Production Cost Factors in Cross-Laminated Timber Manufacturing: A Comparative Study between North America and Europe

Lili Yang

A thesis

submitted in partial fulfillment of the

requirements for the degree of

Master of Science

University of Washington

2026

Committee:

Kent Wheiler

Indroneil Ganguly

CC Yao

Program Authorized to Offer Degree:

School of Environmental and Forest Sciences

University of Washington

Abstract

Production Cost Factors in Cross-Laminated Timber Manufacturing: A Comparative Study between North America and Europe

Lili Yang

Chair of the Supervisory Committee:

Kent Wheiler
School of Environmental and Forest Sciences

Cross-laminated timber (CLT) has emerged as one of the fastest-growing engineered wood products for sustainable and low-carbon construction. Although previous studies have identified lumber as the largest production cost in CLT manufacturing, relatively little attention has been given to how lumber characteristics and upstream supply chain organization influence manufacturing efficiency. This study compares production cost factors in North American and European CLT manufacturing to examine how differences in lumber preparation, manufacturing practices, and industrial organization affect production systems. The analysis draws on interviews with eight CLT producers (four in North America and four in Europe), field visits to three CLT manufacturing facilities and two sawmills, and a review of academic

literature and industry reports.

The findings indicate that production efficiency depends not only on lumber price but also on lumber readiness, defined as the extent to which lumber is prepared for CLT manufacturing before entering the production line. European producers generally received lumber requiring less downstream preparation, whereas North American producers more frequently processed commodity dimensional lumber through additional drying, planing, and machining prior to panel production. These differences increased processing requirements, material handling, and opportunities for material loss. The study also found that many of the observed differences originated upstream in sawmill operations and supply chain organization rather than in CLT manufacturing technology itself.

The study identifies lumber readiness as an important factor influencing production efficiency beyond raw material cost alone and demonstrates how industrial development pathways have shaped contemporary CLT manufacturing systems in Europe and North America. The findings suggest that greater coordination between sawmills and engineered wood manufacturers, together with the development of CLT-specific lumber products and increased product standardization, may improve manufacturing efficiency as the North American mass timber industry continues to mature. By linking lumber preparation, supply chain organization, and industrial development to production costs, this study contributes to a broader understanding of factors influencing the competitiveness of CLT manufacturing.

Acknowledgements

I would like to express my sincere gratitude to my advisor, Professor Kent Wheiler, for his guidance, encouragement, and support throughout my graduate studies. His mentorship, constructive feedback, and high academic standards have been invaluable to the completion of this thesis.

I am also grateful to my supervisory committee, Professor Indroneil Ganguly and Dr. CC Yao, for their thoughtful comments, insightful suggestions, and generous support. Their feedback significantly strengthened both the quality of this research and the final manuscript.

I would like to thank the CLT manufacturers, sawmill representatives, machinery specialists, and other industry professionals who generously shared their time, knowledge, and experience through interviews and site visits. Their willingness to discuss manufacturing practices and supply chain development provided insights that could not have been obtained from published literature alone. To honor the confidentiality promised during this study, I gratefully acknowledge their contributions collectively.

Finally, I wish to express my deepest appreciation to my daughter, Yuexin, my brother, Lin, and the rest of my family for their love, patience, and unwavering encouragement throughout this journey. Their understanding, sacrifices, and steadfast support made it possible for me to pursue my graduate studies while balancing the many challenges along the way.

Table of Contents

Abstract i

Chapter 1 Introduction and Background 1

1.1 Background 1

1.2 Problem Statement 5

1.3 Research Questions 7

1.4 Scope of the Study 8

1.5 Thesis Organization 9

Chapter 2 Literature Review 10

2.1 Introduction 10

2.2 Production Cost Factors in CLT Manufacturing 11

2.2.1 Raw Material Costs 13

2.2.2 Capital Investment and Production Scale 15

2.2.3 Transportation and Market Access 17

2.2.4 Limitations of Existing Cost Studies 18

2.3 Lumber Preparation and Utilization 19

2.3.1 Moisture Control, Grading, and Defect Removal 20

2.3.2 Lumber Processing 22

2.3.3 Lumber Utilization 23

2.4 Supply Chain Structure and Vertical Integration 25

2.4.1 Lumber Sourcing and Industrial Integration 25

2.4.2 European and North American Supply chain Systems 27

2.5 Research Gap 28

Chapter 3 Methodology 30

3.1 Research Design 30

3.2 Data Sources 32
3.3 Selection of Case Study Producers 34
3.4 Semi-Structured Interviews with Producers 36
3.5 Field Visits and Operational Observations 37
3.6 Comparative Analytical Framework 39
3.7 Limitations of the Methodology 42
Chapter 4 Interview and Field Observation Results 44
4.1 Overview of Participating Producers 44
4.2 Lumber Sourcing and Supply Systems 46
4.3 Lumber Readiness for CLT Manufacturing 48
4.3.1 Moisture Control 48
4.3.2 Lumber Dimensions and Edge Conditions 50
4.3.3 Grading and Defect Removal 52
4.4 Finger-Jointing and Lumber Processing 53
4.5 Panel Production and Layup Operations 55
4.6 Chapter Summary 58
Chapter 5 Discussion, Conclusions and Recommendations 60
5.1 Lumber Readiness as a Production Cost Factor 60
5.1.1 Lumber Costs in Existing Literature 61
5.1.2 Lumber Readiness and Processing Requirements 63
5.1.3 Comparison with the North American Glulam Industry 66
5.2 Supply Chain Integration and Industrialization of CLT Manufacturing 69
5.2.1 Integration and Lumber Readiness 70
5.2.2 Industry Development Pathways and Supply Chain Organization 72
5.2.3 Supply Chain Maturity and Future Development 75
5.3 Panel Design Flexibility and Lumber Specifications 78

5.4 Industrial Ecosystems Supporting CLT Manufacturing ... 80

5.4.1 Industrial Ecosystems and Material Utilization ... 81

5.4.2 Industrial Fragmentation and Supply Chain Constraints in North America ... 83

5.4.3 Implications for North American Development ... 85

5.4.4 Future Development Pathways ... 86

5.5 Katerra: A Case Study of Vertical Integration in North America ... 88

5.6 Limitations ... 92

5.7 Conclusions and Recommendations ... 93

5.7.1 Conclusions ... 93

5.7.2 Industry Recommendations ... 95

5.7.3 Recommendations for Future Research ... 97

References ... 99

Chapter 1 Introduction and Background

1.1 Background

Mass timber construction has gained increasing global attention as a low carbon alternative to conventional steel and concrete building systems. Among mass timber products, cross-laminated timber (CLT) has emerged as one of the most significant engineered wood products due to its structural performance, dimensional stability, prefabrication potential, and applicability in mid-rise and high-rise construction. Since its commercial development in Central Europe during the 1990s, CLT has experienced rapid growth in both production capacity and market adoption, particularly in Europe and, more recently, North America.

Cross-laminated timber (CLT) is a prefabricated engineered wood product manufactured by bonding multiple layers of lumber with structural adhesives, with adjacent layers oriented perpendicular to one another. This crosswise configuration provides high dimensional stability, two-way structural performance, and efficient load transfer, enabling CLT panels to serve as structural walls, floors, and roofs in residential, commercial, and institutional buildings. Typical panels consist of three, five, seven, or more layers, depending on structural and fire-resistance requirements.

Figure 1.1 Typical cross-laminated timber panel construction. Source: KLH UK

The manufacturing of CLT generally begins with sawmilling and kiln drying, followed by lumber preparation, including moisture control, grading, finger-jointing where required, and planing to achieve suitable dimensions and bonding surfaces. Individual laminations are then assembled into panel layups, bonded under pressure using structural adhesives, and machined into finished building components using computer numerical control (CNC) equipment. While these fundamental manufacturing steps are similar across regions, differences in lumber preparation and readiness, supply chain organization, and product standardization distinguish European and North American production systems and provide the foundation for the comparative analysis presented in this study.

The origins of CLT were closely linked to the European sawmill industry. Early CLT development in Austria was motivated by the need to create higher-value applications for sideboards generated during sawmilling operations. Although sideboards were often perceived as lower-value products within traditional lumber markets, their favorable mechanical properties made them suitable for engineered wood applications. The development of CLT provided an opportunity to convert these underutilized resources into structural construction products, contributing to the early commercialization of the technology (Brandner, 2013).

Europe currently represents the most mature CLT manufacturing region globally. The European CLT industry emerged during the 1990s through the efforts of a small number of pioneering manufacturers, many of which initially operated as independent or relatively small-scale producers. As market demand for mass timber continued to expand, the industry gradually evolved through increasing collaboration and integration among forestry, sawmilling, engineered wood manufacturing, and timber construction sectors. Established forest products companies progressively expanded from traditional products such as structural timber and glulam into CLT manufacturing, while some early CLT producers became part of larger forest products groups. Today, the majority of European CLT producers operate within highly coordinated and vertically integrated organizations that include forest ownership, sawmills, kiln drying facilities, engineered wood manufacturing, and, in some cases, downstream operations such as bioenergy, pellets, pulp, and other wood-based products. These diversified production systems improve overall raw material utilization by directing lower-grade material and manufacturing byproducts toward higher-value secondary products and energy applications. The gradual development of this integrated industrial ecosystem has supported the growth of large-scale CLT manufacturing and the evolution of lumber products and preparation systems specifically designed for engineered wood applications.

In North America, the commercial CLT industry has developed more recently, with substantial industry growth occurring primarily during the past decade. The expansion of mass timber construction in the United States and Canada has been supported by increasing interest in sustainable construction, updates to building codes permitting taller timber structures, and growing investment in domestic CLT manufacturing capacity. However, compared with Europe, North American CLT production systems operate within a different industrial and supply chain context. Lumber supply systems in North America have historically been optimized for light-frame construction markets based on standardized dimensional lumber products rather than engineered wood panel manufacturing.

The development of CLT manufacturing in the two regions has also been influenced by different technical standards and industrial frameworks. In Europe, CLT manufacturing has largely developed under European technical standards and certification systems associated with engineered wood production and timber construction, including EN 16351: Timber structures - Cross laminated timber – Requirements (European Committee for Standardization, 2015) and Eurocode 5:

Design of timber structures (European Committee for Standardization, 2004). In North America, CLT production has developed under ANSI/APA PRG 320: Standard for Performance Rated Cross-Laminated Timber (APA – The Engineered Wood Association, 2019) and North American building code systems, particularly the International Building Code (IBC), which evolved within a construction market historically dominated by light-frame dimensional lumber systems. These differing industrial and regulatory contexts have influenced both manufacturing practices and material preparation requirements within regional CLT production systems.

Differences in industrial structure, lumber supply systems, and manufacturing standards influence how lumber is prepared and processed before entering CLT manufacturing facilities. Factors such as moisture control, dimensional preparation, edge condition, and supply chain coordination affect downstream manufacturing requirements, material utilization, and overall production efficiency. While modern CLT production facilities in both regions employ advanced automation and high-capacity manufacturing systems, differences in upstream lumber preparation systems influence the amount of material adaptation required during production.

1.2 Problem Statement

Although CLT manufacturing has expanded rapidly in both Europe and North America, limited research has examined how operational manufacturing practices and lumber preparation systems influence material utilization and production cost within CLT manufacturing facilities. Existing research related to CLT manufacturing economics has primarily focused on techno-economic analysis, raw material pricing, equipment investment, transportation, and plant scale (Brandt et al., 2019; Zelaya, 2020). Comparatively less attention has been given to operational factors affecting downstream production conditions and effective material yield during manufacturing.

Publicly available production-cost data for CLT manufacturing also remain limited, particularly in North America where the industry is comparatively young and commercially sensitive. As a result, many existing studies rely on generalized assumptions regarding manufacturing conditions and material processing requirements. Operational characteristics such as moisture control, dimensional preparation, edge condition, finger-jointing configurations, corrective machining, and material rejection associated with drying-related deformation remain insufficiently documented within comparative CLT manufacturing research.

In addition, differences in lumber supply systems between North America and Europe influence how lumber is prepared and processed before entering CLT production lines. These upstream differences affect downstream manufacturing requirements, material utilization, and production flow within CLT facilities, yet relatively little comparative case-study research has examined these relationships directly through producer interviews and field observations.

Consequently, there remains a need for comparative operational research examining how lumber preparation systems, supply chain coordination, and manufacturing practices influence material utilization and production cost drivers within CLT production systems. Improved understanding of these relationships help support the development of more efficient manufacturing strategies and provide practical insight for emerging CLT industries.

1.3 Research Questions

This study examines how lumber preparation systems and operational manufacturing practices influence material utilization and production cost drivers within CLT manufacturing systems in North America and Europe. The research is guided by the following questions:

1. How do lumber sourcing systems and material preparation practices differ between North American and European CLT producers?
2. How do lumber characteristics and preparation requirements influence downstream manufacturing processes and material utilization within CLT production systems?
3. What operational factors contribute to regional differences in CLT production cost drivers and manufacturing efficiency?

These research questions guide the comparative case-study analysis presented in the subsequent chapters and provide the basis for examining relationships between upstream lumber systems and downstream production outcomes within CLT production.

1.4 Scope of the Study

This study focuses on operational factors influencing material utilization and production cost drivers within CLT manufacturing systems in North America and Europe. The research examines how lumber sourcing systems, material preparation practices, moisture control, dimensional preparation, machining requirements, and supply chain coordination influence downstream manufacturing conditions within CLT production facilities.

The study is based on comparative case studies of eight CLT producers, including four producers from North America and four from Europe. Participating producers were located in the United States and Canada in North America, and Austria, Germany, and Sweden in Europe. The CLT industry remains relatively small compared with conventional forest products sectors. A review of the *Global Mass Timber Projects & Producers* database identified 57 CLT production facilities in Europe and 11 facilities in North America, highlighting both the relatively limited population of manufacturers and the more mature development of the European CLT sector (Yang et al., 2026). Given the commercially sensitive nature of operational information and the limited number of producers, the study adopted a purposive sampling approach that sought representation across different production capacities, sourcing arrangements, and organizational structures rather than a statistically representative sample of the broader industry. Data collection consisted primarily of semi-structured producer interviews and field observations conducted at selected CLT manufacturing facilities and associated sawmills. The analysis emphasizes comparative operational interpretation rather than large-scale statistical or economic modeling of CLT production costs.

1.5 Thesis Organization

This thesis is organized into five chapters. Chapter 1 introduces the background of CLT manufacturing and mass timber construction, presents the research problem, and outlines the research questions and scope of the study. Chapter 2 reviews existing literature related to CLT manufacturing systems, lumber preparation, material utilization, supply chain structures, and production cost factors.

Chapter 3 describes the research methodology, including the comparative case study design, producer interviews, field observations, data sources, and framework for comparative analysis. Chapter 4 presents the findings from the case studies, focusing on lumber sourcing systems, material preparation practices, operational observations, and manufacturing characteristics observed among the participating producers.

Chapter 5 discusses and interprets the findings in relation to material utilization, production efficiency, supply chain coordination, and regional differences in CLT manufacturing systems. The chapter also considers implications for future CLT manufacturing development and summarizes the overall conclusions of the study.

Chapter 2 Literature Review

2.1 Introduction

Research examining CLT manufacturing has expanded considerably during the past decade, addressing topics such as structural performance, environmental impacts, manufacturing technologies, supply chain development, and techno-economic analysis. However, comparatively less attention has been given to operational factors that influence material utilization and production efficiency within CLT manufacturing facilities.

Existing studies have identified raw material costs, capital investment, transportation, and production scale as important cost factors in CLT manufacturing (Brandt et al., 2019). Less well understood are the effects of lumber preparation systems, moisture control, dimensional requirements, finger-jointing practices, and supply chain coordination on downstream manufacturing conditions and effective material utilization. These factors influence production costs indirectly through their effects on processing requirements, material recovery, and manufacturing efficiency.

This chapter reviews literature relevant to production cost factors in CLT manufacturing, with particular emphasis on lumber preparation, manufacturing efficiency, material utilization, and supply chain integration. The chapter first reviews major production cost factors identified in previous studies, followed by literature related to lumber preparation systems and manufacturing efficiency. The review then examines the role of supply chain coordination and vertical integration before identifying research gaps addressed by the present study.

The development of the CLT industry has occurred at different rates across Europe and North America. Europe remains the most mature CLT manufacturing region globally, supported by decades of industry development and established forest products sectors. A review of the Global Mass Timber Projects & Producers database identified 57 CLT production facilities in Europe compared with 11 facilities in North America (Yang et al., 2026). The database further indicates that many European producers operate within larger forest-products groups that include sawmills and other engineered wood manufacturing operations, whereas the North American industry consists of a smaller number of manufacturers distributed across the United States and Canada. These differences in industry maturity and organizational structure provide important context for understanding regional variations in lumber sourcing systems, manufacturing practices, and supply chain integration discussed in subsequent sections.

2.2 Production Cost Factors in CLT Manufacturing

The production cost of CLT is influenced by a combination of raw material, capital, operational, and logistical factors. Previous studies have commonly evaluated CLT manufacturing economics using techno-economic analyses, investment assessments, and supply chain studies to identify the major factors affecting production costs and market competitiveness. Across these studies, raw material costs, capital investment, production scale, asset utilization, and transportation logistics are consistently identified as the primary determinants of manufacturing economics.

Although the relative importance of individual cost components varies among studies and production contexts, lumber is generally reported as the largest cost component in CLT manufacturing. Existing research suggests that lumber accounts for between 40% to 80% of total production costs depending on species selection, manufacturing assumptions, and facility configuration (Adhikari et al., 2024; Brandt et al., 2019; Espinoza & Buehlmann, 2018; Zelaya, 2020). In addition to lumber costs, substantial investments are required for specialized manufacturing equipment and facility infrastructure, making CLT production a capital-intensive industry. As a result, production scale and equipment utilization play important roles in determining overall manufacturing competitiveness (Brandt et al., 2019; Crawford et al., 2015; Zelaya, 2020; Zhang & Lan, 2022).

Transportation and supply chain logistics further influence production costs through their effects on raw material procurement and product distribution. Previous studies have examined the influence of transportation distances, market access, and supply chain organization on manufacturing economics, while more recent research has highlighted the importance of lumber procurement systems and supplier relationships within CLT production networks (Adhikari et al., 2024; Crawford et al., 2015; Nepal et al., 2021; Zelaya, 2020). Collectively, these studies demonstrate that CLT manufacturing costs are influenced by both direct economic inputs and broader characteristics of the production system.

The following sections review the principal cost factors identified in the literature, including raw material costs, capital investment and production scale, and transportation and logistics considerations. Particular attention is given to how these factors influence manufacturing efficiency and production competitiveness within CLT production systems.

2.2.1 Raw Material Costs

Raw materials are consistently identified as the largest cost component in CLT manufacturing. Existing studies generally report that lumber accounts for between 40% to 80% of total production costs, depending on species selection, manufacturing assumptions, and facility configuration (Brandt et al., 2019; Crawford et al., 2015; Nepal et al., 2021; Zelaya, 2020; Zhang & Lan, 2022). Because lumber constitutes the majority of panel volume, fluctuations in lumber prices can have a substantial impact on manufacturing economics. Zhang & Lan (2022) found that lumber price was the single most influential variable affecting the minimum selling price (MSP) of CLT panels, while Brandt et al. (2019) similarly identified lumber costs as one of the most significant determinants of manufacturing competitiveness.

In addition to market price, several studies suggest that lumber characteristics and procurement requirements influence overall manufacturing costs. Species selection affects both material cost and structural performance requirements. For example, Crawford et al. (2015) reported that the use of hardwood species substantially increases material costs compared with conventional softwood CLT products.

Likewise, studies examining regional CLT production have noted that lumber availability, grading requirements, certification premiums, and moisture specifications all contribute to differences in procurement costs (Brandt et al., 2019; Zelaya, 2020). The 2025 PNW Regional Mass Timber Market Study further reported that manufacturers often pay substantial premiums for lumber meeting the moisture content and structural grade requirements necessary for CLT production (Anderson et al., 2025). Global market analyses further indicate that increasing demand for mass timber products influences future lumber prices through changes in regional and international wood-product markets (Nepal et al., 2021).

Material preparation requirements also affect the effective cost of lumber within CLT manufacturing systems. Previous studies have reported that manufacturing losses associated with defect removal, trimming, and finger-jointing can significantly influence production economics (Brandt et al., 2019; Zhang & Lan, 2022). Zelaya (2020) further noted that obtaining lumber at the moisture content required for CLT production involves additional drying costs or procurement premiums compared with standard kiln-dried lumber. Similarly, Brandt et al. (2019) demonstrated that manufacturers could economically justify paying higher prices for pre-processed lumber supplied at the appropriate moisture content if doing so reduced internal processing requirements and material losses.

Although existing studies clearly establish the importance of lumber costs in CLT manufacturing, most analyses evaluate lumber primarily as a purchased material input and focus on variables such as price, species, grade, and availability. Comparatively less attention has been given to how lumber preparation requirements, material utilization, and supply chain coordination influence manufacturing efficiency and effective raw material costs within CLT production facilities. These operational considerations are examined in greater detail in the following sections.

2.2.2 Capital Investment and Production Scale

CLT manufacturing is generally characterized as a capital-intensive industry requiring substantial investment in specialized equipment and production infrastructure. Typical production facilities incorporate planing systems, finger-jointing lines, panel layup stations, presses, CNC machining centers, and automated material handling systems. Previous studies have estimated equipment investments ranging from approximately USD 13 million for smaller facilities to more than USD 21 million for larger modeled production scenarios, with total capital investment often exceeding USD 60 million when buildings, installation, land, and supporting infrastructure are included (Brandt et al., 2019; Zelaya, 2020). Additional investments are required for integrated lumber preparation systems, such as grading and drying equipment, further increasing capital requirements.

Due to the high fixed costs associated with manufacturing facilities and equipment, production scale has been consistently identified as a major determinant of CLT manufacturing economics. Multiple techno-economic studies have demonstrated that larger facilities generally achieve lower unit production costs through economies of scale. Zhang & Lan (2022) reported that increasing annual production capacity from 30,000 m^3 to 150,000 m^3 substantially reduced the estimated minimum selling price (MSP) of CLT panels, while Brandt et al. (2019) similarly found that larger facilities achieved lower production costs through improved utilization of capital-intensive equipment. These findings suggest that the ability to distribute fixed costs across greater production volumes is a key factor affecting manufacturing competitiveness.

In addition to physical plant size, several studies emphasize the importance of asset utilization and operational volume. Brandt et al. (2019) identified facility utilization as the single most influential variable affecting CLT manufacturing economics, demonstrating that underutilized facilities experience significantly higher production costs despite possessing similar installed capacity. Similar concerns have been observed within the North American industry. The 2025 PNW Regional Mass Timber Market Study reported that regional manufacturers were operating at only 28% of effective production capacity in 2024, suggesting that market demand and production scheduling substantially influence the economic performance of manufacturing facilities (Anderson et al., 2025). Consequently, previous research generally concludes that successful CLT manufacturing depends not only on investment in production capacity but also on maintaining sufficient volume to maximize the utilization of capital-intensive assets.

Together, these findings indicate that capital investment, production capacity, and facility utilization are closely interconnected factors influencing the economic performance of CLT manufacturing operations.

2.2.3 Transportation and Market Access

Transportation and market access represent additional factors influencing the economic performance of CLT manufacturing facilities. Although transportation costs generally account for a smaller proportion of total production costs than raw materials or capital investment, they significantly affect manufacturing competitiveness where suppliers, production facilities, and end-use markets are geographically dispersed. Previous techno-economic studies have incorporated transportation costs associated with both lumber procurement and product distribution, recognizing their influence on overall manufacturing economics (Brandt et al., 2019; Zhang & Lan, 2022). Several studies further suggest that proximity to both raw material sources and construction markets influence procurement efficiency, transportation costs, and overall manufacturing competitiveness (Adhikari et al., 2024; Anderson et al., 2025; Zelaya, 2020).

The geographic location of manufacturing facilities influence both access to raw materials and proximity to construction markets. Studies examining mass timber supply chains have noted that transportation infrastructure, trucking availability, and distribution networks can affect procurement costs and delivery efficiency (Zelaya, 2020). The 2025 PNW Regional Mass Timber Market Study similarly reported that trucking remains the primary transportation mode for logs, lumber, and finished mass timber products, while driver shortages, rising fuel costs, and transportation regulations continue to present operational challenges. Transportation requirements are further complicated by the movement of large prefabricated timber components, which often require specialized trailers, permits, and oversized-load escorts (Anderson et al., 2025).

Market access also influences the regional competitiveness of CLT manufacturing. A United Kingdom CLT manufacturing viability assessment found that domestic production could reduce transportation distances and improve competitiveness relative to imported European products (Crawford et al., 2015). Likewise, Nepal et al. (2021) demonstrated that transportation costs, trade flows, and regional supply networks influence the long-term economics of mass timber production at both national and international scales. Collectively, these studies suggest that transportation considerations affect not only manufacturing costs but also the ability of producers to access raw materials, serve construction markets, and compete within broader regional supply networks.

2.2.4 Limitations of Existing Cost Studies

Existing studies have substantially improved understanding of the economic factors influencing CLT manufacturing, particularly with respect to raw material costs, capital investment, production scale, and transportation considerations. Techno-economic analyses have also provided valuable estimates of manufacturing costs under different production scenarios and market conditions.

However, many of these studies rely on generalized production assumptions and focus primarily on quantifiable cost categories. As a result, less attention has been directed toward the operational conditions underlying production outcomes, including how production systems interact with material characteristics and processing requirements. Consequently, economic analyses may not fully capture the factors influencing production outcomes within individual facilities.

To better understand these operational influences, the following section reviews literature related to lumber preparation and manufacturing processes within CLT production systems.

2.3 Lumber Preparation and Utilization

Although raw material costs, capital investment, and transportation are widely recognized as important factors influencing CLT manufacturing economics, the characteristics and condition of lumber entering production also affect production outcomes. Prior to panel assembly, lumber typically undergoes a series of preparation and processing stages, including drying, grading, defect removal, finger-jointing, and planing. These processes are intended to ensure that lumber meets the dimensional, mechanical, and moisture requirements necessary for CLT production.

The effectiveness of these preparation and processing stages influences lumber utilization throughout the manufacturing process. Material losses associated with drying, defect removal, trimming, and machining reduce the volume of finished CLT that can be produced from a given quantity of lumber. Consequently, lumber utilization has important implications for both production efficiency and manufacturing costs. The following sections review literature related to moisture control, lumber processing, and lumber utilization within CLT manufacturing systems.

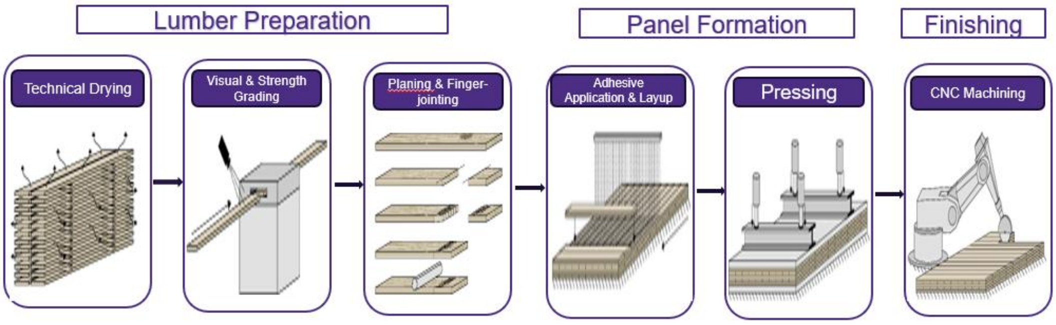


Figure 2.1 Typical CLT Manufacturing Process. Source: adapted from [Cross laminated timber (CLT, X-Lam) - Manufacture - brettsperrholz.org]

2.3.1 Moisture Control, Grading, and Defect Removal

Moisture control is a fundamental requirement in CLT manufacturing because the moisture content of lumber influences dimensional stability, adhesive bonding performance, and the long-term structural behavior of finished panels. Most CLT manufacturers target lumber moisture contents of approximately 12% (typically 12 ± 2–3%), which is lower than the moisture content of conventional kiln-dried dimensional lumber (KD19, approximately 15–19%). Lower moisture contents reduce subsequent dimensional changes after panel pressing, improve adhesive bond quality, and minimize the risk of shrinkage, warping, and internal stresses during service. Consequently, industry standards and manufacturing guidelines typically specify moisture content ranges for lumber used in CLT production. To meet these requirements, lumber is commonly kiln dried prior to manufacturing and undergo additional conditioning or drying processes when necessary. Previous studies have identified moisture control as an important consideration affecting both manufacturing operations and raw material procurement, particularly where lumber is sourced from suppliers that primarily serve conventional lumber markets (Anderson et al., 2025; Brandt et al., 2019; Zelaya, 2020).

Following drying, lumber is typically graded to verify that material properties meet structural and manufacturing requirements. Grading is conducted visually, mechanically, or through a combination of methods depending on regional standards and manufacturing practices. The purpose of grading is to ensure that lumber incorporated into CLT panels satisfies strength and stiffness requirements while maintaining consistency in finished products. Because CLT performance depends on the characteristics of individual lamellae, grading represents an important quality control step within the manufacturing process.

Defect removal constitutes an additional stage of lumber preparation. Knots, splits, checks, wane, warp, and other defects reduce structural performance or interfere with downstream manufacturing processes. Consequently, sections containing unacceptable defects are commonly removed before further processing. Previous techno-economic analyses have identified defect removal as a source of material loss within CLT manufacturing systems and have incorporated these losses into manufacturing cost calculations (Brandt et al., 2019; Zhang & Lan, 2022). Although defect removal reduces the volume of lumber available for production, it contributes to product quality and enables subsequent processing stages such as finger-jointing and planing.

Collectively, moisture control, grading, and defect removal establish the conditions necessary for subsequent lumber processing operations. These preparation stages influence both the quality of incoming material and the quantity of lumber ultimately available for conversion into finished CLT panels.

2.3.2 Lumber Processing

Following moisture control, grading, and defect removal, lumber typically undergoes additional processing operations to prepare material for panel assembly. Common processing stages include finger-jointing, planing, and surfacing, all of which are intended to improve dimensional consistency, bonding performance, and manufacturing efficiency. These operations transform individual lumber pieces into lamellae suitable for CLT production and help ensure that material characteristics meet manufacturing requirements.

Finger-jointing is widely used within CLT manufacturing to increase lumber utilization and produce longer lamellae from shorter lumber sections. Following defect removal, shorter pieces are joined together using engineered finger joints, allowing manufacturers to recover material that might otherwise be unsuitable for production. Previous studies have identified finger-jointing as an important component of CLT manufacturing systems because it improves raw material utilization while contributing to dimensional consistency and production efficiency

(Anderson et al., 2025; Brandt et al., 2019). However, the process also introduces additional processing costs and material losses associated with trimming and quality control.

Planing and surfacing represent additional processing stages intended to achieve dimensional accuracy and prepare lumber surfaces for adhesive bonding. Surface quality is particularly important in CLT manufacturing because bonding performance is affected by surface roughness, contamination, and dimensional variation. Consequently, lumber is commonly planed prior to layup, to improve surface uniformity and facilitate adhesive application. Previous studies have noted that dimensional consistency, which is also required by manufacturing standards, and surface preparation contribute to manufacturing quality and influence downstream production processes (Brandt et al., 2019).

Collectively, lumber processing operations are intended to prepare material for efficient panel production while maximizing the value obtained from available lumber resources. The effectiveness of these processing stages influences both production outcomes and the quantity of lumber ultimately incorporated into finished CLT products.

2.3.3 Lumber Utilization

Lumber utilization is an important consideration in CLT manufacturing because it impacts both raw material efficiency and overall production costs. During the conversion of lumber into finished panels, material losses occur through drying, defect removal, trimming, finger-jointing, planing, and other processing operations. Consequently, the proportion of incoming lumber ultimately incorporated into finished products varies depending on material characteristics, processing requirements, and manufacturing practices.

Previous studies have identified lumber utilization as an important factor affecting manufacturing economics. Because lumber typically represents the largest cost component in CLT production, the proportion of incoming material retained within finished products directly influences effective raw material costs. Techno-economic analyses therefore incorporate assumptions regarding material losses throughout the production process, recognizing that drying, defect removal, trimming, and machining affect the volume of finished product obtained from a given quantity of lumber (Brandt et al., 2019; Zhang & Lan, 2022). As a result, improving lumber utilization is frequently regarded as an important strategy for enhancing manufacturing competitiveness.

The relationship between lumber utilization and production outcomes extends beyond the quantity of material retained within finished products. Processing requirements intended to improve product quality also increase material losses, creating trade-offs between quality control and resource efficiency. Defect removal, dimensional preparation, and quality assurance procedures contribute to the production of structurally reliable CLT products but reduce the proportion of lumber retained within finished panels. As a result, lumber utilization reflects not only the characteristics of incoming material but also the manufacturing decisions and processing strategies employed within production facilities.

In summary, the literature suggests that lumber utilization represents an important link between raw material characteristics, manufacturing processes, and production economics. Understanding the factors affecting lumber utilization therefore provides insight into how manufacturing systems convert raw material inputs into finished CLT products and where opportunities for improving production efficiency exist.

2.4 Supply Chain Structure and Vertical Integration

The performance of CLT manufacturing systems depends not only on processes within individual production facilities but also on the organization of upstream supply chains. Lumber is the primary raw material input in CLT manufacturing, and supply chain arrangements influence not only material availability but also the characteristics of lumber entering production. The following sections review literature related to lumber sourcing, industrial integration, and regional differences in supply chain organization within the CLT industry.

2.4.1 Lumber Sourcing and Industrial Integration

The production of CLT requires a consistent supply of lumber that meets structural, dimensional, and moisture specifications. As a result, lumber sourcing plays an important role in manufacturing operations. Previous studies have shown that CLT manufacturers obtain lumber through various procurement arrangements, including purchases from independent sawmills, long-term supply agreements, and vertically integrated production systems. These arrangements influence the availability, consistency, and characteristics of lumber entering the manufacturing process.

Vertical integration is common among many established mass timber producers, particularly in Europe. In integrated systems, forestry operations, sawmills, drying facilities, and engineered wood manufacturing operate within the same organization, often alongside a broader portfolio of wood products such as structural lumber, glulam, LVL, panels, pellets, and bioenergy products. This structure enables manufacturers to coordinate production across multiple stages of the value chain, maintain greater control over raw material specifications, and allocate material among different product streams according to quality and market requirements. Researchers have noted that integration can improve coordination between lumber production and downstream manufacturing while reducing dependence on external suppliers (Anderson et al., 2025; Zelaya, 2020).

Many manufacturers, however, operate without full vertical integration. In these cases, cooperation between sawmills and CLT producers becomes an important part of the supply chain. Long-term supplier relationships and contractual arrangements help manufacturers secure lumber that satisfies production requirements and supports stable manufacturing operations. The effectiveness of these relationships is particularly important where CLT production requires lumber characteristics that differ from those commonly supplied to conventional lumber markets (Adhikari et al., 2024; Zhang & Lan, 2022).

2.4.2 European and North American Supply chain Systems

The development of CLT manufacturing has occurred under different industrial conditions in Europe and North America. Europe is generally regarded as the birthplace of modern CLT manufacturing and has developed a mature mass timber sector supported by established supply chains, standardized production systems, and long-standing experience in engineered wood products. North American CLT manufacturing has expanded more recently, with industry growth occurring within a lumber sector historically oriented toward light-frame construction and commodity lumber production.

These differing industrial contexts have influenced how lumber is supplied to CLT manufacturers. Studies comparing Austrian and U.S. producers have reported that European manufacturers often operate within highly integrated forest-products groups, where sawmills, drying facilities, and engineered wood manufacturing are closely connected (Adhikari et al., 2024; Anderson et al., 2025). Such arrangements facilitate coordination between lumber production and downstream manufacturing. In North America, although some producers operate integrated facilities, manufacturers more commonly rely on external lumber suppliers and procurement arrangements that were originally developed to serve conventional lumber markets (Anderson et al., 2025; Zelaya, 2020; Zhang & Lan, 2022).

Differences have also been observed in production strategies. European manufacturers frequently produce standardized products and maintain continuous production systems supported by established supply networks. While North American producers often operate within a project driven market where production schedules and product specifications are closely linked to individual construction projects (Anderson et al., 2025). These differences influence procurement practices, inventory management, and the flow of material through manufacturing systems.

Taken together, the literature suggests that European and North American CLT industries operate within distinct supply chain environments shaped by their historical development, market structures, and industrial organization. Understanding these differences provides important context for evaluating how lumber sourcing and manufacturing practices vary between regions.

2.5 Research Gap

Existing literature has provided valuable insights into the economics, manufacturing processes, and supply chain organization of CLT production. Previous studies have identified raw material costs, capital investment, production scale, and transportation as important factors affecting manufacturing competitiveness. Research has also examined lumber preparation requirements, processing operations, material utilization, and supply chain structures within the mass timber sector.

However, these topics are often investigated independently. Techno-economic analyses typically evaluate manufacturing costs using broad cost categories and production assumptions, while studies of manufacturing processes frequently focus on technical performance rather than their implications for production costs. Similarly, supply chain research has examined procurement systems and industrial integration but has provided limited discussion of how these arrangements influence material preparation and manufacturing operations within CLT facilities.

As a result, relatively little research has examined the connections between lumber sourcing, material preparation, and production outcomes. In particular, limited attention has been given to how lumber characteristics and preparation requirements influence downstream processing and material utilization within CLT manufacturing systems. Understanding these relationships is important because the condition of lumber entering production affects manufacturing operations beyond the direct cost of raw materials.

This study addresses this gap through a comparative examination of CLT manufacturing systems in North America and Europe. By combining industry interviews, facility observations, and literature review, the research investigates how lumber sourcing, preparation practices, and manufacturing operations interact within different production environments and how these factors influence operational efficiency.

Chapter 3 Methodology

3.1 Research Design

This study employs a comparative multiple case study to examine material utilization and production cost drivers in cross-laminated timber (CLT) manufacturing across North America and Europe. Case study research is particularly suitable for investigating complex real-world operational systems where contextual factors and process interactions are important to the analysis (Hancock et al., 2021; Yin, 2018). The research focuses on eight CLT producers selected to represent variation in production scale, supply chain organization, and manufacturing practices across the two regions. By comparing operational characteristics and production systems across multiple producers, the study aims to identify factors influencing production cost and material efficiency within different regional manufacturing contexts.

The research adopts a qualitative and exploratory comparative design. This approach is appropriate because the body of publicly available research on CLT production cost remains limited, particularly operational manufacturing practices and material preparation systems. The limitation of available quantitative cost data is especially significant in North America, where the CLT industry has developed relatively recently and the number of producers remains comparatively small. As a result, a case study methodology provides a suitable framework for examining production practices and identifying operational factors that are not fully visible in published cost data alone.

The study is also explanatory in nature, seeking to analyze how specific factors, including lumber characteristics, moisture control, material preparation practices, supply chain coordination, finger-jointing configurations, and panel layup requirements, influence material utilization and production cost. Rather than focusing solely on reported production costs, the research aims to explain the mechanisms through which upstream lumber preparation systems and manufacturing practices affect operational efficiency within CLT production.

To achieve these objectives, the study integrates multiple sources of evidence, including published literature, semi-structured interviews, and field observations from CLT manufacturing facilities. The interviews were conducted with eight CLT producers located in North America and Europe, while field visits provided direct observation of production processes and material preparation practices. Synthesizing information from multiple sources allows findings from published information, producer-reported practices, and direct operational observations to be compared across multiple sources of evidence (Hancock et al., 2021).

Because the study seeks to understand the factors influencing CLT manufacturing practices and production costs rather than to achieve statistical generalization, a comparative case study approach was considered appropriate. This approach enables the research to develop a contextually grounded understanding of how differences in lumber preparation systems, supply chain structures, and manufacturing practices contribute to regional variation in CLT production cost and material utilization.

3.2 Data Sources

This study integrates multiple sources of evidence to examine material utilization and production cost drivers in CLT manufacturing. The research draws on published literature, semi-structured interviews with producers, and field observations to develop a comparative understanding of manufacturing practices in North America and Europe. The use of multiple data sources allows findings to be cross-checked across different forms of evidence and provides greater contextual depth for interpreting operational differences between producers.

Published literature was used to establish the theoretical and industrial context of the study. Sources included peer-reviewed journal articles, industry reports, technical manuals, conference proceedings, manufacturer publications, and engineering guidelines related to CLT manufacturing, lumber preparation, moisture control, supply chain organization, and production cost factors. Literature sources were used primarily to identify existing knowledge, establish analytical categories, and support the interpretation of observed manufacturing practices rather than to conduct a meta-analysis of production costs.

The primary empirical data source consisted of semi-structured interviews conducted with eight CLT producers located in North America and Europe. The interviews focused on topics including lumber sourcing, moisture control, dimensional preparation, finger-jointing practices, production flow, material utilization, and operational factors affecting production cost. A standardized set of guiding questions was used to improve comparability across producers while still allowing participants to provide detailed explanations of site-specific manufacturing practices and operational challenges.

Four interviews were conducted with North American producers and four with European producers. Interviews with North American producers were conducted primarily through face-to-face discussions at the 2024 International Mass Timber Conference, supplemented by follow-up emails when clarification or additional information was required. Interviews with European producers were conducted primarily via email correspondence. This combination of interview formats allowed data collection from producers across multiple regions while maintaining flexibility in communication and participation.

Field observations were conducted during visits to three CLT manufacturing facilities, including two North American facilities and one European facility. These visits provided direct observation of production processes, lumber preparation systems, machining sequences, moisture control practices, and material handling procedures. Discussions with plant personnel, engineers, and machinery specialists during site visits also provided additional operational insight that complemented interview responses.

The combination of literature review, producer interviews, and field observations enabled the comparison and evaluation of findings from published information, reported manufacturing practices, and direct operational observations across multiple sources of evidence. This multi-source approach improves the reliability of the analysis by allowing production characteristics and operational interpretations to be evaluated across multiple forms of evidence, rather than relying on a single data source.

3.3 Selection of Case Study Producers

The study selected eight CLT producers as comparative case studies to examine differences in material utilization, lumber preparation systems, and production cost drivers between North America and Europe. The selected producers were not intended to represent a statistically representative sample of the global CLT industry. Instead, the cases were selected based on producer willingness to participate and the availability of operational information relevant to the study objectives. Efforts were made to include variation in manufacturing scale, supply chain organization, lumber sourcing practices, and production systems across the two regions.

Four producers were selected from North America and four from Europe. The North American cases represent manufacturers operating within a relatively young and developing CLT industry, while the European cases represent producers within a more mature and vertically integrated manufacturing environment. This regional comparison provides an opportunity to examine how different industrial structures and lumber supply systems influence production practices and material utilization.

Case selection also considered diversity in operational characteristics, including production capacity, degree of vertical integration, lumber sourcing arrangements, moisture control practices, finger-jointing configurations, and panel manufacturing approaches. Some participating producers operated as part of large integrated forest-products groups with internal sawmill supply and multiple manufacturing facilities, while others operated single CLT production facilities relying on external sawmill networks. This variation allowed the study to compare a range of operational models rather than focusing on a single production structure.

Accessibility and willingness to participate were important factors influencing case selection. In North America, outreach was conducted to a broader group of CLT manufacturers; however, only four producers agreed to participate in the study. North American participants were identified primarily through professional engagement and participation at the 2024 International Mass Timber Conference, where face-to-face discussions and follow-up communication were conducted. European producers were identified through industry contacts and direct communication with manufacturers willing to provide operational information relevant to the study objectives.

The selected producers collectively represent a range of manufacturing approaches and operational conditions within the two regions. Although the sample size remains limited, the purpose of the study is analytical rather than statistical. The selected cases therefore provide an appropriate basis for comparative examination of manufacturing practices, material preparation systems, and operational factors influencing CLT production cost and material utilization.

3.4 Semi-Structured Interviews with Producers

Semi-structured interviews were conducted with CLT producers in North America and Europe to collect information regarding lumber sourcing, material preparation practices, manufacturing processes, and operational factors influencing production cost and material utilization. The interview approach was selected to allow consistent comparison across producers while also providing flexibility for participants to discuss site-specific manufacturing conditions and operational challenges in greater detail.

A standardized set of guiding questions was developed to improve comparability between producers. The interview topics included lumber sourcing arrangements, moisture control practices, dimensional preparation, finger-jointing configurations, panel layup practices, production capacity, material utilization, and operational constraints affecting production efficiency. Additional questions were asked where necessary to clarify production practices or explore issues identified during interviews and field observations.

A total of eight valid interview responses were obtained, including four from North American producers and four from European producers. Interviews with North American producers were conducted primarily through face-to-face discussions at the 2024 International Mass Timber Conference, supplemented by follow-up email communication where clarification or additional operational details were required. Interviews with European producers were conducted primarily through email correspondence due to geographic and logistical constraints.

Interview responses were documented through written notes, completed questionnaires, and follow-up correspondence. To preserve confidentiality, producers were anonymized within the study. Any commercially sensitive information not directly relevant to the research objectives was excluded from the analysis.

The interview data served as the primary empirical source for the comparative case study analysis. The responses were evaluated comparatively across producers to identify recurring operational patterns, regional differences, and factors influencing production cost and material utilization within CLT manufacturing systems.

3.5 Field Visits and Operational Observations

Field visits were conducted to obtain direct observation of CLT manufacturing processes and to provide operational context for the producer interviews. While interview responses provided detailed information regarding manufacturing practices and production systems, on-site observations allowed the study to examine how these practices were implemented within actual production environments. Field observations therefore served as an important source of contextual and operational evidence supporting the comparative case study analysis.

Field visits were conducted at three CLT manufacturing facilities, including two facilities in North America and one facility in Europe. The facilities were selected based on accessibility, willingness to provide site access, and relevance to the study objectives. Although the number of site visits was limited, the selected facilities represented different production systems, supply chain arrangements, and lumber preparation practices relevant to the comparative analysis. In addition, two sawmill visits were conducted, including one in North America and one in Europe. Both sawmills operated within the same corporate groups as the respective CLT manufacturing facilities visited, providing additional insight into upstream lumber preparation and supply chain coordination within vertically integrated production systems.

Observations focused on operational stages related to material preparation, production flow, and manufacturing efficiency. Particular attention was given to lumber receiving, moisture control, dimensional preparation, finger-jointing operations, panel layup preparation, machining sequences, material handling, and quality-control procedures. The field visits also allowed observation of how lumber characteristics influenced downstream production processes, including material removal, resurfacing requirements, and production flow continuity.

Discussions conducted during site visits included plant personnel, production staff, engineers, and machinery specialists with knowledge of manufacturing operations and process requirements. These discussions provided additional explanation regarding operational decision-making, production constraints, lumber preparation systems, and process adjustments used during manufacturing.

Field observations also provided insight into operational conditions that were difficult to evaluate through interview responses alone. These included the physical organization of production flow, intermediate material handling, temporary staging areas, moisture-conditioning procedures, and the interaction between lumber preparation and downstream machining operations. Observations related to material rejection following secondary drying were also documented where relevant, particularly in cases where twisting, waning, cracking, or cupping prevented lumber from meeting dimensional or quality requirements for CLT production. Additional observations included dimensional adjustment before panel layup and corrective machining following finger-jointing.

Field notes were recorded during and immediately after site visits to document observations and operational discussions. The observational findings were then compared with interview responses and published literature to identify recurring patterns and support interpretation of manufacturing practices across the case studies.

Although the field visits provided important operational insight, the observations represent only a limited number of facilities and production conditions. Operational practices also vary over time depending on production schedules, product specifications, and lumber supply conditions. The field observations were therefore used primarily to support contextual interpretation of the broader comparative findings rather than to provide statistically generalizable conclusions.

3.6 Comparative Analytical Framework

The comparative analysis in this study focuses on identifying operational factors that influence material utilization and production cost within CLT manufacturing systems. Rather than evaluating production cost solely through reported monetary values, the analytical framework examines how differences in lumber preparation, supply chain organization, and manufacturing practices affect effective material yield and operational efficiency across producers.

The analytical framework was developed based on themes identified through literature review, producer interviews, and field observations. Particular emphasis was placed on factors affecting the relationship between incoming lumber characteristics and downstream manufacturing requirements. These factors were evaluated comparatively across the North American and European case studies to identify recurring operational patterns and regional differences.

The analysis focused on two primary dimensions:

(1) material utilization and preparation requirements, and

(2) supply chain coordination and input consistency.

The first dimension examines how lumber characteristics influence downstream processing requirements and effective material yield within CLT production. Factors considered under this dimension include moisture control requirements, dimensional preparation, edge condition, material removal during machining, finger-jointing practices, corrective processing, and material rejection associated with drying or dimensional instability. The analysis also considers how these factors affect bonding preparation, production flow continuity, and overall material utilization during manufacturing.

The second dimension examines how supply chain organization influences production conditions within CLT facilities. Factors considered under this dimension include the degree of vertical integration, coordination between sawmills and CLT facilities, lumber sourcing arrangements, transport distances, and consistency of incoming lumber characteristics. The framework evaluates how differences in supply chain coordination influence moisture consistency, dimensional preparation, material handling requirements, and operational stability during production.

The analytical framework emphasizes relationships between upstream lumber preparation systems and downstream production outcomes. Rather than treating production stages as isolated processes, the study examines how conditions established earlier in the supply chain influence subsequent production requirements, material utilization, and operational efficiency within CLT manufacturing facilities.

Comparative interpretation was conducted across all case studies to identify recurring operational characteristics and regionally distinct manufacturing approaches. The purpose of the framework is not to establish universal quantitative relationships, but rather to provide a structured basis for interpreting how production systems and lumber preparation practices contribute to differences in material utilization and production cost across the selected cases.

3.7 Limitations of the Methodology

Several limitations should be considered when interpreting the findings of this study. First, the research is based on a limited number of case studies and interview participants. Although the selected producers represent a range of manufacturing systems and operational conditions in North America and Europe, the sample is not statistically representative of the global CLT industry. The findings should therefore be interpreted as comparative case-study insights rather than universally generalizable conclusions.

Participation in the study was dependent on producer willingness to provide operational information and allow communication regarding manufacturing practices. In North America, outreach was conducted to a broader group of CLT manufacturers; however, only a limited number agreed to participate. As a result, the study may not fully capture the diversity of production systems operating within either region.

The study also relied partially on self-reported interview information provided by participating producers. Although efforts were made to compare interview responses with field observations and published information, some operational details could not be independently verified. In addition, commercially sensitive information related to exact production costs, manufacturing efficiency, and proprietary processing practices was often unavailable or intentionally withheld by participants.

Field observations were conducted at a limited number of facilities and therefore reflect only specific operational conditions observed during the site visits.

Manufacturing practices vary depending on production schedules, product specifications, lumber supply conditions, and plant-specific operational decisions. Consequently, the observations should be interpreted as contextual evidence supporting comparative analysis rather than comprehensive representation of all production conditions.

Another limitation relates to the availability of publicly accessible quantitative production cost data. Due to the relatively young development of the North American CLT industry and the limited publication of detailed manufacturing cost information, the study was not able to conduct large-scale statistical analysis or formal economic modeling of production cost structures. Instead, the research focused on comparative interpretation of operational factors influencing material utilization and production efficiency.

Despite these limitations, the study provides valuable comparative insight into how lumber preparation systems, supply chain coordination, and manufacturing practices influence material utilization and production cost within CLT manufacturing. The combination of literature review, producer interviews, and field observations provides a contextually grounded basis for examining operational differences between North American and European production systems.

Chapter 4 Interview and Field Observation Results

This chapter presents the results obtained from producer interviews and field observations conducted in North America and Europe. The findings are organized according to the major stages of the CLT manufacturing process and summarize the similarities and differences observed among participating producers. Tables and figures are used to synthesize the interview responses and field observations, while interpretation of the findings is presented in Chapter 5.

4.1 Overview of Participating Producers

A total of eight valid interview responses were obtained from CLT manufacturers located in North America and Europe. The North American sample included producers from Canada and the United States, while the European sample included producers from Austria, Germany and Sweden. Based on the purposive sampling strategy described in Chapter 3, eight producers with established commercial CLT manufacturing operations and representing a range of production capacities, ownership structures, and sourcing models were included in the final analysis. The final sample was evenly divided between the two regions, comprising four North American and four European producers. To preserve participant confidentiality, individual producers are not identified in the discussion of the findings. Instead, references are limited to generalized descriptions unless comparison of the complete sample is required.

The participating producers represented a range of manufacturing scales, supply chain structures, and organizational models. Some producers operated as part of large vertically integrated forest products groups with internal sawmill networks and multiple manufacturing facilities, while others operated single CLT production facilities relying on external sawmill sourcing. This diversity provided an opportunity to examine different approaches to lumber sourcing, material preparation, and manufacturing operations within CLT production systems.

Reported production capacities varied substantially across the study sample, ranging from approximately 30,000 m^3 to more than 250,000 m^3 annually.

Table 4.1 summarizes the key characteristics of the participating producers. To maintain confidentiality, production capacities are presented as categories. For descriptive purposes, producers were grouped into three capacity ranges: small (<50,000 m^3/year), medium (50,000–100,000 m^3/year), and large (>100,000 m^3/year). These categories were developed for this study and do not represent an industry standard.

Table 4.1 Summary of Participating Producers

Region	**Lumber Sourcing**	**Capacity Category**	**No. of CLT Facilities**
North America	External sourcing	Large	Multiple
North America	Internal sourcing	Medium	Single
North America	External sourcing	Large	Multiple

Region	Lumber Sourcing	Capacity Category	No. of CLT Facilities
North America	Internal sourcing	Small	Single
Europe	Internal sourcing	Large	Multiple
Europe	Internal sourcing	Large	Single
Europe	Internal sourcing	Medium	Single
Europe	Internal sourcing	Medium	Single

Note: *Internal sourcing* indicates lumber sourced primarily from affiliated sawmills, whereas *external sourcing* indicates lumber sourced primarily from external sawmills.

4.2 Lumber Sourcing and Supply Systems

Participating producers reported a range of lumber sourcing arrangements, including fully integrated supply systems, external procurement networks, and mixed sourcing strategies. The degree of integration varied considerably among producers and influenced how lumber was supplied to CLT manufacturing facilities. While several producers obtained most or all lumber from internally affiliated sawmills, others relied primarily on independent lumber suppliers.

Among the European producers, vertically integrated supply systems were common. All participating European producers operated within forest products groups with affiliated sawmilling operations. While some producers were established as part of existing forest products groups, one producer became integrated following acquisition by a larger forest products company. As a result, all participating European producers reported obtaining most or all lumber from affiliated sawmills operating within the same ownership structure.

North American producers reported a wider range of lumber sourcing approaches. Two participating producers operated vertically integrated systems with direct access to affiliated sawmills, while the other two relied primarily on external sawmills for their lumber supply. Among the externally sourced producers, procurement strategies varied, including purchases from multiple sawmills across different locations as well as long-term supplier relationships.

Differences were also observed in transportation distances and supplier relationships. Producers sourcing internally generally reported shorter transportation distances and more direct coordination between sawmills and CLT facilities. Producers relying on external suppliers reported sourcing lumber from a broader geographic area and interacting with multiple sawmill partners. Several participants noted that lumber procurement involved communication regarding moisture content, dimensions, grades, and delivery schedules.

Field observations confirmed that integrated lumber sourcing was closely associated with coordination between sawmill operations and downstream CLT manufacturing. Lumber sourcing also influences the condition and preparation of lumber entering the manufacturing process. The following sections examine how these differences are reflected in moisture control, dimensional precision, and other manufacturing practices observed among the participating producers.

4.3 Lumber Readiness for CLT Manufacturing

Interview responses and facility observations indicated that the condition of lumber entering CLT production varied among participating producers. Differences were reported in moisture content, dimensional characteristics, grading practices, and defect removal procedures prior to panel manufacturing. These factors influenced the amount of preparation required before lumber could enter subsequent production stages. The following sections summarize observations related to moisture control, lumber dimensions, edge conditions, and grading practices reported by participating producers.

4.3.1 Moisture Control

All participating producers reported moisture control as an important requirement for CLT manufacturing. Producers in both North America and Europe reported target moisture contents of approximately 12%, consistent with regional manufacturing standards. However, differences were observed in how lumber was supplied and prepared to meet these requirements.

European producers and North American producers operating integrated supply systems generally reported receiving lumber from affiliated sawmills at moisture contents suitable for CLT manufacturing. Because drying operations were coordinated within the same organization, participants indicated that lumber was typically delivered to the CLT facility at the required moisture specification and ready for production.

Producers relying on external lumber suppliers reported additional steps to achieve the moisture specifications required for CLT manufacturing. One producer operated a dedicated drying chamber to further reduce lumber moisture content; however, drying capacity was limited relative to production requirements. Another producer reported not using a drying chamber and instead relied on air drying prior to manufacturing. This approach required additional storage space to accommodate lumber conditioning before processing. Participants noted that moisture conditioning involved more than simply achieving a target moisture content. Defects including twist, cup, checking, and wane frequently became more apparent during moisture conditioning and drying processes. Lumber exhibiting these defects was subsequently removed trimmed, or downgraded before entering downstream processing stages. One producer reported rejection rates of approximately 10% following secondary drying and reprocessing due to defects that became evident after moisture conditioning. Several participants described grading and defect removal as routine steps following moisture conditioning, particularly when lumber was sourced from external suppliers and required additional drying prior to manufacturing.

Although moisture requirements were similar across participating producers, interview responses and field observations indicated differences in the preparation steps required to achieve those requirements. These differences were most apparent between producers receiving lumber directly from affiliated sawmills and those relying on externally sourced lumber.

4.3.2 Lumber Dimensions and Edge Conditions

Interview responses and field observations indicated notable differences in the dimensional characteristics and edge profiles of lumber supplied to CLT manufacturers in North America and Europe. Participants reported that incoming lumber dimensions influenced the amount of preparation required before material could enter subsequent manufacturing stages.

All four European producers reported receiving square-edged lumber manufactured specifically for engineered wood applications. During visits to European sawmills, lumber intended for CLT production was observed to be sawn several standard metric thicknesses, including 23, 33, and 43 mm, allowing the lumber to be planed to common finished CLT lamination thicknesses of 20, 30, and 40 mm. Several CLT producers reported that incoming lumber generally required only limited dimensional modification before entering grading, finger-jointing, and panel production processes.

North American producers relying on external sourcing commonly reported receiving lumber manufactured primarily for conventional light-frame construction markets. During the visit to a North American sawmill, production was observed to be primarily oriented toward standard dimensional lumber products such as 2×4, 2×6, and 2×8 lumber. The sawmill also supplied rough-sawn kiln-dried lumber to its affiliated CLT manufacturing facility, although this represented a smaller portion of overall production. CLT producers sourcing lumber externally indicated that lumber obtained from conventional dimensional lumber production frequently required additional preparation before being suitable for CLT manufacturing. Differences in lumber edge conditions observed during field visits are shown in Figure 4.1.

Figure 4.1. Comparison of lumber edge profiles observed during field visits: (left) square-edged lumber observed at a European sawmill and (right) eased-edge lumber observed at a North American CLT manufacturing facility.

Several producers reported that incoming lumber required additional planing, resizing, or edge preparation prior to further processing. These procedures were conducted before downstream operations such as finger-jointing and panel layup. Participants noted that dimensional preparation was necessary to achieve lumber geometries compatible with CLT manufacturing requirements.

Overall, interview responses and field observations indicated that European producers generally received lumber that more closely matched the dimensional and edge requirements of CLT manufacturing, whereas North American producers more frequently reported additional preparation steps before lumber could enter production.

4.3.3 Grading and Defect Removal

Interview responses indicated that grading and defect removal represented important stages of lumber preparation prior to CLT manufacturing. Following lumber preparation, producers reported that lumber was graded to assess its suitability for downstream processing. Grading procedures evaluated multiple characteristics, including moisture content, dimensional conformity, and physical defects affecting manufacturing performance.

The sequence of preparation steps differed among producers. European producers and North American producers operating integrated supply systems generally reported receiving lumber at moisture contents suitable for CLT manufacturing, allowing lumber to proceed directly to planing and grading. In contrast, producers relying on externally sourced dimensional lumber often reported additional drying or conditioning requirements before grading could occur. Participants noted that moisture content outside manufacturing specifications represented a common cause for additional processing and material sorting.

Commonly identified defects included moisture contents outside manufacturing specifications, twist, cup, checking, wane, knots, resin pockets, and other dimensional irregularities. Participants also noted that grading requirements varied according to the intended application of the lumber. For example, blue stain was generally considered unacceptable in appearance grade face layers but could remain acceptable for use in non-visible core layers where visual appearance was not a primary consideration. Lumber not meeting production requirements was removed, trimmed, downgraded, or redirected to alternative product streams before entering subsequent manufacturing operations. Several participants noted that defects often became more apparent following drying and conditioning processes.

One producer reported rejection rates of approximately 10% following secondary drying and reprocessing due to defects identified during grading. Interview responses and discussions with machinery specialists further indicated that insufficient drying time or storage capacity could increase the proportion of lumber requiring downgrading, particularly during periods of high production demand.

Interview responses and field observations demonstrated that grading and defect removal formed an integral part of lumber preparation prior to CLT manufacturing. The extent of reprocessing and material sorting varied among producers and was influenced by incoming lumber characteristics, moisture conditions, and supply chain arrangements.

4.4 Finger-Jointing and Lumber Processing

Finger jointing was reported by most participating producers as an important stage of lumber preparation prior to CLT manufacturing. Participants indicated that finger jointing was used to join shorter lumber segments into longer laminations suitable for production. One North American producer reported not using finger jointing, while the remaining producers incorporated finger jointing into their manufacturing systems.

Differences were observed in the finger jointing configurations used by participating producers. Producers reported placing fingers either on the surface of the lumber or on the side. Three European producers reported using fingers on the surface, while one European producer used fingers on the side. Among North American producers, two reported using fingers on the side, one reported using both surface and side finger jointing configurations, and one reported not using finger jointing. Although both configurations were represented in both regions, fingers on the surface were more commonly reported among European producers, whereas fingers on the side were more frequently reported among North American producers. Several North American producers indicated that fingers on the side were preferred for aesthetic reasons because the finger joints were less visible on exposed panel surfaces. One North American producer reported not using finger-jointing, indicating that this reflected an operational preference.

Participants reported that finger jointing was typically performed after lumber preparation and grading. Defective sections identified during grading were removed, and the remaining lumber segments were joined to produce laminations of the required length for subsequent manufacturing processes.

Discussions with machinery specialists indicated that finger jointing configuration could influence subsequent processing requirements. Specialists reported that configurations with fingers on the side typically required greater resurfacing to achieve a uniform surface prior to production. As a result, additional material could be removed during subsequent machining and preparation processes. However, the present study did not quantify differences in material removal associated with alternative finger jointing configurations.

Interview responses indicated that finger jointing represented an important step in converting graded lumber into laminations suitable for panel manufacturing.

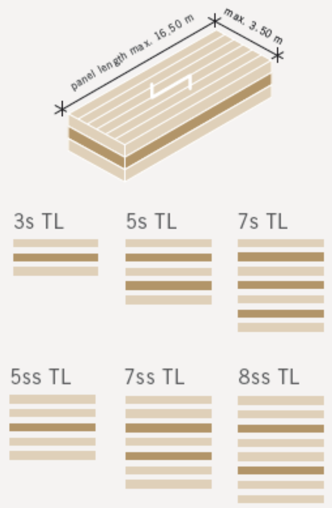
4.5 Panel Production and Layup Operations

Panel production represents the stage at which incoming lumber is assembled into the final CLT panel configuration. Interview responses indicated that differences in panel layup practices were closely associated with the dimensions of lumber supplied to the manufacturing process. Several European producers explained that early CLT production involved a wide variety of proprietary panel thicknesses and layup configurations. As the industry matured, panel dimensions gradually became more standardized, with many producers adopting lamination thicknesses and panel dimensions based on 10 mm increments. In contrast, North American panel configurations were generally constrained by the dimensions of lumber supplied from conventional dimensional lumber production.

Interview responses indicated that participating producers operated highly automated CLT manufacturing systems. Although equipment suppliers and production capacities varied among facilities, the overall manufacturing sequence was generally similar and included lamination preparation, layup, adhesive application, pressing, and panel finishing.

Current panel layup practices also reflected these differences in lumber preparation. European producers generally reported manufacturing panels across a broad range of standardized thicknesses using combinations of different lamination thicknesses. In contrast, North American producers commonly reported using laminations of approximately 35 mm thickness, resulting in standardized three-, five-, and seven-layer panel configurations. Representative examples of the reported panel layup configurations are shown in Figure 4.2.

		L	T	L	T	L	T	L
60 mm	3s TL	20	20	20				
70 mm	3s TL	20	30	20				
80 mm	3s TL	30	20	30				
90 mm	3s TL	30	30	30				
100 mm	3s TL	40	20	40				
110 mm	3s TL	40	30	40				
120 mm	3s TL	40	40	40				
100 mm	5s TL	20	20	20	20	20		
110 mm	5s TL	20	20	30	20	20		
120 mm	5s TL	30	20	20	20	30		
130 mm	5s TL	30	20	30	20	30		
140 mm	5s TL	40	20	20	20	40		
150 mm	5s TL	40	20	30	20	40		
160 mm	5s TL	40	20	40	20	40		
170 mm	5s TL	40	30	30	30	40		
180 mm	5s TL	40	30	40	30	40		
190 mm	5s TL	40	40	30	40	40		
200 mm	5s TL	40	40	40	40	40		
160 mm	5ss TL	30+30	40	30+30				
180 mm	7s TL	20	40	20	20	20	40	20
200 mm	7s TL	20	40	20	40	20	40	20
220 mm	7s TL	30	40	30	20	30	40	30
240 mm	7s TL	30	40	30	40	30	40	30
180 mm	7ss TL	30+30	20	20	20	30+30		
200 mm	7ss TL	30+30	20	40	20	30+30		
220 mm	7ss TL	40+40	20	20	20	40+40		
240 mm	7ss TL	40+40	20	40	20	40+40		
260 mm	7ss TL	40+40	30	40	30	40+40		
280 mm	7ss TL	40+40	40	40	40	40+40		
300 mm	8ss TL	40+40	30	40+40	30	40+40		
320 mm	8ss TL	40+40	40	40+40	40	40+40		



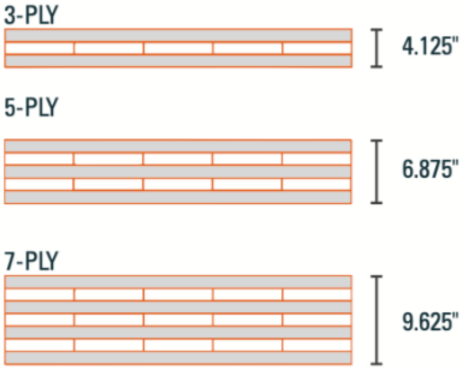


Figure 4.2. Representative panel layup configurations reported by participating producers. A European producer (top) offers a broad range of panel thicknesses through variable lamination combinations, while a North American producer (bottom) utilizes standardized three-, five-, and seven-layer layups with fixed panel thicknesses.

Interview responses further suggested that differences in panel layup were also associated with production organization. Producers relying primarily on externally sourced dimensional lumber generally reported using standardized lamination thicknesses, supporting longer production runs. In contrast, producers with internal lumber sourcing reported greater flexibility in lamination thicknesses and panel configurations.

Differences were observed in the application of edge gluing during panel production. One North American producer reported applying edge glue to all panels, while another reported applying edge glue only to face layers intended for visual applications. Among European producers, three reported offering edge-glued panels as an optional product depending on customer requirements and project specifications. These responses indicated that edge-gluing practices varied among producers and product types.

Participants also reported variation in layup strategies and production organization. Several producers described manufacturing a combination of standard and customized panel configurations, while others emphasized production efficiency through greater standardization. Despite these differences, all producers reported following similar manufacturing sequences once lumber preparation had been completed.

Interview responses indicated that panel production represented a highly automated stage of manufacturing in which differences among producers were more closely associated with product specifications and production preferences than with fundamental differences in manufacturing technology.

4.6 Chapter Summary

This chapter presented findings from interviews, field visits, and supporting observations of CLT manufacturing systems in North America and Europe. The findings indicated that differences between producers were most evident in upstream lumber sourcing and preparation processes rather than in core panel manufacturing operations.

Participants reported variation in supply chain organization, moisture control procedures, lumber dimensions, grading requirements, finger jointing configurations, and panel layup practices. European producers generally operated within more integrated supply systems and reported receiving lumber that more closely matched CLT manufacturing requirements. While several North American producers reported additional preparation steps related to moisture conditioning, dimensional modification, and grading before lumber could enter production.

Differences were also observed in finger jointing configurations and panel layup practices. Producers reported a range of approaches to lumber processing and panel manufacturing, reflecting differences in product specifications, manufacturing preferences, and supply arrangements.

Although all participating producers operated modern and highly automated CLT manufacturing facilities, the findings suggest that variations in incoming lumber characteristics and preparation requirements influenced subsequent manufacturing processes. These findings provide the basis for the discussion of lumber utilization and production cost factors presented in Chapter 5.

Chapter 5 Discussion, Conclusions and Recommendations

5.1 Lumber Readiness as a Production Cost Factor

Previous studies have consistently identified lumber as the largest cost component in CLT manufacturing and one of the most influential factors affecting production economics (Brandt et al., 2019; Zhang & Lan, 2022). As a result, discussions of manufacturing costs often focus on lumber prices, transportation costs, and market availability.

Recent market research further illustrates the challenges associated with lumber supply for mass timber manufacturing. The 2025 PNW Regional Mass Timber Market Study estimated that project-based mass timber production consumed only 0.5% of total regional lumber production in 2024 (20.5 million m^3 or 8.7 billion board feet). The study further estimated that only about 6.6 million m^3 of lumber (2.8 billion board feet), or approximately 30% of regional lumber production, could be considered well-suited for mass timber applications after accounting for grade, dimensions, and processing requirements (Anderson et al., 2025). These findings suggest that while overall lumber supply is abundant, the supply of lumber readily suited for CLT manufacturing remains comparatively limited. Consequently, most North American sawmills continue to prioritize commodity lumber products serving larger construction markets, with relatively limited incentives to produce lumber specifically optimized for CLT manufacturing.

Against this industry backdrop, the findings of this study suggest that the characteristics of incoming lumber also influence manufacturing performance and production costs. Across interviews and field observations, producers frequently discussed moisture content, dimensional characteristics, edge profiles, grading requirements, and lumber preparation procedures. These factors affected the amount of conditioning, sorting, machining, and reprocessing required before lumber could enter production. The following sections discuss how these findings relate to existing literature and introduce the concept of lumber readiness as a key factor influencing manufacturing efficiency within CLT production systems.

5.1.1 Lumber Costs in Existing Literature

Much of the existing literature on CLT manufacturing economics has focused on the influence of raw material costs. Techno-economic analyses conducted in North America and Europe have consistently shown that lumber represents the largest operating expense in CLT production and is one of the primary determinants of product competitiveness (Brandt et al., 2019; Zhang & Lan, 2022). As a result, fluctuations in lumber prices have a direct impact on manufacturing costs and minimum selling prices.

The importance of lumber costs is particularly evident in sensitivity analyses of CLT production economics. Zhang & Lan (2022) identified lumber price as the single most influential variable affecting the minimum selling price of CLT panels. Similarly, Brandt et al. (2019) reported that lumber costs represented the largest operating expense across multiple production scenarios. These findings suggest that securing a reliable supply of competitively priced lumber is critical to the economic performance of CLT manufacturing facilities.

Previous research has also highlighted the importance of moisture content, lumber quality, and grading requirements. CLT manufacturers typically require kiln-dried structural lumber meeting specified moisture content and grading standards prior to production. Zelaya (2020) reported that premiums are often paid for lumber dried to moisture contents suitable for engineered wood manufacturing, reflecting the additional processing required to meet these specifications. Similarly, Brandt et al. (2019) assumed material losses associated with defect removal and finger jointing during lumber preparation, indicating that incoming lumber characteristics influence manufacturing performance.

Published techno-economic analyses of CLT manufacturing generally include lumber as the largest operating cost component within operating expenditures (OPEX) (Brandt et al., 2019). However, lumber is typically represented as a purchased raw material with assumed specifications and unit costs, while the condition of the incoming lumber and the preparation required before panel production receive comparatively limited attention. As a result, activities such as moisture conditioning, dimensional preparation, grading, defect removal, and edge processing are often incorporated into general manufacturing assumptions rather than being explicitly evaluated as factors influencing production costs.

This approach is appropriate for estimating manufacturing costs under defined production assumptions. However, the findings of the present study indicate that differences in incoming lumber characteristics can substantially influence the amount of preparation required before panel production. Consequently, the relationship between raw material costs and manufacturing costs extends beyond lumber purchase price alone. These observations provide the basis for considering lumber readiness as a distinct factor influencing CLT manufacturing costs.

5.1.2 Lumber Readiness and Processing Requirements

The findings of this study suggest that the economic value of lumber extends beyond its purchase price. While previous studies have primarily evaluated lumber as a raw material input, interview responses and field observations indicated that incoming lumber characteristics can substantially influence the amount of processing required before production. Moisture content, dimensional characteristics, edge profiles, grading requirements, and lumber quality all affected the preparation steps necessary before lumber could enter CLT manufacturing.

One of the clearest examples of lumber readiness was observed in moisture control practices. European producers and North American producers operating integrated supply systems generally reported receiving lumber at moisture contents suitable for CLT manufacturing. As a result, lumber could proceed directly to preparation and production processes. In contrast, some North American producers sourcing dimensional lumber from external sawmills reported additional conditioning requirements before manufacturing. These included secondary drying, air drying, and extended storage periods to achieve target moisture contents. Participants further reported that defects such as twist, cup, checking, and wane often became more apparent during drying and conditioning processes, resulting in additional sorting, grading, and material losses before production.

Differences in lumber dimensions and edge profiles provided another example of how incoming lumber characteristics influence manufacturing requirements. Field observations indicated that lumber supplied to European CLT producers was often produced specifically for engineered wood manufacturing and generally retained square edges following drying. By contrast, North American producers frequently sourced dimensional lumber manufactured primarily for light-frame construction markets. Although lumber is initially sawn with square edges in both regions, North American dimensional lumber is subsequently planed to standard dimensions and eased-edge profiles before leaving the sawmill.

Industry participants indicated that, in North American sawmills producing dimensional lumber, planing operations typically remove approximately 3 mm from both the width and thickness of the lumber to produce finished dimensional lumber. In contrast, the European sawmills visited supplied square-edged, rough-sawn lumber directly to CLT manufacturers without this initial planing stage. At the CLT manufacturing facility, producers in both regions reported removing an additional 2–3 mm during final planing to achieve dimensional consistency and suitable bonding surfaces for adhesive application. However, because North American dimensional lumber has already undergone a previous planing stage, the cumulative amount of fiber removed before panel production is greater than that observed in European systems supplying square-edged lumber directly to CLT manufacturers.

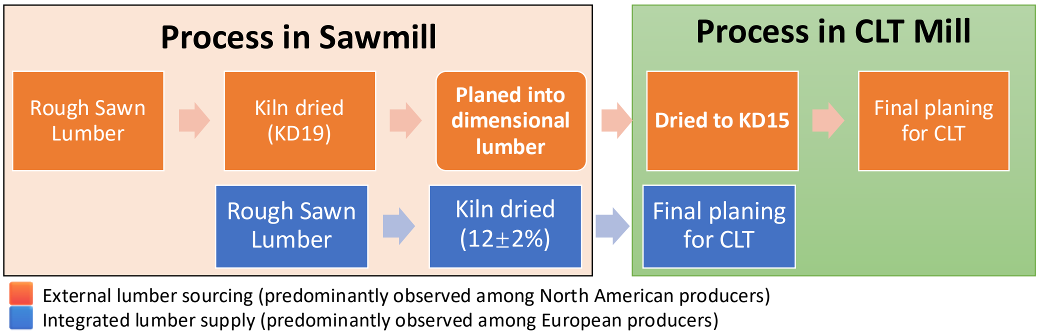


Figure 5.1. Comparison of lumber preparation sequences prior to CLT manufacturing under different lumber sourcing systems.

These observations suggest that lumber specifications developed for different end-use markets can influence manufacturing requirements within CLT production. Lumber prepared for light-frame construction satisfies the needs of traditional building systems while requiring additional processing before use in CLT manufacturing. Conversely, lumber supplied specifically for engineered wood production reduces the amount of preparation required before manufacturing.

The concept of lumber readiness therefore provides a useful framework for interpreting differences in manufacturing processes observed among participating producers. Lumber arriving at the CLT facility with appropriate moisture content, dimensions, edge profiles, and quality characteristics requires fewer preparation steps before production. While the present study did not quantify the costs associated with these additional processes, the findings indicate that incoming lumber characteristics can influence manufacturing operations in ways that are not fully captured by lumber prices alone.

5.1.3 Comparison with the North American Glulam Industry

The North American glulam industry provides a useful comparison for understanding the concept of lumber readiness within engineered wood manufacturing. Unlike many CLT producers that rely on commodity dimensional lumber, glulam manufacturers commonly purchase stress-graded laminating stock (lamstock) specifically prepared for structural applications. Lamstock is typically supplied at appropriate moisture contents, with specified dimensions, square edges, and grading characteristics suitable for manufacturing. Although this material commands a price premium relative to commodity dimensional lumber, many preparation steps are completed upstream before the material reaches the manufacturing facility.

The findings of this study suggest that a similar distinction exists within CLT manufacturing systems. All European producers reported receiving lumber that closely matched manufacturing requirements, including target moisture contents, square edges, and dimensions suitable for panel production. In contrast, several North American producers reported additional preparation requirements associated with dimensional lumber originally manufactured for light-frame construction markets.

These additional steps included moisture conditioning, planing, grading, and dimensional modification before production.

The comparison highlights an important distinction between lumber costs and manufacturing costs. A lower-priced lumber product requires substantial processing before it can be used in production, while a higher-priced product arrives ready for manufacturing. Consequently, the economic value of lumber cannot be evaluated solely on the basis of purchase price. The amount of processing required before production must also be considered.

Differences in species utilization and lumber allocation practices further illustrate this distinction. European producers in this study primarily utilized spruce, with limited use of pine in some regions. Discussions with industry participants and field observations indicated that sawmills commonly allocate lumber according to the requirements of different engineered wood products. Higher-grade center-cut lumber, which generally exhibits superior strength characteristics, is frequently directed toward glulam and other structural applications. Sideboards are commonly supplied to CLT manufacturers, where appearance, dimensional consistency, and material utilization is prioritized over maximum strength performance. This allocation strategy is consistent with the historical development of CLT in Austria, where the technology was originally developed as a higher-value application for sideboards generated during sawmilling operations (Brandner, 2013).

In North America, producers reported using a broader range of species, including Douglas-fir and Hem-Fir in the Pacific Northwest and Southern Yellow Pine in the southeastern United States. However, lumber production remains largely oriented toward dimensional lumber markets, and sawmill outputs are generally optimized for light-frame construction rather than mass timber manufacturing. As a result, CLT producers frequently adapt products originally intended for other end uses. The findings of this study suggest that lumber preparation requirements observed among North American producers are partly a consequence of this broader market orientation.

The European approach suggests that greater specialization within sawmill operations creates opportunities to improve alignment between lumber characteristics and manufacturing requirements. Similar approaches could potentially be applied within North American mass timber supply chains. For example, higher-strength center-cut lumber could be directed toward glulam lamstock production, while rough-sawn sideboards could be supplied directly to CLT manufacturers for subsequent processing. Such arrangements could improve lumber utilization, reduce unnecessary machining, and strengthen coordination between sawmills and engineered wood manufacturers. Although the feasibility of these approaches would depend on regional species characteristics, market conditions, and sawmill economics, they illustrate how supply chain organization can influence manufacturing efficiency beyond the boundaries of the CLT facility itself.

From this perspective, the future development of CLT manufacturing in North America depends not only on increasing production capacity but also on the evolution of lumber products and supply systems designed specifically for mass timber applications. The experience of the glulam sector demonstrates that manufacturers are willing to pay a premium for lumber prepared specifically for engineered wood production when that premium reduces downstream processing requirements. The findings of this study suggest that similar opportunities exist within CLT manufacturing as the industry continues to mature.

5.2 Supply Chain Integration and Industrialization of CLT Manufacturing

The findings presented in Chapter 4 suggest that differences in incoming lumber characteristics were closely related to the organization of the supply chain. Producers receiving lumber from affiliated sawmills generally reported fewer preparation requirements prior to manufacturing, while producers relying on external suppliers more frequently reported additional conditioning, grading, and processing steps. These observations indicate that the benefits of lumber readiness are not determined solely at the manufacturing facility, but also by the degree of coordination between sawmills and downstream manufacturers.

The findings further suggest that these differences reflect the relative maturity of the forest products supply chain supporting CLT manufacturing. Supply chain integration has long been a characteristic of the European engineered wood products industry. All

European producers participating in this study operated within vertically integrated organizations spanning sawmilling and CLT manufacturing. North American producers employed a mix of integrated and externally sourced supply systems. This distinction was reflected in differences in lumber preparation requirements observed throughout the study.

The findings suggest that integration can influence the alignment between lumber supply and manufacturing requirements. However, the relationship between integration, scale, and competitiveness appears more complex than a simple distinction between integrated and non-integrated systems. The following sections examine how differences in supply chain maturity and organizational structure influence lumber readiness, manufacturing efficiency, and the broader industrialization of CLT production.

5.2.1 Integration and Lumber Readiness

The findings of this study suggest that supply chain integration plays an important role in determining the readiness of lumber supplied to CLT manufacturing facilities. All European producers participating in this study operated within vertically integrated organizations spanning sawmilling and CLT manufacturing. North American producers employed a combination of integrated and externally sourced supply systems. These differences were reflected in the lumber preparation requirements reported by participants.

European producers generally reported receiving lumber from affiliated sawmills at moisture contents, dimensions, and quality specifications suitable for CLT manufacturing. Because sawmilling and manufacturing operations were coordinated within the same organization, lumber production could be aligned with downstream manufacturing requirements. Interview responses indicated that moisture targets, dimensional specifications, and production scheduling were coordinated across facilities, reducing the need for additional conditioning and preparation before manufacturing.

Field observations provided further evidence of this coordination. At the Austrian sawmill visited during this study, lumber production was closely connected to downstream engineered wood manufacturing. The sawmill supplied lumber to affiliated mass timber operations while also maintaining relationships with neighboring industrial facilities. Residual materials including sawdust and bark were sold to pellet and pulp producers, while kiln drying operations utilized thermal energy supplied from a nearby industrial facility. These observations suggest a highly integrated industrial system in which material flows and production processes are coordinated across multiple stages of the value chain.

In contrast, some North American producers reported sourcing dimensional lumber from external suppliers whose primary markets were light-frame construction and other traditional lumber applications. As discussed in Section 5.1, lumber produced for these markets often required additional conditioning, grading, and dimensional modification before entering CLT production. The findings suggest that these additional preparation requirements were influenced not only by lumber characteristics but also by the structure of the supply chain itself.

Integration appears to facilitate communication and coordination between sawmills and manufacturers, allowing lumber specifications to be more closely aligned with production requirements. The resulting benefits include reduced preparation requirements, improved material consistency, and greater control over production scheduling. However, the extent to which these advantages translate into economic benefits likely depends on production scale, market conditions, and broader organizational factors.

The findings therefore suggest that supply chain integration contributes to lumber readiness by improving coordination between lumber production and manufacturing requirements. From this perspective, the advantages of integration arise not solely from ownership of upstream facilities, but from the ability to align sawmill outputs with the specific needs of CLT production.

5.2.2 Industry Development Pathways and Supply Chain Organization

While the findings suggest that vertical integration improves coordination between sawmills and CLT manufacturing facilities, the relationship between integration and production scale appears more complex. Differences observed between European and North American producers are partially explained by the historical development of the mass timber industry in each region.

The origins of CLT in Austria were closely linked to the sawmill industry. Early CLT development was motivated by the need to create higher-value applications for sideboards generated during sawmilling operations (Brandner, 2013). Although sideboards were often perceived as lower-value products within traditional lumber markets, their favorable mechanical properties made them suitable for engineered wood applications. Because many early CLT manufacturers emerged directly from sawmill businesses, integration between lumber production and manufacturing developed alongside the technology itself. As a result, many European producers expanded from existing sawmill and engineered wood operations, allowing integration to evolve gradually with manufacturing growth.

This historical development pathway was reflected in the findings of the present study. All participating European producers operated within vertically integrated organizations while also maintaining substantial manufacturing capacities. Discussions with participants and field observations suggested that lumber allocation decisions were often coordinated at the sawmill level according to the requirements of different engineered wood products. Higher-strength center-cut (without center) lumber was commonly directed toward glulam and other structural applications, while sideboards were supplied to CLT manufacturing. Although this allocation strategy has received limited attention in the published literature, previous studies have demonstrated that Norway spruce sideboards possess suitable structural properties for engineered wood applications following appropriate strength grading (Oscarsson et al., 2011). Such practices indicate a high degree of coordination between sawmilling and downstream manufacturing processes and illustrate how different portions of the log can be utilized according to product requirements, thereby improving overall resource utilization across the forest products value chain.

In contrast, the North American CLT industry developed within a forest products sector largely oriented toward dimensional lumber production and light-frame construction. Existing lumber supply chains, grading systems, and manufacturing infrastructure were primarily designed to serve these markets. Consequently, CLT producers have often adapted lumber products originally intended for other end uses rather than relying on supply systems specifically developed for mass timber manufacturing. This context helps explain the additional preparation requirements discussed in Section 5.1, including moisture conditioning, planing, grading, and dimensional modification prior to production.

The findings from North American producers further suggest that integration and production scale are not necessarily linked. Among the producers participating in this study, the vertically integrated producers operated fewer CLT manufacturing facilities and generally reported lower production capacities than those relying primarily on externally sourced lumber. Producers relying on external lumber sourcing operated multiple manufacturing facilities and represented the higher-capacity operations within the North American sample. These observations indicate that expansion can be achieved through procurement networks capable of sourcing lumber from multiple suppliers, rather than solely through ownership of upstream sawmill operations.

The contrasting patterns observed between Europe and North America suggest that integration and scale represents separate dimensions of industrial development. Integration improves alignment between lumber production and manufacturing requirements, while external procurement systems provide greater flexibility for expansion and access to larger volumes of raw material. The relative advantages of these approaches are likely influenced by regional market conditions, resource availability, transportation networks, and the maturity of supporting industries.

Integrated and externally sourced lumber supply systems represent different approaches to organizing raw material procurement for CLT manufacturing. The findings suggest that multiple pathways currently exist for the expansion of CLT manufacturing capacity. In Europe, large-scale production has evolved within integrated forest-products companies that developed alongside the emergence of CLT technology. In North America, growth has occurred through a combination of integrated operations and externally sourced procurement systems. These differing development pathways highlight the importance of considering regional industrial context when evaluating the organization and future expansion of CLT manufacturing.

5.2.3 Supply Chain Maturity and Future Development

The observations presented throughout this study suggest that the organization of CLT manufacturing is closely associated with the maturity of the supporting forest products supply chain. The differences identified in lumber readiness, supply chain integration, and panel design flexibility appear to reflect broader industrial development processes rather than isolated manufacturing decisions. European CLT production emerged within an established forest products industry where sawmills, engineered wood manufacturers, and downstream users had developed long-term relationships over several decades. North American CLT manufacturing has expanded more recently and continues to evolve within a forest products sector that has historically been oriented toward conventional lumber markets.

Table 5.1. Comparison of softwood lumber production and CLT market scale in the Pacific Northwest and Austria (2024)

Indicator (2024)	Pacific Northwest (Washington and Oregon States)	Austria
Annual softwood lumber production	8.7 BBF (≈20.5 million m^3)	9.8 million m^3
CLT production	62,000 m^3 project-based mass timber (CLT + custom glulam)	≈700,000 m^3
Estimated share of annual lumber production consumed by mass timber / CLT	≈0.5%	≈10%

Data source: Anderson et al., 2025; Jauk, 2025a, 2025b

The current market for mass timber products also influences the degree of coordination between sawmills and downstream manufacturers. According to the 2025 Pacific Northwest Regional Mass Timber Market Study, the Pacific Northwest produced approximately 20.5 million m^3 (8.7 billion board feet) of softwood lumber in 2024, whereas project-based mass timber products, including CLT and custom glulam, totaled only about 62,000 m³. This production represented approximately 28% of the region's effective mass timber manufacturing capacity and consumed only approximately 0.5% of the region's total lumber production (Anderson et al., 2025). These figures indicate that mass timber manufacturing remains a relatively small segment of the regional forest products industry. Under these conditions, conventional structural lumber continues to represent the primary market for regional sawmills, limiting the economic incentive to produce lumber specifically tailored to CLT manufacturing.

Austria represents a markedly different industrial context. In 2024, Austrian sawmills produced approximately 9.8 million m³ of softwood lumber (Jauk, 2025a), while CLT production reached approximately 700,000 m³ (Jauk, 2025b). Although Austria has a relatively small domestic construction market, approximately two-thirds of its CLT production was exported to international markets. Based on these production volumes, CLT manufacturing consumes approximately 10% of the country's annual softwood lumber production, making engineered wood products an established market segment for the Austrian sawmilling industry. This sustained demand provides strong incentives for coordinating lumber production with downstream manufacturing requirements and supports the development of specialized lumber specifications for CLT production.

The comparison illustrates that differences in supply chain organization are closely associated with the relative importance of engineered wood products within the regional forest products industry. In the Pacific Northwest, conventional structural lumber continues to dominate production, providing limited economic incentive for sawmills to modify lumber specifications for CLT manufacturing. In Austria, the substantially larger and export-oriented CLT sector has created sufficient and sustained demand to support specialized lumber production and closer integration between sawmills and downstream manufacturers. These broader industrial conditions are consistent with the observations presented in this study regarding lumber readiness, supply chain coordination, and panel manufacturing practices.

5.3 Panel Design Flexibility and Lumber Specifications

The findings presented in Chapter 4 indicate that differences in panel design flexibility were closely associated with the lumber specifications supplied to CLT manufacturers. Although participating producers employed similar manufacturing processes once lumber entered production, the dimensions and characteristics of the incoming lumber influenced the range of panel configurations that could be manufactured efficiently. Consequently, differences in panel layup systems appear to reflect adaptations to upstream lumber specifications and supply arrangements.

Panel layup systems developed differently as the CLT industry expanded in Europe and North America. European manufacturers initially produced proprietary panel dimensions based on individual production practices and available lumber. As production volumes increased and the market matured, panel dimensions gradually became more standardized, with thicknesses commonly offered in 10 mm increments.

The availability of multiple lumber thicknesses supplied by integrated sawmills supported this development by allowing different lamination combinations to achieve standardized panel dimensions while accommodating diverse project requirements.

North American panel layup systems evolved within a different manufacturing environment. Producers relying primarily on externally sourced dimensional lumber generally manufactured standardized three-, five-, and seven-layer panels using a single lamination thickness. Access to multiple lumber dimensions was more limited because lumber was produced primarily for conventional construction markets. Producers operating integrated sawmill systems demonstrated greater flexibility through access to nominal 1-inch lumber and other lumber dimensions, illustrating that panel design flexibility was influenced by the characteristics of the upstream lumber supply.

These differences also influenced manufacturing organization. Standardized layup systems based on a single lamination thickness simplified production planning and supported longer manufacturing runs, while multiple lumber thicknesses provided greater flexibility to produce a broader range of panel dimensions. Both approaches supported efficient manufacturing within their respective production systems, although they reflected different relationships between lumber supply and downstream manufacturing requirements.

As the CLT industry continued to develop, panel standardization also facilitated coordination among manufacturers, designers, and structural engineers. Standardized panel dimensions simplified product specification and structural design while allowing manufacturers to maintain repeatable production processes. The observations from this study suggest that panel layup systems evolved together with upstream lumber specifications, manufacturing practices, and market development, reflecting long-term adaptation to the industrial conditions supporting CLT production.

5.4 Industrial Ecosystems Supporting CLT Manufacturing

The preceding sections examined how lumber characteristics, supply chain organization, and panel design influence manufacturing efficiency and production costs in CLT manufacturing. However, many of the differences observed between European and North American producers cannot be fully explained at the facility level alone. Interviews, field observations, and industry data suggest that manufacturing practices are strongly influenced by the broader industrial ecosystems in which producers operate. These ecosystems include relationships among forests, sawmills, engineered wood manufacturers, pulp and paper facilities, bioenergy producers, designers, contractors, and end-use markets.

The observations presented in Chapter 4 indicate that the European producers examined operated within highly interconnected forest products systems that enable lumber, residuals, and byproducts to be allocated across multiple manufacturing streams. The North American producers participating in this study generally operated within supply chains that evolved around commodity lumber markets and light-frame construction, reflecting the dominant structure of the regional forest products industry. As a result, differences in lumber readiness, panel flexibility, and material utilization reflect not only decisions made within individual manufacturing facilities but also the maturity and structure of the surrounding industrial ecosystem.

Understanding these broader relationships is important because future improvements in CLT competitiveness depend as much on supply chain development and industrial coordination as on advances in manufacturing technology. The following sections discuss how industrial ecosystems influence material utilization, supply chain specialization, and future opportunities for mass timber development in North America.

5.4.1 Industrial Ecosystems and Material Utilization

The findings of this study suggest that many of the differences observed between European and North American CLT manufacturing extend beyond individual production facilities and are closely connected to the broader industrial ecosystems in which manufacturers operate. While discussions of CLT competitiveness often focus on production technology and manufacturing costs, the ability to efficiently utilize raw materials across multiple product streams is equally important.

All European producers participating in this study operated within vertically integrated organizations that included sawmilling operations and, in many cases, additional forest products businesses. These organizations commonly produced a range of products beyond CLT, including glulam, pellets, bioenergy, pulp products, or other engineered wood products. As a result, lumber allocation decisions could be made across multiple manufacturing streams rather than being optimized solely for CLT production.

During a visit to an Austrian sawmill supplying to a CLT production, mill personnel described operational relationships with several nearby wood processing facilities. Thermal energy used for kiln drying was supplied through an underground pipeline connected to a pulp production facility located approximately 3 km from the sawmill. The sawmill also reported selling bark, chips, sawdust, and other wood residues to nearby pellet and pulp producers. Mill personnel indicated that these residual materials represented marketable by-products rather than waste streams and contributed additional revenue to sawmill operations. As a result, residual materials generated during sawmilling were utilized through other industrial processes, while thermal energy and material flows were shared among multiple forest products facilities.

This integrated approach was also reflected in lumber utilization strategies. Participants reported that sideboards were frequently directed toward CLT production, while higher-grade center-cut material was often reserved for glulam and other structural products requiring superior mechanical properties. This observation aligns with the historical development of the European CLT industry. Brandner (2013) noted that early CLT development was motivated in part by the need to create higher-value markets for sideboards generated during sawmilling operations. Through cross-lamination, these materials could be transformed into structural panels while benefiting from the dimensional stability provided by the layered configuration. The continued allocation of sideboards for CLT production observed in this study suggests that this principle remains embedded within many European manufacturing systems.

The ability to allocate materials across multiple products improves overall resource utilization by matching lumber characteristics to the requirements of specific applications. CLT manufacturing therefore operates as one component of an integrated forest products ecosystem designed to maximize value recovery from available timber resources.

5.4.2 Industrial Fragmentation and Supply Chain Constraints in North America

A different pattern was observed among North American producers. While vertically integrated examples were present, the industry as a whole appeared more fragmented, with lumber production, engineered wood manufacturing, design services, and construction activities frequently occurring within separate organizations. Under these conditions, optimization often occurs at the level of individual businesses rather than across the broader value chain.

Several participants noted that lumber supplied to CLT manufacturers was commonly sourced from production systems optimized for dimensional lumber markets. As discussed in previous sections, the dominant North American lumber industry remains closely tied to residential light-frame construction, which continues to represent the largest market for structural lumber products. Consequently, lumber dimensions, moisture specifications, grading systems, and processing practices are frequently established based on the needs of commodity lumber markets rather than mass timber manufacturing.

The findings of this study suggest that this industrial structure influences manufacturing efficiency throughout the value chain. Lumber supplied to CLT manufacturers often requires additional processing, including planing, moisture conditioning, grading, or sorting before entering production. While these practices are technically feasible, they represent additional steps that are not necessary when lumber specifications are more closely aligned with manufacturing requirements.

The broader forest products sector in the Pacific Northwest has also undergone significant structural changes over recent decades. Numerous pulp and paper facilities have closed or consolidated, and regional sawmill capacity remains below historical levels. As a result, opportunities to utilize manufacturing residuals across multiple product streams are more limited than in highly integrated forest products systems. Although markets remain for chips, sawdust, bark, and other byproducts, the supporting industrial infrastructure is often less concentrated than the systems observed among European participants.

These observations do not suggest a lack of manufacturing capability within North America. Rather, they indicate that the supporting industrial ecosystem surrounding mass timber production remains in an earlier stage of development than those observed in Europe.

5.4.3 Implications for North American Development

The findings do not suggest that North American producers should attempt to directly replicate European manufacturing systems. Differences in forest ownership, species composition, market structure, transportation networks, and building traditions create distinct operating environments. Nevertheless, several characteristics of the European model provide useful insights for future industry development.

First, the European experience demonstrates the value of coordinating lumber production and engineered wood manufacturing. The concept of lumber readiness discussed throughout this study appears to be closely linked to long-term relationships between sawmills and downstream manufacturers. Rather than producing lumber for a broad commodity market, sawmills within integrated systems often produce material tailored to specific manufacturing requirements.

Second, European producers demonstrate how multiple engineered wood products can coexist within a broader forest products ecosystem. The allocation of center-cut material to glulam production and sideboards to CLT production illustrates how different products can complement one another rather than compete for identical raw materials. Such specialization can improve overall material utilization while supporting a wider range of value-added manufacturing activities.

Third, the historical development of CLT in Europe suggests that industrial specialization emerged gradually rather than through deliberate planning alone. The current system appears to be the result of decades of interaction among sawmills, engineered wood manufacturers, architects, engineers, and construction markets. Consequently, many of the advantages observed today likely reflect long-term industry evolution rather than isolated technological innovations.

5.4.4 Future Development Pathways

The findings of this study suggest that future improvements in the competitiveness of North American CLT manufacturing will depend not only on continued advances in production technology but also on the development of supporting industrial ecosystems. Considerable progress has already been achieved in automation, production equipment, and manufacturing capacity. The remaining opportunities identified in this study are associated primarily with lumber preparation, supply chain coordination, and product specialization, indicating that future gains are likely to come increasingly from improvements beyond the individual manufacturing facility.

Greater collaboration between sawmills and CLT manufacturers will encourage the development of lumber products specifically intended for mass timber applications. Similar to the historical evolution of laminating stock for glulam manufacturing, continued growth in CLT production will eventually justify lumber dimensions, moisture specifications, grading systems, and edge profiles better aligned with the requirements of engineered wood manufacturing. Such developments will reduce downstream processing requirements while improving manufacturing flexibility and material utilization throughout the production chain.

At present, the North American mass timber industry continues to face a coordination challenge. Although CLT manufacturers would benefit from lumber products better aligned with mass timber production, the current market remains too small to justify widespread changes in sawmill production practices. As discussed in Section 5.2, mass timber currently represents only a small proportion of regional lumber consumption, limiting the economic incentive for sawmills to develop specialized products for CLT manufacturing. Continued market growth will strengthen this business case, encouraging closer coordination between sawmills and downstream manufacturers and supporting further specialization throughout the supply chain.

Ultimately, the findings suggest that the future competitiveness of North American mass timber manufacturing will depend not only on the performance of individual CLT facilities but also on the development of supporting industrial ecosystems capable of coordinating activities across the value chain. The European examples examined in this study indicate that lumber readiness, manufacturing flexibility, and material utilization are closely connected to broader relationships among forests, sawmills, engineered wood manufacturers, designers, and construction markets. As North American mass timber markets continue to mature, strengthening these connections represent one of the most significant opportunities for improving industry competitiveness and expanding the adoption of mass timber construction.

Despite the challenges discussed throughout this study, the long-term outlook for mass timber development in North America remains positive. Recent projections of mass timber adoption indicate substantial long-term growth driven by expanding building code acceptance, increasing demand for low-carbon construction, and broader adoption across residential and non-residential building sectors (Nepal et al., 2024). International demand projections similarly indicate continued growth in CLT and glulam markets across both mature and emerging economies, with North America expected to remain one of the major growth regions for mass timber construction (Ganguly et al., 2025). As production volumes increase and supply chains continue to mature, opportunities will emerge for greater specialization, improved coordination between sawmills and manufacturers, and the development of industrial ecosystems capable of supporting more efficient mass timber production. Consequently, many of the constraints identified in this study represent characteristics of an emerging industry rather than permanent limitations of the North American market.

5.5 Katerra: A Case Study of Vertical Integration in North America

Katerra provides a useful case study for examining the challenges associated with industrializing mass timber construction in North America. Founded in 2015, the company represented one of the most ambitious attempts to transform the construction industry through vertically integrated off-site manufacturing, combining architecture, engineering, procurement, manufacturing, and construction within a single organization (Davis, 2021). Through acquisitions such as Michael Green Architecture and Lord Aeck Sargent, Katerra expanded beyond manufacturing to integrate multiple stages of the building delivery process (Gragg, 2018). Unlike the European producers examined in this study, whose integration primarily evolved from upstream forestry and sawmilling into engineered wood manufacturing, Katerra pursued integration from the downstream end of the value chain. The underlying premise was that greater coordination across these activities would improve efficiency, reduce costs, and accelerate the adoption of industrialized construction methods.

Several aspects of Katerra's strategy reflected challenges identified in this study. The company's integrated business model sought to improve coordination among material suppliers, manufacturers, designers, and contractors through a single organizational structure. Its investment in mass timber manufacturing therefore represented an effort to establish an integrated industrial system capable of supporting the large-scale adoption of prefabricated timber construction.

One of the most significant components of this strategy was the development of the CLT manufacturing facility in Spokane, Washington. At the time of its construction, the facility represented one of the largest and most technologically advanced CLT plants in North America. The scale of this investment demonstrated confidence in the long-term growth of mass timber construction and reflected expectations that manufacturing capacity would become a key constraint to industry expansion.

Notably, the facility continued operating following Katerra's bankruptcy after being acquired by Mercer Mass Timber, suggesting that the manufacturing technology itself remained viable and valuable within the broader industry.

The comparison between Katerra and the European producers examined in this study highlights an important distinction between corporate integration and industrial ecosystem development. The findings of this study suggest that successful CLT production depends not only on manufacturing equipment and plant capacity but also on supporting systems that coordinate raw material supply, lumber preparation, product development, market demand, and downstream construction activities. European CLT producers developed within industrial systems that evolved gradually over several decades, allowing sawmills, engineered wood manufacturers, designers, and contractors to adapt alongside one another. Katerra attempted to establish multiple components of this system simultaneously within a relatively short period.

The findings presented in Sections 5.1 and 5.2 suggest that the effectiveness of industrialization strategies depend on the maturity of supporting supply chains. The European producers participating in this study benefited from established relationships between sawmills and engineered wood manufacturers, specialized lumber products developed for mass timber applications, and production systems that evolved alongside market demand. North American producers continue to operate within a forest products sector largely oriented toward dimensional lumber production. Under these conditions, rapid industrialization faces challenges that extend beyond manufacturing technology itself.

Katerra's integration of architecture, engineering, manufacturing, and construction also reflects a broader challenge within industrialized timber construction. Manufacturing efficiency is influenced not only by production technology but also by the extent to which building design aligns with manufacturing capabilities. Design decisions affect panel dimensions, layup configurations, material utilization, and production scheduling. Greater coordination between designers and manufacturers therefore creates opportunities to improve efficiency throughout the value chain. This relationship was also reflected in the findings of the present study. European producers reported greater flexibility in panel layup configurations, allowing panel thicknesses to be more closely matched to project requirements. Such flexibility depends not only on manufacturing technology but also on coordination between design requirements, lumber supply, and production systems. The implications of panel layup flexibility and its influence on material utilization are discussed further in Section 5.3.

Katerra illustrates that large-scale investment in manufacturing capacity alone is insufficient to accelerate industrial development when supporting supply chains and market structures are still evolving. While industrialization remains a promising pathway for increasing the adoption of mass timber construction, the findings of this study suggest that long-term success depends on coordinated development across the broader value chain, including lumber production, manufacturing, design, and construction. Viewed in this context, Katerra illustrates both the opportunities and the challenges of accelerating industrial transformation within an emerging mass timber industry, while reinforcing the importance of gradual ecosystem development alongside advances in manufacturing technology.

5.6 Limitations

This study employed a comparative case study approach involving interviews, field observations, and site visits with a limited number of CLT producers in North America and Europe. Although the participating companies represented a range of production capacities, ownership structures, and manufacturing systems, the sample was not intended to be statistically representative of the global CLT industry. Consequently, the findings should be interpreted as observations derived from the participating producers rather than conclusions applicable to the entire CLT industry.

Much of the analysis relied on interviews with industry participants. Due to the commercial sensitivity of manufacturing operations, detailed quantitative data relating to production costs, material yields, rejection rates, and operating performance were generally unavailable. The study therefore emphasizes patterns that were consistently observed across interviews and field visits rather than direct quantitative comparisons among producers.

The European cases were concentrated primarily in Central Europe, where vertically integrated forest products companies have played a prominent role in the development of CLT manufacturing. The North American cases were limited to producers operating within the United States and Canada. Other regions may exhibit different industrial structures, market conditions, and manufacturing practices that were beyond the scope of this study.

Future research could expand the number of participating producers and incorporate more comprehensive quantitative manufacturing data as the North American mass timber industry continues to develop. Longitudinal studies examining changes in lumber readiness, supply chain coordination, and industrial ecosystem development over time would further improve understanding of the relationships identified in this research. Additional investigation of the economic impacts of specialized lumber production for CLT manufacturing would also provide valuable support for future industry development.

Despite these limitations, the study provides one of the first comparative examinations of lumber readiness, supply chain organization, and industrial ecosystems as interconnected factors influencing CLT manufacturing costs in North America and Europe.

5.7 Conclusions and Recommendations

5.7.1 Conclusions

This study examined factors influencing CLT manufacturing systems in Europe and North America through interviews with eight CLT producers, field observations, sawmill visits, and a review of relevant literature. The original objective was to investigate production cost factors within CLT manufacturing. While previous studies have identified lumber costs as a major determinant of CLT economics, the findings of this research suggest that the characteristics of lumber entering the manufacturing process are also important in explaining differences in manufacturing efficiency and production practices.

The findings indicate that the most significant differences between European and North American producers were associated with lumber readiness, supply chain organization, and panel design flexibility rather than manufacturing technology itself. European producers generally received lumber that more closely matched manufacturing requirements in terms of moisture content, dimensions, edge profiles, and processing condition. As a result, less downstream processing was required before production. By comparison, North American producers frequently relied on lumber products originally developed for dimensional lumber markets, resulting in additional preparation requirements before manufacturing.

The study also found that supply chain integration played an important role in shaping manufacturing practices. All European producers participating in this study operated within vertically integrated organizations, while North American producers utilized a wider range of sourcing models. The findings suggest that integration improves coordination between sawmills and manufacturers and contributes to greater lumber readiness. However, the study also found that large production capacities can be achieved through externally sourced supply chains, indicating that integration is not the only pathway for industry growth.

Differences were also observed in panel layup systems and product flexibility. European producers generally offered a wider range of panel thicknesses and configurations, while North American producers relied more heavily on standardized panel systems. These differences appeared to be influenced by lumber supply characteristics, market requirements, and historical industry development rather than technological constraints. The findings suggest that panel design flexibility can influence not only manufacturing operations but also structural design, fire performance, material consumption, and project-level decision making.

Taken together, the results indicate that many of the observed differences between European and North American CLT manufacturing systems are best understood as outcomes of different industrial development pathways. The advantages observed among European producers appear to reflect decades of specialization and integration among forests, sawmills, engineered wood manufacturers, and construction markets. Consequently, differences in manufacturing efficiency are not solely attributable to technology or equipment but are closely connected to the maturity of the broader industrial ecosystem.

5.7.2 Industry Recommendations

The findings suggest opportunities for improving coordination between sawmills and CLT manufacturers within North America. Current production systems remain largely dependent on lumber products originally developed for light-frame construction markets. As mass timber markets continue to expand, greater collaboration between sawmills and manufacturers could support the development of lumber specifications better aligned with CLT manufacturing requirements. Such developments could reduce downstream processing requirements while improving manufacturing efficiency.

The study also highlights the importance of considering CLT manufacturing within the context of the broader forest products industry. The European examples examined in this research demonstrate how lumber allocation, engineered wood manufacturing, and by-product utilization can function as interconnected components of a larger industrial ecosystem. While direct replication of European systems may not be feasible, strengthening collaboration among sawmills, engineered wood manufacturers, designers, and construction markets improves resource utilization and industry competitiveness.

Opportunities also exist to increase coordination between design and manufacturing. Greater collaboration among architects, engineers, and manufacturers could improve alignment between panel specifications and manufacturing capabilities, potentially enhancing material efficiency and reducing unnecessary processing requirements. The findings suggest that future competitiveness depends not only on improvements in manufacturing technology but also on stronger integration across the value chain.

Despite current challenges, the long-term outlook for mass timber development in North America remains positive. Continued market growth will eventually support greater specialization within lumber supply chains, similar to the historical development of laminating stock for the glulam industry. As production volumes increase and markets mature, opportunities will emerge for more specialized feedstocks, expanded panel flexibility, and stronger industrial coordination.

5.7.3 Recommendations for Future Research

Future research should focus on quantifying the economic impacts of lumber readiness within CLT manufacturing systems. While this study identified moisture content, dimensions, edge profiles, and processing requirements as important factors influencing manufacturing efficiency, additional research is needed to determine their effects on production costs, material utilization, and product pricing.

Further investigation into panel layup optimization and material consumption would also be valuable. The differences in panel flexibility observed between European and North American producers suggest potential opportunities for improving material efficiency and design optimization. Quantitative studies evaluating the relationship between panel configurations, structural performance, fire requirements, and material use could provide additional insight into these issues.

Finally, future research should continue to examine the development of mass timber industrial ecosystems within North America. As manufacturing capacity expands and supply chains evolve, opportunities will arise to better understand the relationships among sawmills, engineered wood manufacturers, designers, contractors, and end-use markets. Longitudinal studies tracking industry development over time will help determine whether some of the differences identified in this study diminish as the North American mass timber sector matures.

The findings of this study indicate that many of the differences observed between European and North American CLT manufacturing systems reflect different stages of industrial development rather than differences in technological capability. North America possesses abundant forest resources, advanced manufacturing technologies, and growing market demand for mass timber construction. Continued research documenting the evolution of lumber supply chains, manufacturing practices, and industrial ecosystems will improve understanding of how these systems develop as the North American mass timber sector continues to mature.

References

Adhikari, S., Bond, B., Quesada, H. J., & Smith, R. L. (2024). Lumber Supply-Chain Practice in Cross-Laminated Timber Industries in the United States: A Comparison with Austrian Producers. *Forest Products Journal*. https://doi.org/10.13073/fpj-d-23-00018

Anderson, R., Spiritos, E., Sills, N., & Slavin, K. (2025). *2025 PNW Regional Mass Timber Market Study*.

APA – The Engineered Wood Association. (2019). *ANSI/APA PRG 320: Standard for Performance Rated Cross-Laminated Timber* (ANSI/APA PRG 320). APA – The Engineered Wood Association.

Brandner, R. (2013). *Production and Technology of Cross Laminated Timber (CLT): A state-of-the-art Report*.

Brandt, K., Wilson, A., Bender, D., Dolan, J. D., & Wolcott, M. P. (2019). Techno-economic analysis for manufacturing cross-laminated timber. *BioResources*, *14*(4), 7790–7804. https://doi.org/10.15376/biores.14.4.7790-7804

Crawford, D., Hairstans, R., Smith, S. D., & Papastavrou, P. (2015). *Viability of cross-laminated timber from UK resources*. https://doi.org/10.1680/COMA.14.00064

Davis, D. (2021, June 18). Katerra's $2 Billion Legacy. *Architect Magazine*. https://www.architectmagazine.com/technology/katerras-2-billion-legacy_o

Espinoza, O., & Buehlmann, U. (2018). Cross-Laminated Timber in the USA:

Opportunity for Hardwoods? *Current Forestry Reports*, *4*(1), 1–12. https://doi.org/10.1007/s40725-018-0071-x

European Committee for Standardization. (2004). *Eurocode 5: Design of timber structures* (EN 1995-1-1). CEN.

European Committee for Standardization. (2015). *EN 16351: Timber structures—Cross laminated timber—Requirements* (EN 16351). CEN.

Ganguly, I., Akintola, A., & Chen, C. (2025). *Projected Mass Timber Use in Residential and Non-Residential Construction: A Twelve-Country Analysis*. https://doi.org/10.2139/ssrn.5365642

Gragg, R. (2018). Design-Build Giant Katerra Acquires Lord Aeck Sargent, Michael Green Architecture. *Architectural Record*. https://www.architecturalrecord.com/articles/13471-design-build-giant-katerra-acquires-lord-aeck-sargent-michael-green-architecture

Hancock, D. R., Algozzine, B., & Lim, J. H. (2021). *Doing Case Study Research: A Practical Guide for Beginning Researchers* (Fourth Edition). Teachers College Press.

Jauk, G. (2025a, January 15). *2024 production analysis*. Timber Online. https://www.timber-online.net/content/holz/holzkurier/en/sawn_timber/2025/01/2024-production-analysis.html

Jauk, G. (2025b, April 23). *Cross-laminated timber as export success*. Timber Online. https://www.timber-online.net/content/holz/holzkurier/en/wood_products/2025/04/cross-laminated-timber-as-export-success.html

Nepal, P., Johnston, C., & Ganguly, I. (2021). Effects on Global Forests and Wood Product Markets of Increased Demand for Mass Timber. *Sustainability*. https://api.semanticscholar.org/CorpusId:245370187

Nepal, P., Prestemon, J. P., Ganguly, I., Kumar, V., Bergman, R. D., & Poudyal, N. C. (2024). The potential use of mass timber in mid-to high-rise construction and the associated carbon benefits in the United States. *PLOS ONE*, *19*(3), e0298379. https://doi.org/10.1371/journal.pone.0298379

Oscarsson, J., Olsson, A., Johansson, M., Enquist, B., & Serrano, E. (2011). Strength grading of narrow dimension Norway spruce side boards in the wet state using first axial resonance frequency. *International Wood Products Journal*, *2*(2), 108–114. https://doi.org/10.1179/2042645311Y.0000000015

Yang, L., Mo, J., Read, I., & Wheiler, K. (2026). *Global Mass Timber Projects & Producers*. Center for International Trade in Forest Products, University of Washington. https://cintrafor.org/research-brief/global-mass-timberprojects-producers/

Yin, R. K. (2018). *Case study research and applications: Design and methods* (Sixth edition). SAGE.

Zelaya, A. (2020). *Identifying Drivers and Barriers for Investment in Oregon's Mass Timber Manufacturing Supply Chain*. TallWood Design Institute & Business Oregon.

Zhang, Z., & Lan, K. (2022). Understanding the Impacts of Plant Capacities and Uncertainties on the Techno-Economic Analysis of Cross-Laminated Timber Production in the Southern U.S. *Journal of Renewable Materials*, *10*(1), 53–73. https://doi.org/10.32604/jrm.2022.017506