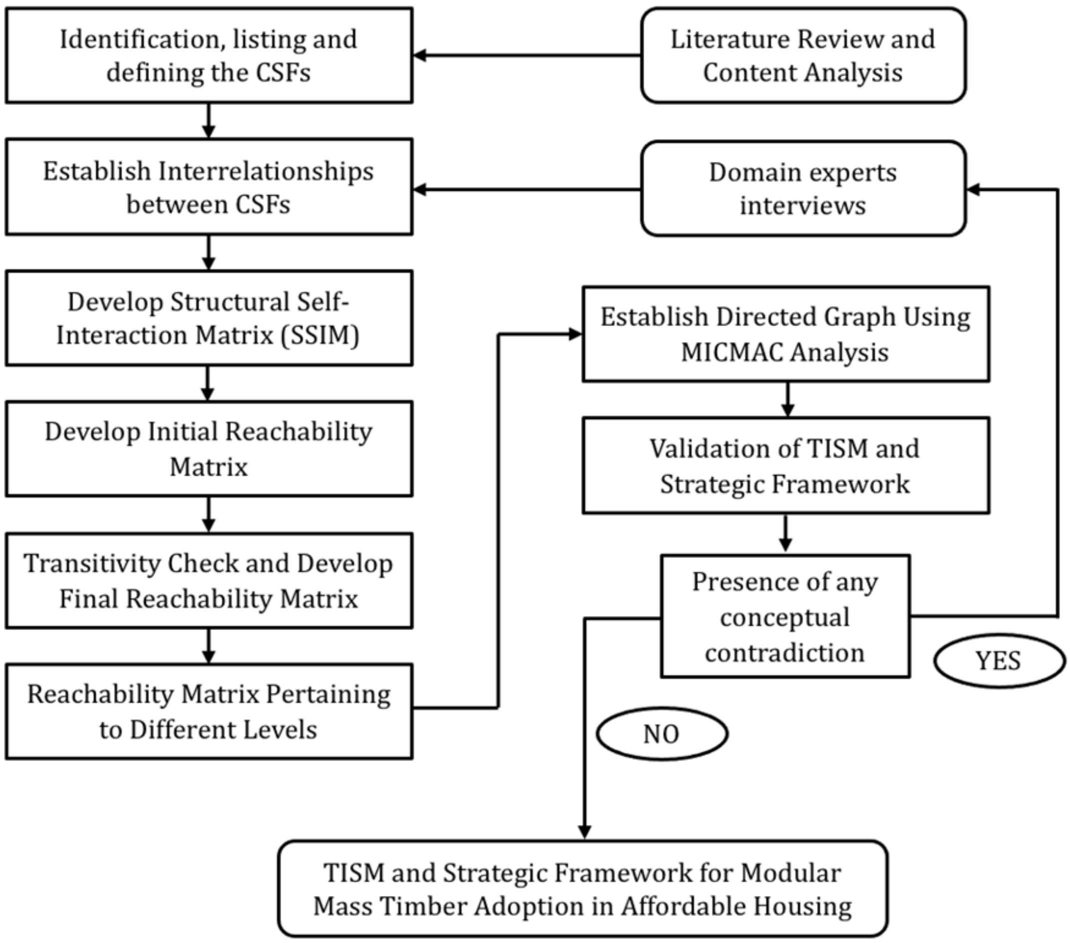

Figure 1: Steps in TISM Approach

a structural self-interaction matrix (SSIM) of the variables. In a paired comparison, the ith element is individually compared with all elements. As shown in Table 1, the contextual relationship between the different drivers forming the adjacency matrix were denoted by letters V, A, X and O:

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

Step 3 – Reachability Matrix (RM)

The third phase of the analysis involves the construction of the Reachability Matrix (RM), which stands in contrast to the adjacency matrix. While the adjacency matrix solely delineates the direct relationships or connections among the critical success factors, the RM extends this by elucidating both direct and indirect interrelations among the factors.

Table 1: SSIM of CSFs

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

The preliminary stage of the RM was characterized by the adoption of binary values 0 and 1 to substitute for the symbols V, A, X, and O, as per the guidelines delineated by (Sushil 2012). This binary coding serves to simplify and clarify the matrix, making it easier to discern the nuanced network of relationships among the success factors. showcasing the interconnected nature of these factors. Analysis in Table 2 highlights the presence of several transitive connections among the CSFs, ensuring the preservation of consistency within the model as it progresses through the iteration stages.

Table 2: Reachability Matrix (RM) for Critical Success Factors.

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

Note: (*) denotes the transitivity relation check.

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

The procedure for ensuring relational consistency among the factors involves the application of a Boolean operation of self-multiplication until a stable configuration is attained (Wu et al. 2015). This operation is predicated on the logic that if a critical success factor CSF-1 influences CSF-2, and in turn, CSF-2 influences CSF-3, it implies an indirect influence of CSF-1 on CSF-3. The methodology employed to generate the final RM is encapsulated in the following equation (Khan et al. 2022):

$$R_f = R_i^{k} + R^{k+1}, k > 1$$

within the framework of this analysis, Rf signifies the developed final Reachability Matrix, while Ri represents the initial Reachability Matrix, as delineated by (Shen et al. 2016). The term 'Driving Power' associated with a Critical Success Factor (CSF) refers to the quantity of other CSFs that it impacts, thus influencing the project's outcome. Conversely, the 'Dependence Power' of a CSF indicates the count of other CSFs that are impacted by it,

Step 4 – Level Partitioning Matrix

The fourth phase involves constructing the Level Partitioning Matrix by defining the Reachability, Antecedent, and Intersection sets for each CSF. The Reachability set identifies CSFs a given factor can influence, the Antecedent set includes CSFs that influence it, and the Intersection set contains common elements from both sets.

Levels were assigned by iteratively comparing the Reachability and Intersection sets derived from the Reachability Matrix. CSFs with identical sets were grouped into the same level, resulting in a three-level hierarchy (Level I–III). This approach follows TISM principles and is consistent with prior studies (Gan et al. 2018; Nair & Suresh 2021). The detailed results are presented in Table 9.

As shown in Table 3, Level I contains thirteen CSFs, excluding CSF9 (Logistics) and CSF6 (Sustainability), which appear in Level II and Level III, respectively. CSFs at higher levels exert greater influence on those above, while intermediate CSFs act as both influencing and influenced factors.

Step 5 - Analysis of the CSFs for Modular Mass Timber Adoption in Housing

This analytical method focuses on assessing the influence distribution of various variables by pinpointing their driving and dependence powers. Factors within the MMT construction for housing framework were categorized into four distinct groups: dependent' (characterized by low driving power and high dependence power), 'driving or independent' (marked by high driving power and low dependence power), autonomous' (noted for low driving and dependence Power), and 'linkage' (defined by high driving and dependence power). This categorization aids in analyzing the dynamics among CSFs in terms of their influence and susceptibility, as previously outlined in the fourth step. Figure 2 graphically represents the positioning of the CSFs across four quadrants, determined using a scale-centric approach as recommended by (Sushil 2018) and (Warfield and Member 1974). The positioning of each CSF is based on its Driving Power and Dependence Power derived from the Reachability Matrix.

their pivotal roles and the intricate dynamics between their influence and reliance. The pronounced influencing capacity of logistics and the even- handed impact and reliance of other CSFs highlight the imperative for thoughtful strategic planning and cohesive project management methodologies to adeptly manage these interconnections.

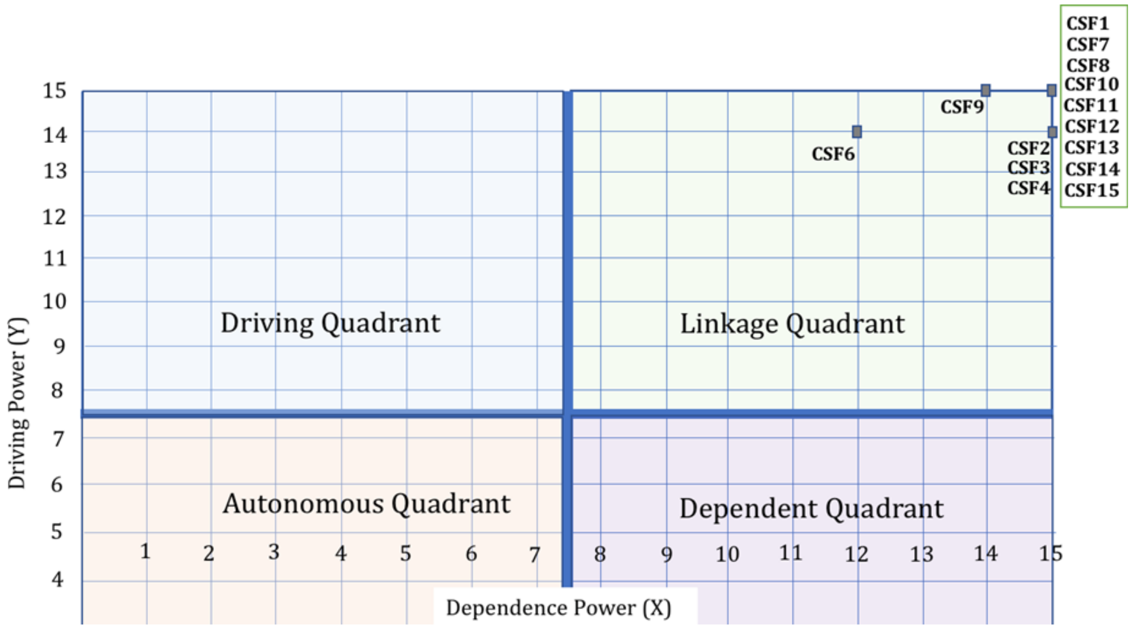

Figure 2: Influence Distribution Analysis of the CSFs via Reachability Matrix

According to the insights derived from Figure 2, all the fifteen critical success factors are identified within the linkage quadrant, evidencing both substantial driving and dependence powers: CSF1 (Cost), CSF2 (Time), CSF3 (Quality), CSF4 (Efficiency), CSF5 (Demand), CSF6 (Sustainability), CSF7 (Legislation), CSF8 (Safety), CSF9 (Logistics), CSF10 (Training), CSF11 (Customization), CSF12 (Coordination), CSF13 (Commoditization), CSF14 (Standardization) and CSF15 (Research). Their positioning in the linkage quadrant underscores their critical role in both influencing and being influenced by the MMT adoption process, highlighting the necessity for a balanced and integrated approach to address these factors simultaneously.

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

The detailed examination of elements such as sustainability, logistics, and the trio of time, quality, and efficiency underscores

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

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

Step 6 - Application of TISM model

The culmination of the analysis involves the establishment of transitive relationships among various CSFs and the construction of a Total Interpretive Structural Modelling (TISM) framework. Drawing on the foundational work of developing the reachability matrix and conducting MICMAC analysis, transitive relationships are delineated to elucidate the interconnections among the CSFs (Sushil 2012). Leveraging the principles of systems thinking and interpretive logic, the TISM framework was formulated. The prioritized rubric illustrates the transitive relationships among the CSFs, shedding light on their dynamic interactions as depicted in Figure. The TISM framework depicted in Figure 3 maps out the intricate web of fifteen Critical Success Factors central to the adoption of MMT construction for housing in the US. This figure presents a visual representation of the Reachability Matrix developed through the MICMAC analysis process. It highlights the transitive relationships among the CSFs, thereby clarifying how factors are interconnected beyond their direct links and revealing the broader structural dependencies within the model.

domain, as evidenced by the transitive relationships highlighted in Figure 2. For example, efficiency (CSF 4) is profoundly influenced by sustainability (CSF 6) considerations, necessitating a deep comprehension of sustainability dynamics. All the experts remarked on the significance of sustainability features, particularly those for end- users as well as researchers, as crucial for facilitating successful outcomes, suggesting that without external pressure for change, significant progress remains elusive.

The dominant positioning of sustainability (CSF 6) and logistics (CSF 9) factors exerts influence over those situated in the linkage quadrant such as cost (CSF 1), time(CSF 2), quality (CSF 3), efficiency (CSF 4), demand (CSF 5), legislation (CSF 7), safety (CSF 8), training (CSF 10), customization (CSF 11), coordination (CSF 12), commoditization (CSF 13), standardization (CSF 14), and research (CSF 15). Specifically, the cost, demand,

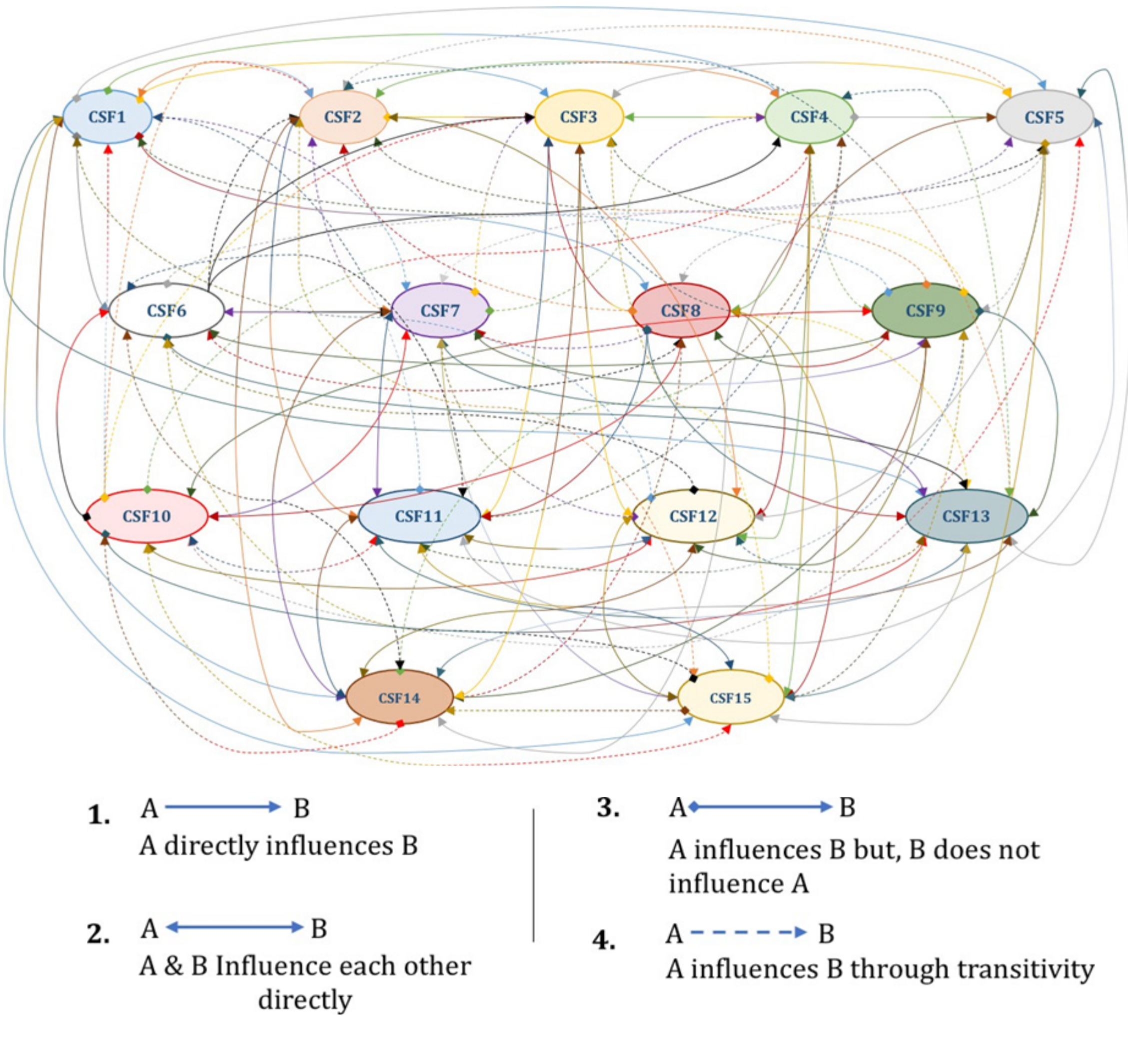

Figure 3: Prioritized Rubric - TISM Model of the CSFs

It becomes apparent through the TISM framework that the sustainability factor (CSF6) emerges as a paramount element, characterized by its pronounced influence and minimal dependency. This factor acts as a cornerstone, with all other critical success factors being influenced by the sustainability

legislation, safety, logistics, training, customization, coordination, commoditization, standardization, and research affect the time, quality, and efficiency factors through transitive relationships, such as improved scheduling, building codes adherence, and higher production. The Level I CSFs also play a pivotal role in

MMT adoption for housing, yet their effectiveness is contingent upon the advancement of other critical success factors such as Sustainability and Logistics at lower levels. Insights from Figure 2 indicate that Sustainability aspects like biophilia and low embodied carbon drive demand, while affordability, safety or customization bolster it. Several experts suggested that the integration of circular economy principles into modular mass timber could broaden its application and amplify its environmental benefits. One of the experts working in manufacturing modular homes and having experience of working on installation process, projected a significant surge in the circular economy following MMT success. Research by (Brissi et al. 2021; Sunday et al. 2021a) corroborated the influential role of sustainable, social, environmental, and economic factors in shaping affordability, demand, highlighting consumer attitudes, perceptions, and financial constraints as key determinants.

factors influence each other indirectly.

This underscores the importance of prioritizing the critical success factors in Levels II and III to enhance the performance of those in Level I. Although some critical success factors may not be directly connected, their mutual influence is palpable. For instance, the quality factor's (CSF 3) association with demand (CSF 5) is influenced by consumer expectations and the quest for superior products. In summary, the TISM framework offers a comprehensive overview of critical success factors and their interconnectedness, illuminating their significance in the adoption of MMT for housing.

Step 7 - Implementation Strategies

Implementation strategies provided here highlight a methodical process that emphasizes the importance of each CSF. The foundation of these strategies stems primarily from insights gathered through expert interviews and comprehensive literature reviews. This section explores how these factors are interconnected, offering clarity on how the study's findings can

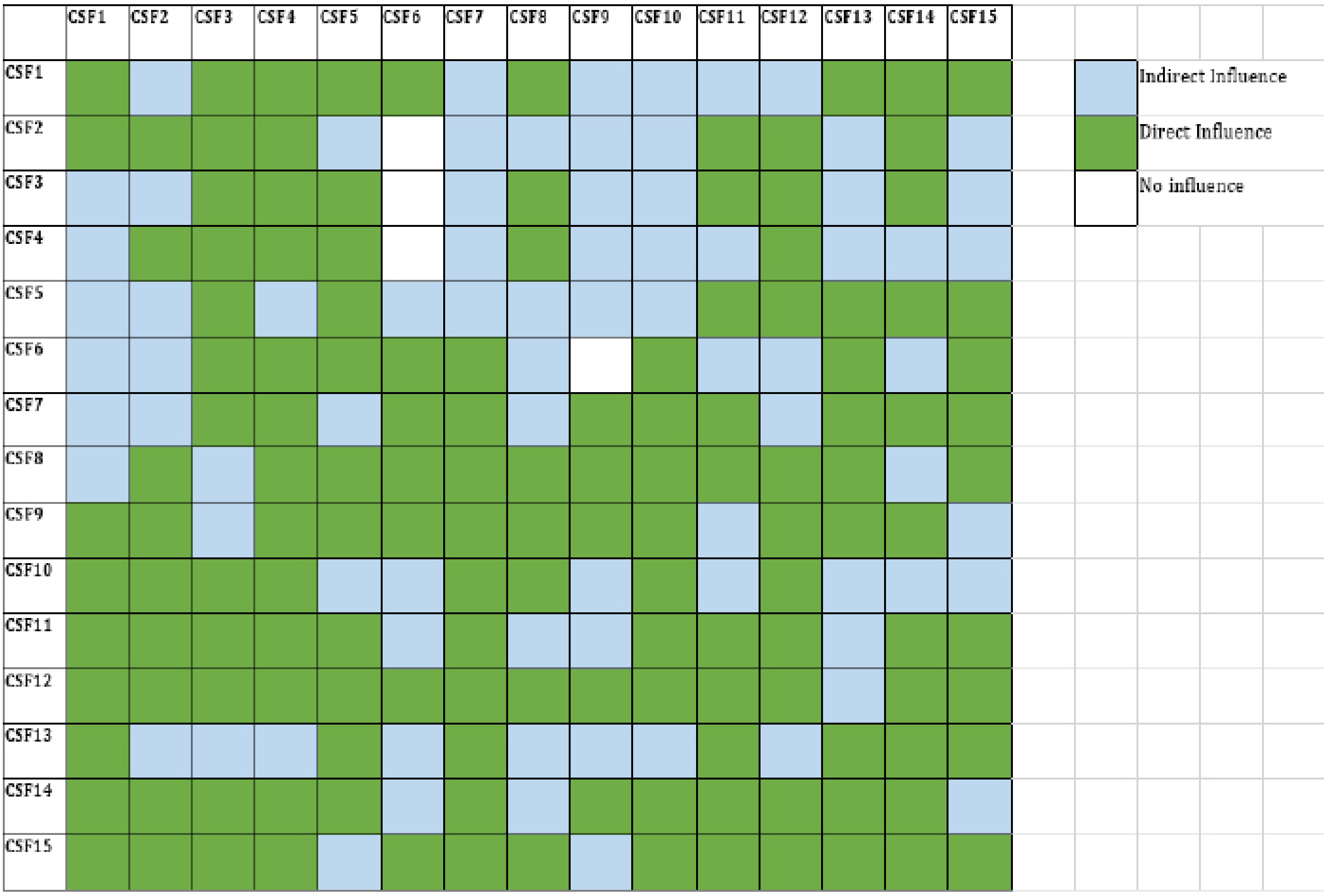

Figure 4: CSFs Inter-Influence Diagram

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

be pragmatically applied within the housing construction industry. Figure 4 illustrates the primary (green) and derived (blue) relationships between critical factors in a color-coded matrix, where "indirect influence" represents the connections among CSFs identified through the transitivity rule, and "direct influences" reflect relationships established based on the consensus from interviews with industry experts. The following section describes the implementation strategies of three selected example CSFs using the inter-influence matrix and their implications:

CSF1: Cost

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

CSF15: Research

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

Table 3: Example Inter-Relativity of Cost (CSF 1)

Relationship Type	CSFs Involved	MMT Context	Implications for Housing Projects
Direct influence of cost	Quality, efficiency, demand, sustainability, legislation, safety	Cost decisions directly shape performance, compliance, and acceptance of MMT systems	Financially balanced projects maintain housing quality and regulatory standards
Indirect influence of cost	Time, logistics, training, customization, coordination	Cost allocation affects process integration and workforce readiness in MMT delivery	Improved planning enhances constructability and cost efficiency
Direct influence on cost	Time, efficiency, logistics, training, customization, coordination, standardization	MMT process efficiency and standardization directly determine cost outcomes	Optimized workflows lower production costs and support affordability
Indirect influence on cost	Demand, sustainability, legislation, safety	External and strategic factors shape long-term cost stability of MMT projects	Policy and market alignment improves economic feasibility

Table 4: Example Inter-Relativity of Legislation (CSF 7)

Relationship Type	CSFs Involved	MMT Context	Implications for Housing Projects
Direct influence of legislation	Quality, efficiency, sustainability, logistics, training, customization, commoditization, standardization, research	Regulatory frameworks shape material use, production methods, and process standardization in MMT	Clear regulations enable compliant, efficient, and scalable MMT housing delivery
Indirect influence of legislation	Cost, time, demand, safety, coordination	Legislative requirements affect project timelines, costs, and market acceptance	Early regulatory alignment reduces delays and improves project feasibility
Direct influence on legislation	Sustainability, safety, logistics, training, customization, coordination, commoditization, standardization, research	Industry practices and technological advancements inform regulatory updates	MMT innovation supports evidence-based policy development
Indirect influence on legislation	Cost, time, quality, efficiency, demand	Market performance and project outcomes indirectly shape legislative priorities	Successful MMT projects encourage supportive housing policies

Further, the reachability matrix was further elucidated through a MICMAC analysis and TISM model. The analysis reveals:,

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

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

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

Discussion, Sumary and Conclusions

The aim of this study is to develop a standardized CSFs rubric and an assessment framework to evaluate and support the adoption of Modular Mass Timber (MMT) construction in housing projects across the United States. This study recognizes that the successful implementation of MMT depends on a set of interrelated technicals, economic, and managerial factors, which necessitate a systematic approach for their analysis, prioritization, and application.

The study's aim is supported by the analytical processes undertaken. The identification of CSFs, the construction of the TISM model, and the development of implementation strategies directly align with the stated purpose of establishing a standardized framework for evaluating and advancing MMT adoption. The primary feature of this study is the development of a structured TISM-based framework that maps the interrelationships, driving powers, and dependencies among the identified CSFs, providing a prioritized rubric to guide effective MMT adoption in housing. Recent advancements in offsite construction techniques, particularly MMT construction, represent a progressive stride towards resolving these issues. Despite mass timber's demonstrated potential across various construction types, its advantages have yet to be fully realized within the housing sector. Literature indicates that MMT could address numerous housing challenges through its superior speed, cost-efficiency, sustainability, and quality. This study, therefore, employs a multifaceted approach comprising systematic literature reviews, semi- structured expert interviews, and TISM to explore the CSFs influencing MMT adoption in housing. From the literature and expert interviews, multiple factors were identified and categorized into fifteen clusters: cost, time, quality, efficiency, demand, sustainability, legislation, safety, Logistics, training, customization, coordination, commoditization, standardization, and research, leading to the creation of a level partitioning matrix with a three-level hierarchy.

Sustainability and logistics emerge as dominant factors in MMT-based housing because modular mass timber construction inherently prioritizes environmental performance and relies on tightly coordinated off-site and on-site processes. Sustainability functions as a strategic driver, shaping material choices, regulatory alignment, and long-term project value, while logistics determines whether the efficiency and scalability advantages of MMT can be effectively realized. Practically, this underscores the need for early integration of sustainability objectives and logistics planning in project development. From a policy perspective, supportive regulations and incentives targeting sustainable materials and modular logistics can accelerate MMT adoption. For future research, these findings highlight the importance of empirically examining how sustainability-led strategies and logistics optimization influence cost efficiency, delivery performance, and lifecycle outcomes in affordable housing projects.

The findings of this study advance existing research on modular construction and mass timber by demonstrating that the success of Modular Mass Timber (MMT) adoption in housing projects is not driven by isolated factors, but by a structured system of interrelated Critical Success Factors (CSFs). While prior studies on modular construction and mass timber adoption have largely emphasized individual drivers such as cost, sustainability, or time efficiency, this research extends the literature by empirically revealing how these factors interact hierarchically and influence one another within an integrated decision-making framework.

From a practical perspective, the findings offer direct applicability for developers, designers, contractors, and policymakers involved in affordable housing delivery. By translating the CSF hierarchy into implementation strategies, the study provides a strategic guide for integrating sustainability objectives, optimizing logistics planning, and managing foundational performance factors such as time, quality, and efficiency.

For developers and project managers, the results indicate a need to shift from cost- and schedule-driven decision-making toward early integration of sustainability objectives and logistics planning. Sustainability should be embedded at the design and procurement stages rather than treated as a compliance requirement, while logistics must be planned alongside design standardization and modular sequencing to avoid disruptions that erode MMT's efficiency advantages. Developers adopting MMT should prioritize supply chain coordination and standardized design approaches to improve predictability and affordability.

For policymakers, the prioritized CSFs highlight that supportive regulatory frameworks and incentives play a critical role in enabling MMT adoption. Policies that encourage sustainable materials, streamline approvals for modular construction, and support logistics infrastructure can directly strengthen the dominant drivers identified in this study. Rather than focusing solely on end-cost subsidies, policy interventions should target sustainability performance and modular-friendly regulations to accelerate scalable affordable housing delivery.

For manufacturers and designers, the findings emphasize the importance of design-for-manufacture-and-assembly, standardization, and research-driven innovation. Designers should align architectural flexibility with modular constraints, while manufacturers should invest in process optimization and research to improve repeatability, quality, and cost control. Greater collaboration between designers, manufacturers, and installers is essential to reduce fragmentation and enhance system-level performance.

Overall, this research contributes to the field by bridging theoretical CSF frameworks with industry-informed insights, offering a comprehensive and application-oriented model for MMT adoption in housing. It not only enriches academic understanding of modular mass timber systems but also equips stakeholders with evidence-based tools to support scalable, sustainable, and cost-effective housing development.

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